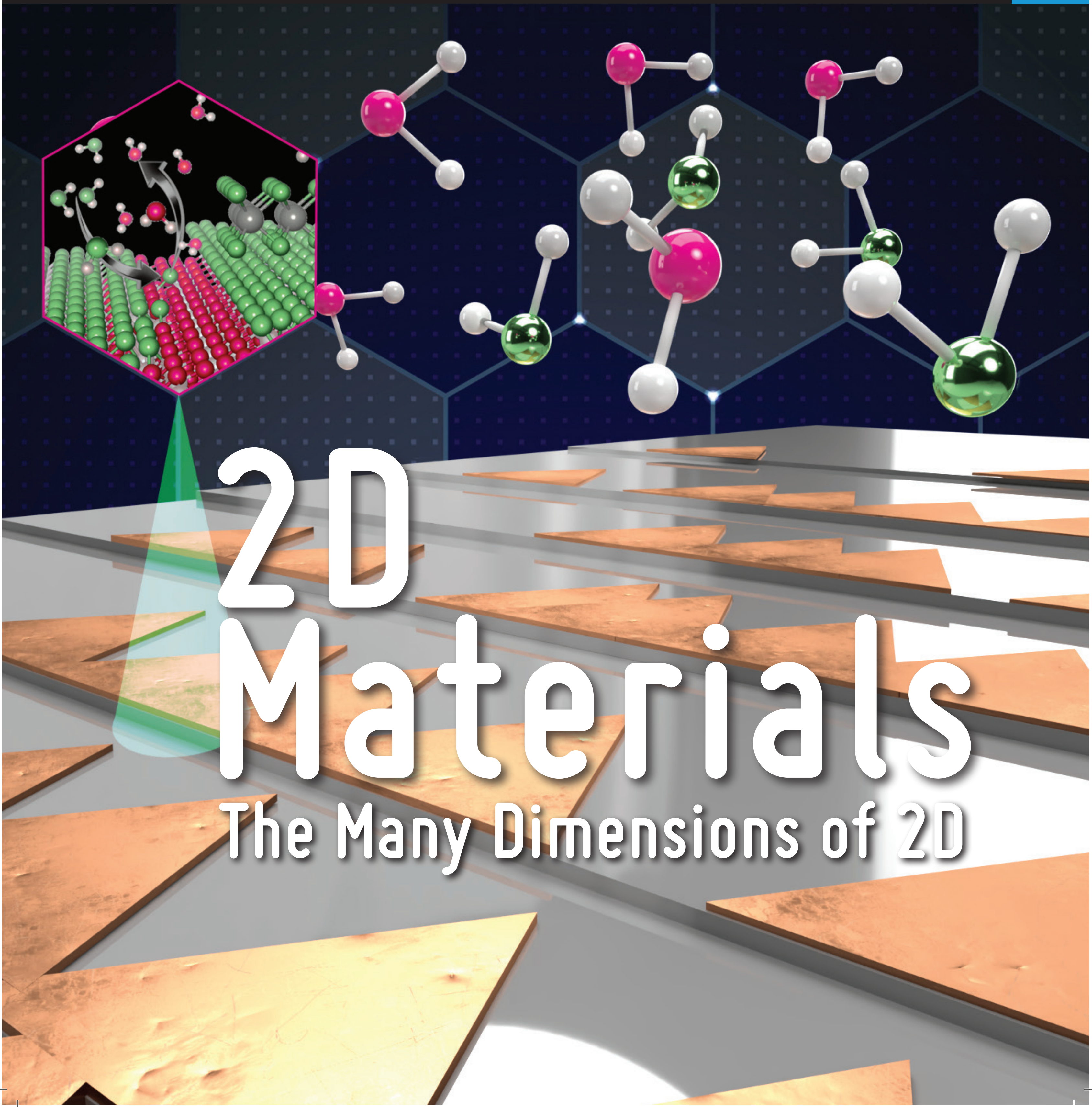
PennState
Materials Research
Institute

FOCUS on MATERIALS

MATERIALS RESEARCH INSTITUTE MAGAZINE

SPRING 2024



2D Materials

The Many Dimensions of 2D

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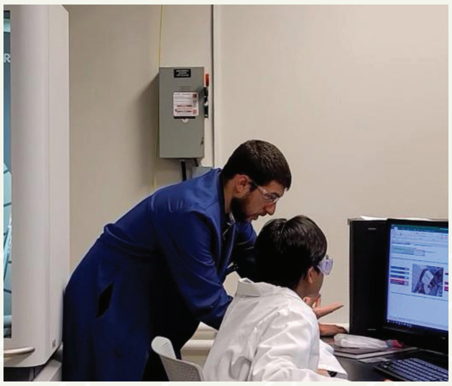

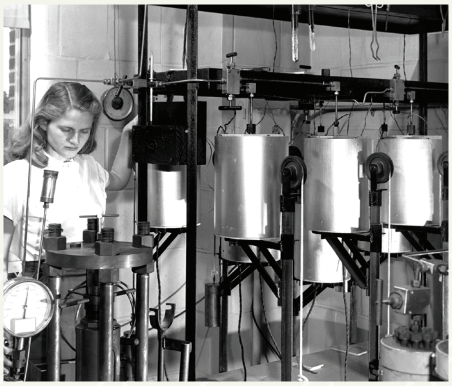

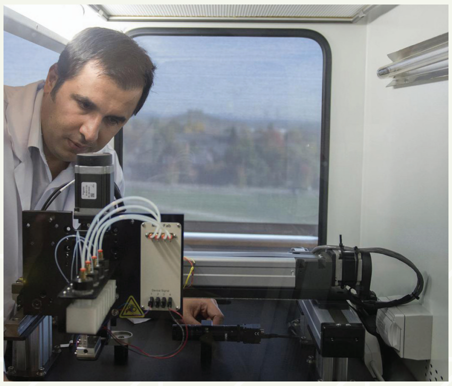

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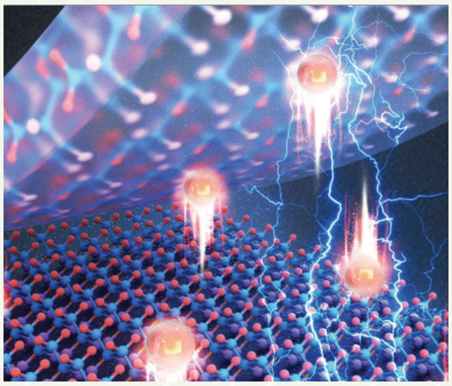
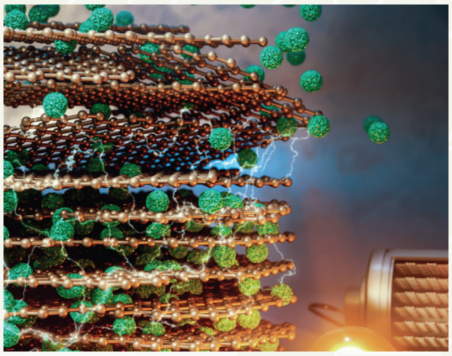
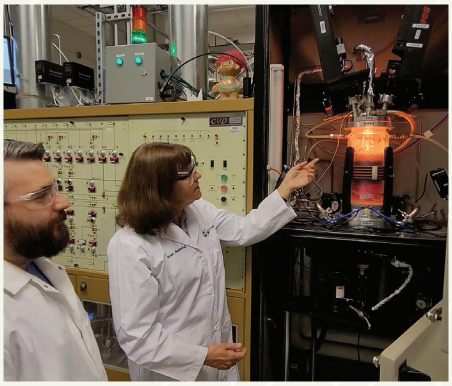
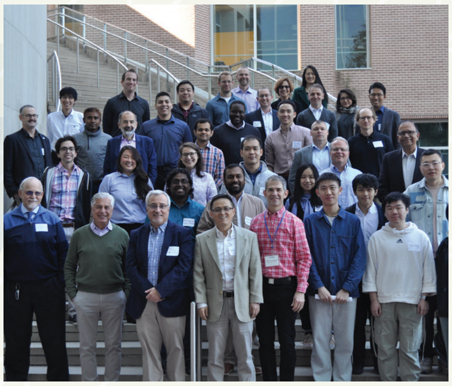
Clive Randall, distinguished professor of materials science and engineering and director of the Materials Research Institute at Penn State, has been named an Evan Pugh University Professor. The Evan Pugh Professorship is the highest distinction bestowed upon faculty by Penn State. Read more at bit.ly/CliveRandall









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MATERIALS RESEARCH INSTITUTE BULLETIN

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

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From the Director

Two-dimensional (2D) materials hold immense promise for developing the next generation of semiconductor technologies. The Material Research Institute's (MRI) goal is to strategically guide investments and intellectual endeavors that will maximize the scientific and societal impact of 2D materials, and this requires carefully considering emerging opportunities and positioning our resources for long-term leadership in the field.

Just under a decade ago, when the National Science Foundation first put out their call for Materials Innovation Platforms (MIP), our team at MRI engaged in thoughtful debate about how best to position ourselves at the forefront of materials science to land an MIP. While graphene had captured the world's attention at that time, we recognized the opportunity to push beyond a single material into the discovery of new 2D materials. MRI had already supported the Center for 2D Layered Materials (2DLM) which was a precursor to exploring a broader number of 2D materials with Mauricio Terrones and Josh Robinson. Penn State was then awarded funding to establish an MIP, which became the Two-Dimensional Crystal Consortium (2DCC), under the leadership of Professor Joan Redwing.

C A Randall

Clive Randall
Director, Materials Research Institute
Evan Pugh University Professor of Materials Science and Engineering

Terrones and Robinson in 2015 founded the Center for Atomically Thin Multi-Functional Coatings (ATOMIC), working with Rice University and later also partnering with Boise State University to drive research in 2D materials and foster collaboration between academia and industry. From that first group of pioneering faculty, our 2D materials research program grew to the point where it has allowed us to recruit or engage over 50 faculty for cutting-edge 2D materials work.

Our faculty, staff, and students working in this area enabled fundamental discoveries in materials growth, characterization, and theory that have positioned us at the forefront of this field. We have learned invaluable lessons about optimizing materials processes by taking a data-driven approach (you can learn more here: https://bit.ly/2DCC-LiST) and heavily instrumenting our synthesis and metrology capabilities, therefore optimizing materials processes. This philosophy will underpin much of the synthesis and device work across MRI in the future. The interdisciplinary research between data science, materials synthesis, and device fabrication is entering a new era in materials development.

Through strategic hires like Saptarshi Das, whom you will read about in this issue, we have built a world-class team spanning materials growth, device fabrication, and computational modeling. This infrastructure has allowed us to establish impactful partnerships with universities nationwide. For example, the 2DCC provides a national user facility for academic and industrial collaborators alike.

With an eye towards diversity, equity, and inclusion in 2D material research, we have also forged partnerships in minority-serving institutions through programs increasing diversity in STEM. One such partnership is highlighted in this issue, our work with Florida International University via the NSF's Partnerships for Research and Education in Materials (PREM) program.

Looking ahead, future challenges will involve leveraging the methodologies we have developed to address the increasing demands for higher-quality materials synthesized at larger scales. This will drive us to progress beyond proof-of-concept device demonstrations and prototyping towards a higher level of quality control that can enable large-scale manufacturing and commercialization, and this would include even more partnerships with industry and academia. One example that is in the very early stages is the 2D Foundry, which would help to drive these efforts.

After over a decade and a half of progress, I am proud that MRI continues pushing the boundaries of 2D materials science with an interdisciplinary perspective and enabling next-generation devices, in turn benefiting society through new technologies and economic opportunities. Our journey with 2D materials exemplifies the power of strategic long-term investments, clustering faculty collaborations within centers, and driving basic science with an application pull for acceleration of transformative research areas.

Chad Eichfeld, left, associate research professor and Nanofabrication Lab director of operations, and Amira Meddeb, research professor, electrical characterizations, in the Nanofabrications Lab with the Lithoz CeraFab Lab 3D printer. Credit: Jamie Oberdick

NEWLY ACQUIRED 3D PRINTER BOOSTS PENN STATE'S ADVANCED CERAMIC RESEARCH

A RECENTLY INSTALLED 3D ceramics printer offers Penn State materials researchers advanced capabilities to easily produce high-resolution ceramic parts and other innovative ceramics for cutting-edge materials research at a lower cost than sourcing them.

While many are familiar with ceramics as art or household items like coffee mugs, ceramics have lesser-known applications ranging from energy storage via solid-state batteries to ferroelectric and piezoelectric devices such as heat sensors. Researchers from Penn State's Materials Research Institute (MRI) said they view the Lithoz CeraFab Lab 3D printer as a necessary tool to further materials-related research across the entire University.

> "This will be part of a user facility here at Penn State, in the Nanofabrication Lab," said Amira Meddeb, associate research professor in MRI. "The number one reason we acquired it is to allow more capabilities not just for the Penn State community but also for our extended user community that we work with, including other higher education institutions and industry."

Enabling this production also allows MRI to create custom scientific tools for other Penn State researchers, which ordinarily are expensive and difficult to source.

"The printer allows us to produce custom and complex parts that are usually costly and have long lead times, such as custom-designed crucibles and microreactors," Meddeb said.

The resin-based printer uses digital light processing technology, a technique that uses light to cure photosensitive liquid resins into hard solids. This enables in-house production of high-resolution parts and full-density ceramics comparable in properties and microstructure to ceramics made by traditional manufacturing methods.

"Ceramics are extremely hard to manufacture traditionally for a variety of reasons, especially because they're so hard when they're finished and sintered, they're very difficult to machine," said Shawn Allan, vice president of Lithoz America LLC. "In addition, they can be delicate before they are sintered so in that state, they are also hard to fixture and machine. Versus with this printer, you can much more easily make multiple iterations of a part with different geometries and different dimensions and get the actual part you need."

▶▶▶

The printer can print a wide variety of ceramic materials. It offers the ability to easily change materials for different projects, and it is relatively simple to learn to use, especially for someone with a traditional ceramics processing background. The printer rounds out the research offerings provided by MRI, according to Chad Eichfeld, associate research professor and director of operations in the Nanofabrication Lab.

Along with research benefits, Eichfeld noted that the new printer has a lot of potential for materials education at Penn State.

“Penn State is a hands-on educational institution,” Eichfeld said. “At other universities, a student might give some of the processing that is done in Amira’s lab and my lab to a technician, and they would do the work for you. But we are all hands-on. That is powerful, with our graduate students and even some undergraduates getting hands-on experience with state-of-the-art technology here. That experience will be really rewarding for them as they begin their career." ■

WORKSHOP FOSTERS PARTNERSHIPS TO POSITION U.S. AS LEADER IN SEMICONDUCTORS

WHEN PRESIDENT JOE BIDEN signed the CHIPS (Creating Helpful Incentives to Produce Semiconductors) and Science Act on Aug. 9, 2022, to accelerate U.S. manufacturing of semiconductors, Penn State took action. The University created the Mid-Atlantic Semiconductor Hub (MASH) with other academic partners, industry, and state governments to lead and leverage the cumulative expertise in this area.

On May 22-23, the newly formed MASH consortium met at University Park to focus on identifying industry-academia-government partnerships that will position the U.S. for technology and workforce leadership in semiconductors and microelectronics.

The two-day event included representatives from partnering universities, government agencies, community colleges, and industries in the Mid-Atlantic region.

Much of the event focused on the critical nature of the CHIPS opportunity and national prioritization of this need, as emphasized by the sharing of a quote from Biden at a CHIPS event in Poughkeepsie, New York, last fall: “The world is at an inflection point, and the decisions we make in the next 10 years are going to fundamentally alter the way we look at the world and our place in the world.”

MASH represents a key location for expertise, facilities, and workforce

The Mid-Atlantic region of the U.S. has the highest density of laboratories and universities in the world. In addition, with more than 60 million people who call the region home, it offers a workforce pipeline to fill the jobs needed to manufacture semiconductors.

Preexisting facilities, expertise, and workforce depth all give the region both agility and the ability to start creating solutions.

Solutions will require the strengths of each MASH partner

Collaboration was a big focus of the event, both in formal sessions and purposeful networking breaks that took place throughout the two days. National semiconductor experts

Daniel Lopez, Liang Professor of Electrical Engineering and Computer Science and director of the Nanofabrication Lab, introduces Penn State President Neeli Bendapudi to kick off the Mid-Atlantic Semiconductor Hub (MASH) Spring 2023 Workshop on May 22. Credit: Jennifer M. McCann/Penn State MRI

ate lunch beside academic researchers, and industry analysts brainstormed with government talent. David Fried, corporate vice president of Lam Research, mentioned the days of Sputnik and the "space race" and how scientists around the nation rushed to collaborate for a common good, and the feeling of unity, determination, and a lot of energy fit the zeitgeist of the event perfectly.

Creating opportunities for all talent with workforce development

A project this massive and impactful on the U.S. requires millions of workers. Experts project that 300,000 direct jobs will be created and the supporting supply chain will create another 1.7 million jobs over the next 10 years.

This scale presents both opportunities for high-paying jobs and a tremendous challenge: Where will all this talent come from? According to National Science Board Vice Chair Victor McCrary, the answer comes down to education and access. He said that to create a workforce to solve these challenges, education needs to be accessible to all students.

The power to make a difference

Penn State's resources and assets — from the state-of-the-art facilities in the Materials Research Institute to the engaging, collaborative panel sessions to those dedicated to research, innovation, and translation — were on full display during the event. It was an opportunity to see Penn State as a collaborative part of a Mid-Atlantic powerhouse and an internationally recognized leader in semiconductor research and development and as a national leader in the education and development of the semiconductor workforce.

By leveraging Penn State's specific strengths along with its proven prowess in collaboration, MASH is ready to meet the CHIPS and Science Act's opportunities. ■

MASH Mid-Atlantic
SEMICONDUCTOR HUB

From upcoming workshops to a listing of partners to subscribing to MASH updates, learn more by visiting the MASH Semiconductor Hub website: mash-semiconductors.org.

Gino Tambourine, technical staff, X-ray/particle/thermal with the Materials Research Institute (MRI), mentors Muhammad Ishak, third-year materials science and engineering and MRI Undergraduate Fellow, on reading research data. Credit: Seana Wood/Penn State MRI

FELLOWSHIP GIVES UNDERGRADUATES CHANCE TO DO RESEARCH WITH REAL IMPACT

ONE OF THE more innovative energy-saving tools at Penn State was not implemented by a faculty member, employee, or graduate student. Instead, it was developed by undergraduate students who are part of an innovative and unique research fellowship offered by the Materials Research Institute (MRI).

MRI's Undergraduate Research Fellowship is unique in that it offers undergraduate students an opportunity to receive training and use the high-end scientific instrumentation available in the Millennium Science Complex. This is something only students at a graduate level usually have access to. Each of the undergraduate fellows are assigned a few main projects for their time working with MRI faculty and research staff, and this included the innovative energy-saving idea, which was a sensor for laboratory fume hoods to make sure the fume hood sash was closed when not in use.

However, the fellowship experience is not limited to their assigned projects. They are exposed to various research projects that enable them to receive hands-on experiential learning working with research staff in MRI's core facilities. And beyond this, they also receive opportunities to work with some of the approximately 1,000 researchers from 45 Penn State departments doing cutting-edge research work at the University. They also have opportunities to interact with MRI's more than 100 external research partners from other higher education institutions and industry, giving them valuable contacts and resume points for future employment and graduate school searches.

The fellowship is the brainchild of its director, Maxwell Wetherington, assistant research professor, molecular spectroscopy. Wetherington was inspired to create the program after recalling his own Penn State student experience, which included earning a bachelor of science degree in engineering science, a master of science degree in material science and engineering, and a doctor of philosophy degree in materials science and engineering.

Each year, five undergraduate students are selected as fellows. For the 2022-2023 version of the program that ended in May 2023, the students included Muhammad Ishak, third-year materials science and engineering; Harshit Jain, third-year computer science; Jongkyeong Kim, third-year year materials science and engineering; Baaz Misra, second-year computer science and engineering; and Alejandro Toro, third-year material science and engineering.

Kim's work during his fellowship included the fume hood sensor. He was inspired by some of his sustainability coursework that taught him that fume hoods have some of the greatest impact on energy use in a lab. This is due to the amount of energy required to keep a consistent airflow to remove hazardous fumes in a lab. Closing the sash when the lab is not in use reduces the volume of air that needs to be treated and exhausted, thus saving energy.

Ishak's project enabled him to work with a faculty member outside of Penn State, Tom Mallouk, currently the chair of the Department of Chemistry at the University of Pennsylvania. Like Kim, his project had an immediate impact on research at Penn State.

"I worked together with Mallouk to improve the accuracy and reproducibility of our Helium pycnometer, which measures the density and mass of solids, to develop a new, standardized operating procedure for that instrument," Ishak said.

For Jain, his projects put into practice what he has learned as a computer science major, especially around machine learning and artificial intelligence. One was developing an innovative web application that allows a researcher anywhere in the United States to find a specific research instrument near their location.

The other computer science-focused Fellow, Misra, credits the program in part with his switching to his current major from electrical engineering.

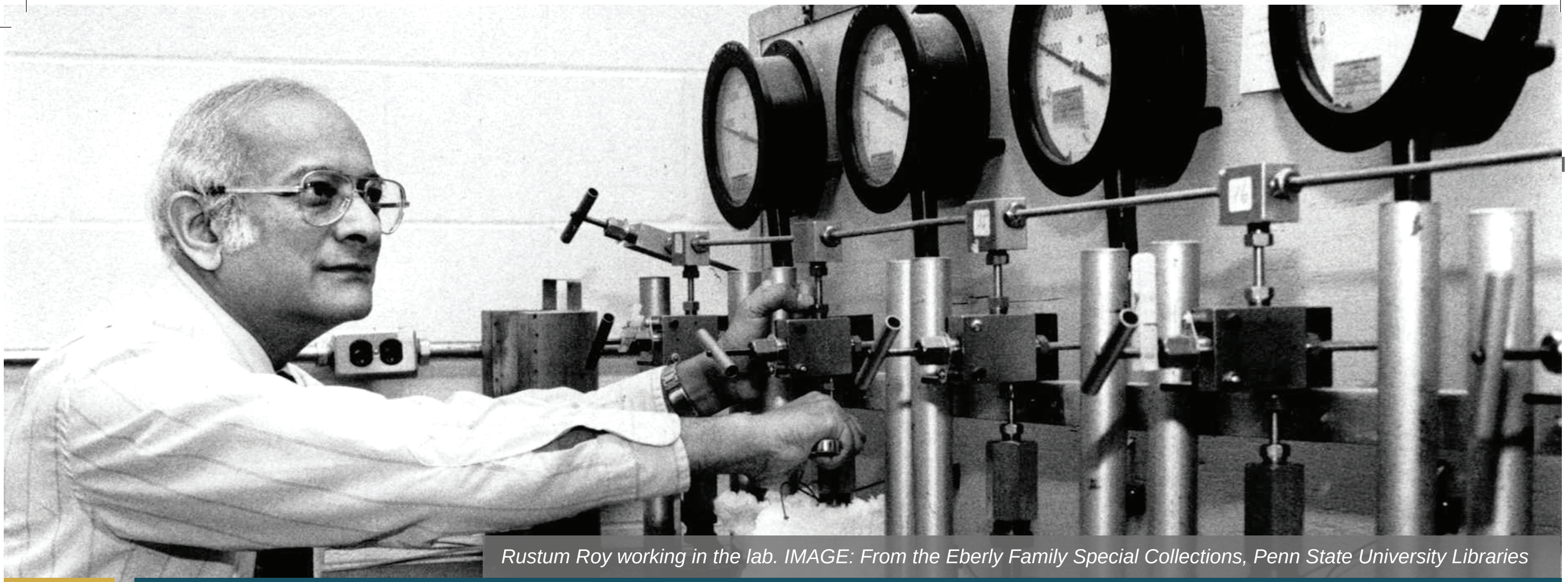
Misra's project work included supporting remote transmission electron microscopy, which involves users outside of University Park logging into a system that enables them to control the microscopes remotely.

> "I help support this capability, including learning how to operate the microscopes and troubleshoot them, which is important because it takes some time to learn all the machines' quirks and how to mitigate them for the remote users," Misra said. "Perhaps most importantly, I've learned when to know I can't solve something, and more advanced maintenance is needed."

Toro also worked with remote users at Penn State Harrisburg on scanning electron microscopy (SEM) and related focused ion beam work, along with prepping samples to be characterized by these tools.

"Right now, professors at Harrisburg are able to commission projects and research to be done on the SEM microscopes and focused ion beam for their own research," Toro said. "Through the fellowship, I can save these researchers time and money since they can do this work on our instruments remotely, so they do not have to travel to University Park from Harrisburg."

For more information on the program and to learn more about industry sponsorships, contact Wetherington at mtw5027@psu.edu or David Fecko, director of MRI industry collaboration, at dlf5023@psu.edu. ■



Rustum Roy working in the lab. IMAGE: From the Eberly Family Special Collections, Penn State University Libraries

AWARD KEEPS THE ROYS' LEGACY OF INTERDISCIPLINARY INNOVATION ALIVE

TWO OF PENN STATE'S most impactful materials researchers were a married couple: the late Rustum and Della Roy. Their collaborative efforts and individual achievements have played a pivotal role in advancing materials science, fostering interdisciplinary collaborations, and inspiring future generations of scientists. Part of this inspiration is an annual award that helps shape the future of materials research at Penn State.

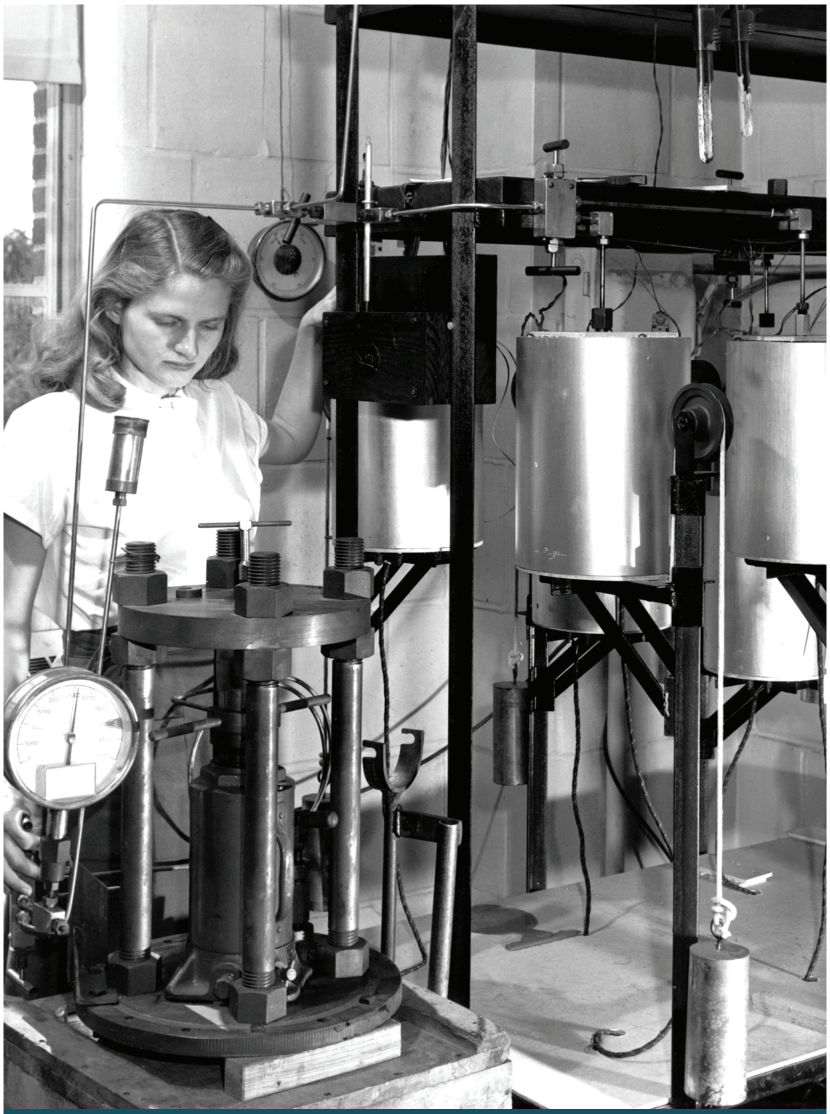
The Rustum and Della Roy Innovation in Materials Research Award is presented by the Materials Research Institute (MRI) and recognizes recent interdisciplinary materials research at Penn State that yields innovative and unexpected results. The award covers a wide range of research with societal impact and includes three categories: Early Career Faculty, Non-Tenure Faculty, and Research Staff, and Graduate Student. It exists thanks to a gift from Della and Rustum.

Della and Rustum were alumni of Penn State's College of Earth and Mineral Sciences and were long-serving faculty in the college. Rustum served for more than 50 years as an Evan Pugh Professor of the Solid State, professor of geochemistry, and professor of science, technology, and society. He gained a global reputation as a pioneer in interdisciplinary research. This included the nation's first Graduate Interdisciplinary Degree Program in Solid State Technology (now known as materials research), the first independent interdisciplinary Materials Research Laboratory (later became the Materials Research Institute), and the first undergraduate program in Science, Technology, and Society. He also founded two major national societies in these fields of research, including the Materials Research Society.

> "He was always full of new ideas, new approaches, and most importantly he was a diehard optimist," said Dinesh Agrawal, professor emeritus who worked with the Roys. "His eternal message was: Think positive, be persistent in your pursuit and you will attain success. He would always find something good or positive out of a hopeless situation or any seemingly failed experiment. He would always give you a sense of hope. Also, he was a workaholic, working almost 16 hours a day. His work-efficiency with alarming speed was amazing, he would be doing 10 things at the same time with quiet ease; even a man of 40 years old would not do that much work in one day what he was doing even when he was 85."

Part of Rustum's legacy is how effective interdisciplinary research has become at Penn State. In December 2019, a research team led by Steve Brint of the University of California, Riverside published an article in The Journal of Higher Education that evaluated the effectiveness of interdisciplinary research and cluster hiring at 20 universities; the study revealed that despite recruiting top experts in the field, interdisciplinary research was having difficulty taking hold. The study noted that "There are exceptions to this rule. One university in our sample stood out," which was Penn State.

During his graduate work, Rustum met Della as they shared an office and lab. Their relationship grew and they married in June 1948, a marriage that spanned 62 years until Rustum's death in 2010. She became renowned as a leader in the world of cement and concrete, known for her work in advanced concrete materials for pavements, chemically bonded cements, ancient cement-based building materials, and high-temperature cements for geothermal wells. Della proved to be an inspiration to female scientists, as her work resulted in a series of pioneering moments for women in STEM. The mineral dellaite was named after her in 1965. She is one of only 112 women to have a mineral named after them as of May 2019. In 1987, she became the first female materials scientist and the first Penn State woman to be inducted into the National Academy of Engineering (NAE). She was the third female scientist overall, and with Rustum's induction into the NAE in 1973, she formed the first spousal couple to be so honored. In 1971, with Penn State colleague Kathleen Mourant, she founded the journal Cement and Concrete, the first in its field, and served as its editor until 2005. Her other firsts included being elected to the World Academy of Ceramics as its first female member.


Della Roy working in the lab. IMAGE: From the Eberly Family Special Collections, Penn State University Libraries

"I was a student at the Materials Research Laboratory (MRL) where Rustum and Della were faculty members," said Michael Lanagan, professor of engineering science and mechanics. "They were part of a faculty team that created an amazing environment for students. The MRL was a unique place where there were shared labs, dedicated staff, and an international community that supported creative research."

The winners of the Roy Awards, the individuals at Penn State carrying on this legacy of interdisciplinary research success, are announced at the annual Materials Day, which is the Materials Research Institute's annual marquee event celebrating the best in materials research at Penn State. The 2023 winners included the following:

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Early Career Faculty

Amrita Basak,
assistant professor of mechanical engineering

Basak's work is built around high-impact transdisciplinary research that addresses the global requirement of sustainable manufacturing in power generation, propulsion, defense, energy storage, and construction. For metals, her research group uses laser powder bed fusion and laser directed energy deposition techniques to process high-performance materials such as iron and nickel alloys and oxide-dispersed strengthened alloys. Her research group is also interested in learning what makes certain materials have superior properties and how to use them.

"Our research has the potential to improve properties of parts fabricated by 3D printing reducing cost and material wastage," Basak said. "These would result in higher performance. For example, if we can make parts that can withstand high temperatures, gas turbines' efficiency would increase."

Elizabeth Elacqua,
assistant professor of chemistry

Elacqua's research group focuses on developing ways to synthesize new polymers. This research is nature-inspired and founded on using polymer chemistry to address bottlenecks in organic synthesis and using organic chemistry to address challenges in polymer synthesis. Her group also studies the use of abundant chemicals, such as those left over from the petroleum refining process, to make new rigid, diamond-like polymers.

"The polymers we are making thus far have specific applications ranging from light-promoted catalysis to organic semiconductors and high tensile strength materials," Elacqua said. "While everything is still in its infancy, we can envision accessing polymers that are integral components of future technologies, such as solar cells and composite materials."

Non-Tenure Faculty and Research Staff

Seng Huat Lee,
assistant research professor of bulk crystal growth

Lee's research revolves around new quantum materials, unique substances with extraordinary properties that make them of interest for developing faster computers, and advanced energy systems. He works to develop new quantum materials with tailored properties, particularly materials that potentially generate new types of quantum technologies. He uses various bulk growth techniques to synthesize and discover emergent quantum phenomena on bulk single crystals, which are crystals that form as a single, uniform piece which gives them unique behaviors.

"Government agencies have recognized the importance of developing novel quantum materials," Lee said. "Quantum materials hold the potential to revolutionize numerous industries, encompassing quantum information science, energy harvesting, and telecommunications, by ushering in next-generation technologies."

Wenjie Li,
associate research professor of materials science and engineering

Li's research focuses on the development of sustainable and renewable energy conversion materials and devices. One example is converting waste heat energy to useful electricity using thermoelectric materials. This research emphasizes both materials innovation and translation of materials properties to device and system performance to deliver practical solutions.

"My research focuses on materials and device innovations to accelerate science-based solutions that solve pressing societal problems in the area of energy, climate, and environmental sustainability," Li said. "My research can ultimately

2023 Roy Award winners include, clockwise from top left, Amrita Basik, Elizabeth Elacqua, Wenjie Li, Seng Huat Lee, Sarbashis Das and Tyus Yeingst. Credit: Materials Research Institute. All Rights Reserved

contribute to development of sustainable and renewable energy supplies and decarbonizations that can benefit everyone.”

Graduate Student

Sarbashis Das,
graduate student in electrical engineering

Das's research includes work to start a 2D materials foundry which will make the high-quality films grown by MRI’s Two-Dimensional Crystal Consortium Materials Innovation Platform available to the commercial marketplace. This was inspired by his participation in the National Science Foundation’s Innovation Corps program, which is for university-based researchers interested in exploring the commercialization potential of their work. His research also involves developing commercial artificial intelligence-aided graphene chemical sensors for use in real-time detection of food spoilage, adulteration, and contamination in food processing facilities.

"Our efforts will potentially lead to the mainstream adoption of 2D materials and their fascinating properties to solve real-world challenges,” Das said. “The use of 2D materials for real-time food spoilage sensors will enable us to tackle the global problem of food safety in a scalable and sustainable manner. Apart from food, this technology could have broad applications such as real-time monitoring of corrosion in critical infrastructure, which will improve public safety."

Tyus Yeingst,
graduate student in biomedical engineering

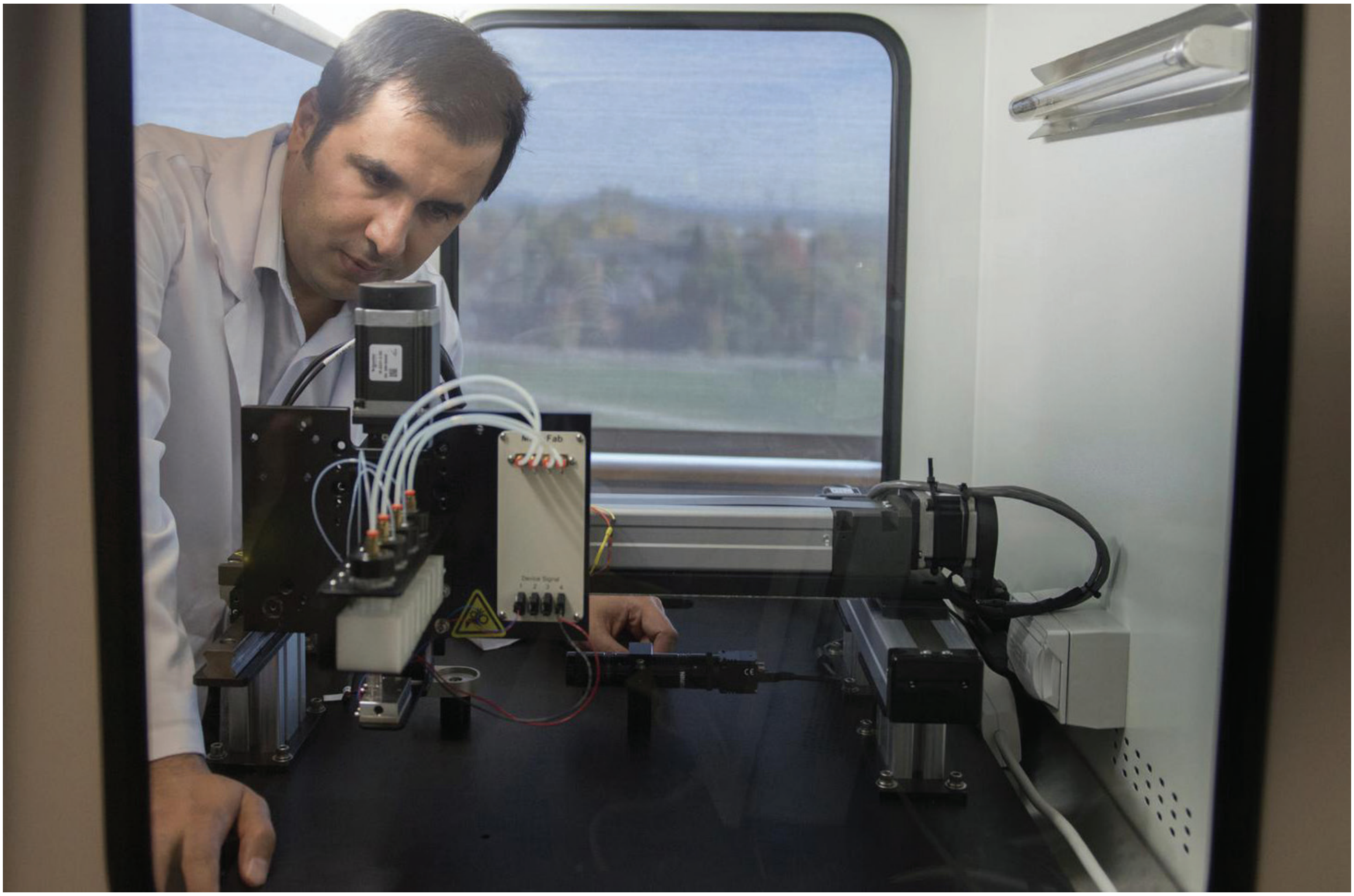
Yeingst’s research focuses on biomaterials, specifically hard polymers, hydrogels, and nanoparticles. The applications of these biomaterials are for tissue regeneration and cancer treatment. These materials are controlled using high-intensity focused ultrasound and near-infrared light to properly deliver and release the therapeutics. Along with his Roy Award, he was recognized as one of six Penn State graduate students to win the prestigious National Defense Science and Engineering Graduate Fellowship.

“Applications for my research include bone regeneration for those suffering from aging, osteomyelitis, cancer, and battlefield injuries,” Yeingst said. “Cancer treatment also covers a large base of the population, as everyone knows someone or is someone who has been affected by cancer.”

More information about the Roy Awards can be found at mri.psu.edu/RoyAwards. ■

FUNDING

NIH grant to facilitate high-speed bioprinting of bones, tracheas, organs



Ibrahim Ozbolat, professor of engineering science and mechanics, biomedical engineering and neurosurgery at Penn State, leads a lab that specializes in 3D printing to create a range of tissues for use in human health. Credit: Patrick Mansell/Penn State Creative Commons

By Adrienne Berard

DEVELOPING TECHNOLOGY TO quickly and efficiently bioprint human tissues at scale is the goal of a new project led by Penn State researchers. When fully developed, the technology will be the first to enable the fabrication of scalable, native tissues such as bones, tracheas, and organs.

The National Institute of Biomedical Imaging and Engineering at the National Institute of Health has awarded over $2 million in support of the project, led by Ibrahim T. Ozbolat, professor of engineering science and mechanics, biomedical engineering, and neurosurgery at Penn State.

> "This will be a platform technology, which can be used for multiple purposes," said Ozbolat. "It could be used for implantation, inserting tissue directly into the body, or it can bioprint model organs for research like drug development and disease modeling. The ultimate use is for healthcare applications, but it can cover a broad range of functions."

Ozbolat's lab has spent years developing a process to bioprint cellular aggregates like spheroids, three-dimensional clusters of cells that mimic the biology of tissues and tumors. In 2019, the research team was awarded funding from NSF to explore the fundamentals of the technique. Now the team will use funding from NIH to scale up the process and quickly bioprint spheroids into desired patterns for the fabrication of tissues with cell densities similar to what is found in nature.

"This technology, once fully developed, can be applied for the fabrication of a variety of human tissues," said co-principal investigator Elias Rizk, a professor of neurosurgery at Penn State College of Medicine. "It could be cardiac tissue or lung tissue. It could be skin or even bone, which is tissue. This technology could repair bone in a rapid manner, even in sensitive places like the skull."

The project is the result of an interdisciplinary collaboration between engineers at Penn State and physicians at Penn State College of Medicine. The team includes experts in bioprinting, instrument development, biomaterials, craniofacial surgery, and bone and lung tissue engineering.

The technology, which the team has titled "high-throughput spheroid (HTS) bioprinting," will have the ability to bioprint multiple spheroids in a range of sizes all at once, according to the researchers. Once developed, it will have high accuracy in all three dimensions and will operate at an unprecedented speed. The technology will be versatile enough that it can print complex structures onto the surface of gel substrates for research purposes or in a scaffold-free manner for the scalable fabrication of tissues.

"We are already printing these tissue 'bricks' with the highest throughput in the literature," Ozbolat said. "That's the most significant and unique part of this technology. It's truly amazing. If we can do it quickly, at scale, then it could fundamentally change the field of medicine." ■

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Soft tissue restoration, blood vessel formation focus of $3M grant

By Mariah R. Lucas

THE ABILITY TO regenerate and pattern blood vessels, the literal lifelines extending deep into soft tissues, remains an elusive milestone in regenerative medicine. Known as tissue revascularization, stimulating blood vessel growth and pattern formation in damaged or diseased tissues could accelerate the field of regenerative medicine, according to Penn State researchers.

With a four-year, $3 million grant awarded by the National Institutes of Health’s National Heart, Lung, and Blood Institute, Penn State chemical engineering and reconstructive surgery researchers plan to develop a new way to help restore soft tissue loss in patients through two coordinating revascularization techniques.

“Tissue revascularization is a bottleneck for regenerative medicine,” said principal investigator Amir Sheikhi, assistant professor of chemical engineering in the College of Engineering, who also has an affiliation with biomedical engineering.

“This is an important award for the whole field, as we hope to develop a fundamentally new way to tackle the problem using a transdisciplinary team.”

When repairing a traumatic injury, surgeons must be able to restore blood flow rapidly to grafts, flaps, and engineered scaffolds. However, this is not always feasible using conventional techniques, according to researchers.

The researchers plan to combine a class of protein-based granular hydrogel biomaterials pioneered by Sheikhi, with a microsurgical tactic known as vascular micropuncture, developed by co-principal investigator Dino Ravnic, Huck Chair in Regenerative Medicine and Surgical Sciences, associate professor of surgery at the Penn State College of Medicine, and an attending plastic surgeon at the Penn State Health Milton S. Hershey Medical Center.

Bulk hydrogel scaffolds — polymer networks that can hold a large amount of water while maintaining their structure — have been used over the past few decades as a platform to restore soft tissues during surgical repair, according to Sheikhi, but they often suffer slow and random vascularization effects upon implantation.

To address the limitations of bulk hydrogels, Sheikhi said he plans to engineer protein-based granular hydrogel scaffolds by attaching microscale hydrogel particles to each other.

Amir Sheikhi (front left), assistant professor of chemical engineering and of biomedical engineering in the College of Engineering, will lead the four-year, $3M National Institutes of Health grant as principal investigator.
Credit: Jennifer M. McCann/Penn State

"By adjusting the empty spaces among the hydrogel particles, we can regulate how cells interact with each other and assemble, guiding tissue architecture and the formation of new blood vessels," Sheikhi said.

At the same time, researchers will implement vascular micropuncture, where Ravnic and his team will puncture blood vessels with microneedles to accelerate the formation of new blood vessels. The tiny size of the needles ensures there is no blood clotting or significant bleeding.

"Our microsurgical approach allows for targeted blood vessel formation without the use of any added growth factors or molecules," Ravnic said. "This is exceedingly relevant to advancing tissue engineering and also in treating blood vessel-related conditions."

The researchers will first test their approach using human cells cultured in vitro from patient samples. Once they establish a baseline understanding of the approach at the cellular level, they will test it in rodents.

The combination of the two techniques, researchers predict, will allow for new blood vessels to rapidly form in an architecturally organized manner. The hierarchical formation — the organization of blood vessels from big to medium to small — helps regulate blood flow, diffuse oxygen, and modulate immune cells throughout reconstructed or injured soft tissue.

"The patterns of blood vessels should resemble tree branches, with a large trunk fanning out into smaller and smaller branches," Sheikhi said. "The reason is that blood needs to flow from the main vessels deep within tissues through capillaries."

Shayn Peirce-Cottler, professor and chair of biomedical engineering at the University of Virginia, will collaborate on the grant. ■

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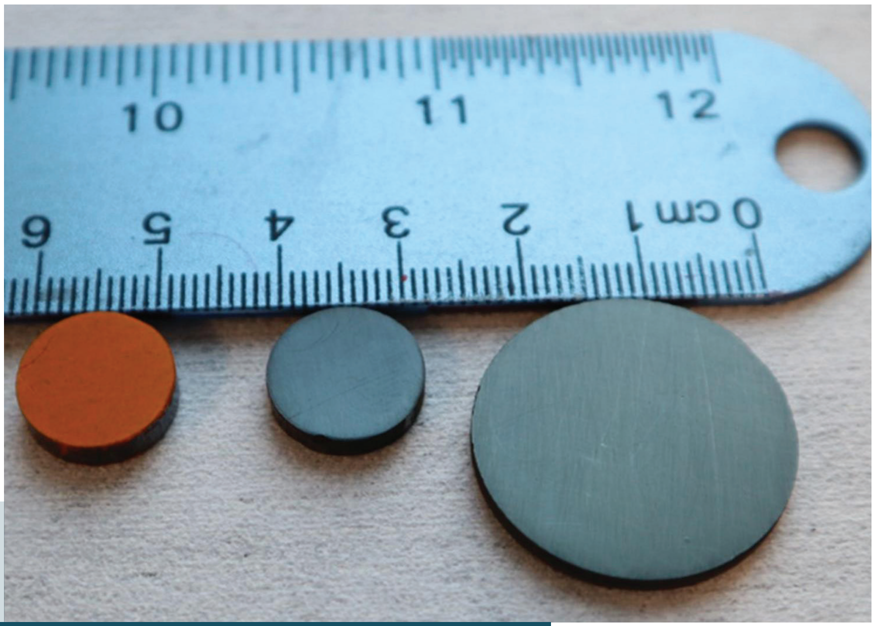
research SNAPSHOTS

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



FAST-synthesized perovskite samples with different sizes and shapes. Credit: Penn State

New method creates material that could create the next generation of solar cells

By Matthew Carroll

PEROVSKITES, A FAMILY of materials with unique electric properties, show promise for use in a variety fields, including next-generation solar cells. A Penn State-led team of scientists created a new process to fabricate large perovskite devices that is more cost- and time-effective than previously possible and that they said may accelerate future materials discovery.

"This method we developed allows us to easily create very large bulk samples within several minutes, rather than days or weeks using traditional methods," said Luyao Zheng, a postdoctoral researcher in the Department of Materials Science at Penn State and lead author on the study. "And our materials are high quality — their properties can compete with single-crystal perovskites."

The researchers used a sintering method called the electrical and mechanical field-assisted sintering technique (EM-FAST) to create the devices. Sintering is a commonly used process to compress fine powders into a solid mass of material using heat and pressure.

A typical process for making perovskites involves wet chemistry — the materials are liquefied in a solvent solution and then solidified into thin films. These materials have excellent properties, but the approach is expensive and inefficient for creating large perovskites and the solvents used may be toxic, the scientists said.

"Our technique is the best of both worlds," said Bed Poudel, a research professor at Penn State and a co-author. "We get single-crystal-like properties, and we don't have to worry about size limitations or any contamination or yield of toxic materials."

Because it uses dry materials, the EM-FAST technique opens the door to include new dopants, ingredients added to tailor device properties, that are not compatible with the wet chemistry used to make thin films, potentially accelerating the discovery of new materials, the scientists said.

"This opens up possibilities to design and develop new classes of materials, including better thermoelectric and solar materials, as well as X- and Y-ray detectors," said Amin Nozariasbmarz, assistant research professor at Penn State and a co-author. "Some of the applications are things we already know, but because this is a new technique to make new halide perovskite materials with controlled properties, structures, and compositions, maybe there is room in the future for new breakthroughs to come from that."

In addition, the new process allows for layered materials — one powder underneath another — to create designer compositions. In the future, manufacturers could design specific devices and then directly print them from dry powders, the scientists said.

EM-FAST, also known as spark plasma sintering, involves applying electric current and pressure to powders to create new materials. The process has a 100% yield — all the raw ingredients go into the final device, as opposed to 20 to 30% in solution-based processing.

The technique produced perovskite materials at .2 inch per minute, allowing scientists to quickly create large devices that maintained high performance in laboratory tests. The team reported their findings in the journal Nature Communications.

Penn State scientists have long used EM-FAST to create thermoelectric devices. This work represents the first attempt to create perovskite materials with the technique, the scientists said.

"Because of the background we have, we were talking and thought we could change some parameters and try this with perovskites," Nozariasbmarz said. "And it just opened a door to a new world. This paper is a link to that door — to new materials and new properties." ■

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3D-printed ceramics may increase gas turbine fuel efficiency, researchers report

By Sarah Small

AIRPLANE ENGINES CAN reach temperatures of more than 3,000 degrees Fahrenheit. The hotter they get, the more fuel efficient they become, but that efficiency is limited by how hot the metallic components inside the turbine can get without deforming.

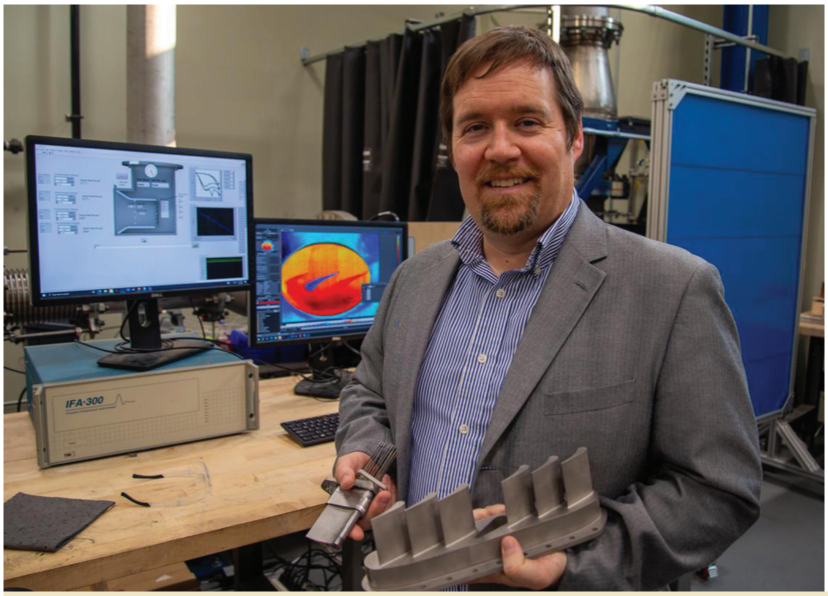
A team that includes Penn State researchers recently 3D printed a turbine component with ceramics, which are more heat tolerant than the conventional metals. The resulting component has complex internal cooling features that enable it to withstand higher temperatures and, as a result, increase fuel efficiency.

The researchers will present their methods and results at the ASME 2023 Turbomachinery Technical Conference and Exposition, which will be held June 26-30 in Boston. Their work will be published in the conference's proceedings and was also recommended for publication in the ASME Journal of Turbomachinery.

"There is a fair amount of research on ceramic materials for gas turbines, but not a lot of it has generated realistically shaped parts because the manufacturing is so difficult to do," said paper co-author Stephen Lynch, associate professor of mechanical engineering at Penn State. "This process was unique in that we could generate complex-shaped parts very easily and very cheaply."

The researchers used design optimization and a novel technique for 3D printing — also known as additive manufacturing — more heat-resistant airfoils using a polymer-derived ceramic material. These turbine components are petal-shaped blades that constantly redirect the hot gas inside the gas turbine engine to extract energy. This energy is used partially to power the rest of the engine, and the rest becomes thrust for an aircraft or power to turn an electric generator.

"We worked with collaborators at the Colorado School of Mines and the University of Wyoming who had embedded ceramic fibers into additively printed ceramics," Lynch said, explaining that these polymer-derived ceramics are created by firing a plastic-like base in a furnace. "We adapted that to create these turbine airfoils, but also leveraged the design freedom of additive manufacturing to create internal features that dramatically improve the effectiveness of the cooling air inside the blade."



Stephen Lynch, associate professor of mechanical engineering, holds metal 3D-printed turbine vanes that are tested in the high speed cascade shown in the background. Lynch was part of a team that 3D printed a turbine component with ceramics, which are more heat tolerant than traditional metals.
Credit: Kate Myers/Penn State

By using 3D printing in conjunction with the polymer-derived ceramics, the researchers were able to create the exact shapes needed to withstand more heat and perform well in the gas turbines. The team tested the parts in Penn State's high speed cascade facility, housed in the Steady Thermal Aero Research Turbine Lab.

"We found that with the right design for the part, the ceramic airfoil shape that we 3D printed can perform just as well as the metal components," Lynch said. "Our hope is that this technology could be used to develop ceramic parts that perform similarly to metallic parts in gas turbine engines but can tolerate higher temperatures for greater fuel efficiency." ■

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research SNAPSHOTS

New ferroelectric material could give robots muscles

By Jamie Oberdick

A NEW TYPE OF ferroelectric polymer that is exceptionally good at converting electrical energy into mechanical strain holds promise as a high-performance motion controller or "actuator" with great potential for applications in medical devices, advanced robotics, and precision positioning systems, according to a team of international researchers led by Penn State.

Mechanical strain is an important property of an actuator which is any material that will change or deform when an external force such as electrical energy is applied. Traditionally, these actuator materials were rigid, but soft actuators such as ferroelectric polymers display higher flexibility and environmental adaptability.

The research demonstrated the potential of ferroelectric polymer nanocomposites to overcome the limitations of traditional piezoelectric polymer composites, offering a promising avenue for the development of soft actuators with enhanced strain performance and mechanical energy density.

"Potentially we can now have a type of soft robotics that we refer to as artificial muscle," said Qing Wang, Penn State professor of materials science and engineering and co-corresponding author of the study recently published in Nature Materials. "This would enable us to have soft matter that can carry a high load in addition to a large strain. So that material would then be more of a mimic of human muscle, one that is close to human muscle."

However, there are a few obstacles to overcome before these materials can meet their promise, and potential solutions to these obstacles were proposed in the study. Ferroelectrics are a class of materials that demonstrate a spontaneous electric polarization when an external electric charge is applied and positive and negative charges in the materials head to different poles. Strain in these materials during the phase transition, in this case conversion of electrical energy to mechanical energy, can completely change properties such as its shape, making them useful as actuators.

While many ferroelectric materials are ceramics, they also can be polymers, a class of natural and synthetic materials made of many similar units bonded together. For example, DNA is a polymer, as is nylon. An advantage of ferroelectric polymers is they exhibit a tremendous amount of the electric-field-induced strain needed for actuation. This strain is much higher than what is generated by other ferroelectric materials used for actuators, such as ceramics.

New glass cuts carbon footprint by nearly half and is 10x more damage resistant

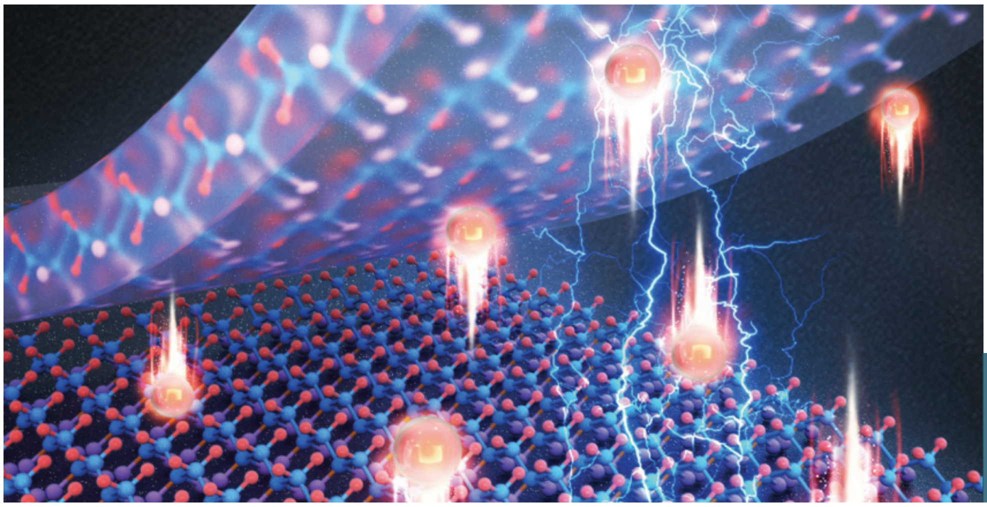
By Adrienne Berard

WORLDWIDE, GLASS MANUFACTURING produces at least 86 million tons of carbon dioxide every year. A new type of glass promises to cut this carbon footprint in half. The invention, called LionGlass and engineered by researchers at Penn State, requires significantly less energy to produce and is much more damage resistant than standard soda lime silicate glass. The research team recently filed a patent application as a first step toward bringing the product to market.

"Our goal is to make glass manufacturing sustainable for the long term," said John Mauro, Dorothy Pate Enright Professor of Materials Science and Engineering at Penn State and lead researcher on the project. "LionGlass eliminates the use of carbon-containing batch materials and significantly lowers the melting temperature of glass."

Soda lime silicate glass, the common glass used in everyday items from windows to glass tableware, is made by melting three primary materials: quartz sand, soda ash, and limestone. Soda ash is sodium

A sample of LionGlass, a new type of glass engineered by researchers at Penn State that requires significantly less energy to produce and is much more damage resistant than standard soda lime silicate glass. Credit: Adrienne Berard/Penn State



Actuation of ferroelectric polymers driven by Joule heating. Credit: Qing Wang

This property of ferroelectric materials, along with a high level of flexibility, reduced cost compared to other ferroelectric materials, and low weight, holds great interest for researchers in the growing field of soft robotics, the design of robots with flexible parts and electronics.

The second challenge is that a ferroelectric polymer actuator typically needs a very high driving field, which is a force that imposes a change in the system, such as the shape change in an actuator. In this case the high driving field is necessary to generate the shape change in the polymer required for the ferroelectric reaction needed to become an actuator.

The solution proposed to improve the performance of ferroelectric polymers was developing a percolative ferroelectric polymer nanocomposite — a kind of microscopic sticker attached to the polymer. By incorporating nanoparticles into a type of polymer, polyvinylidene fluoride, the researchers created an interconnected network of poles within the polymer.

This network enabled a ferroelectric phase transition to be induced at much lower electric fields than would normally be required. This was achieved via an electro-thermal method using Joule heating, which occurs when electric current passing through a conductor produces heat. Using the Joule heating to induce the phase transition in the nanocomposite polymer resulted in only requiring less than 10% of the strength of an electric field typically needed for ferroelectric phase change. ■

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carbonate and limestone is calcium carbonate, both of which release carbon dioxide (CO_2), a heat-trapping greenhouse gas, as they are melted.

But the bulk of the CO_2 emissions come from the energy required to heat furnaces to the high temperatures needed for melting glass. With LionGlass, the melting temperatures are lowered by about 300 to 400 degrees Celsius, Mauro explained, which leads to a roughly 30% reduction in energy consumption compared to conventional soda lime glass.

Not only is LionGlass easier on the environment, it's also much stronger than conventional glass. The researchers said they were surprised to find that the new glass, named after Penn State's Nittany Lion mascot, possesses significantly higher crack resistance compared to conventional glass.

Some of the team's glass compositions had such a strong crack resistance that the glass would not crack, even under a one kilogram-force load from a Vickers diamond indenter. LionGlass is at least 10 times as crack-resistant compared to standard soda lime glass, which forms cracks under a load of about 0.1 kilograms force. The researchers explained that the limits of LionGlass have not yet been found, because they reached the maximum load allowed by the indentation equipment.

Mauro explained that crack resistance is one of the most important qualities to test for in glass because it is how the material eventually fails. Over time, glass develops microcracks along the surface, which become weak points. When a piece of glass breaks, it's due to weaknesses caused by existing microcracks. Glass that is resistant to forming microcracks in the first place is especially valuable, he added.

"Damage resistance is a particularly important property for glass," Mauro said. "Think about all the ways we rely on the strength of glass, in the automotive industry and electronics industry, architecture, and communication technology like fiber optic cables. Even in health care, vaccines are stored in strong, chemically resistant glass packaging."

Mauro is hoping that the improved strength of LionGlass means the products created from it can be lighter weight. Since LionGlass is 10 times more damage resistant than current glass, it could be significantly thinner.

Mauro notes that the research team is still evaluating the potential of LionGlass. They have filed a patent application for the entire family of glass, which means there are many compositions within the LionGlass family, each with its own distinct properties and potential applications. They are now in the process of exposing various compositions of LionGlass to an array of chemical environments to study how it reacts. The results will help the team develop a better understanding of how LionGlass can be used throughout the world. ■

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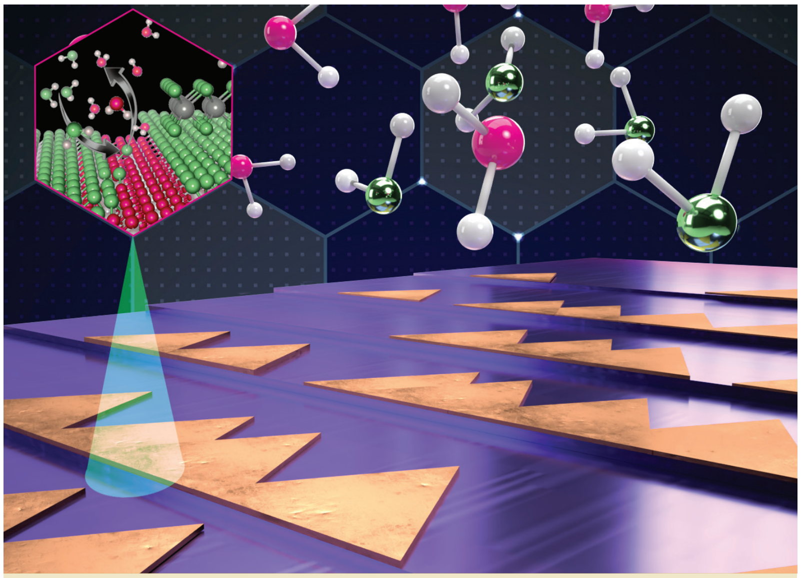
Solution found to problem bedeviling semiconductor researchers

By Jamie Oberdick

RESEARCHERS FROM THE National Science Foundation-sponsored Two-Dimensional Crystal Consortium (2DCC-MIP) - Materials Innovation Platform may have come up with a solution for a bottleneck that has confounded researchers trying to develop high-quality 2D semiconductors for next generation electronics such as Internet of Things (IoT) and artificial intelligence.

Tungsten diselenide is a semiconductor that holds promise as a material for nanosheet transistors. Such research has gained importance since last year's passing of the CHIPS and Science Act, which is designed to boost America's efforts to onshore the production and development of semiconductor technology.

While it would make for a highly effective semiconductor, synthesizing a single-layer sheet of tungsten diselenide that is three atoms thick over sapphire wafer areas as large as 8 to 12 inches in diameter has proven to be a challenge.



Atomic-scale steps on the sapphire substrates enable crystal alignment of 2D materials, reducing defects and improving electronic device performance. Credit: Jennifer M. McCann

Zentropy and the art of creating new ferroelectric materials

By Jamie Oberdick

SYSTEMS IN THE Universe trend toward disorder, with only applied energy keeping the chaos at bay. The concept is called entropy, and examples can be found everywhere: ice melting, campfire burning, water boiling. Zentropy theory, however, adds another level to the mix.

A team led by Zi-Kui Liu, the Dorothy Pate Enright Professor of Materials Science and Engineering at Penn State, developed the theory. The "Z" in zentropy stands for the German word Zustandssumm, meaning "sum over states" of entropy. Alternatively, Liu said, zentropy may be considered as a play on the term "zen" from Buddhism and entropy to gain insight on the nature of a system. The idea, Liu said, is to consider how entropy can occur over multiple scales within a system to help predict potential outcomes of the system when influenced by its surroundings.

Liu and his research team have published their latest paper on the concept, providing evidence that the approach may offer a way to predict the outcome of experiments and enable more efficient discovery and design of new ferroelectric materials. The work, which incorporates some intuition and a lot of physics to provide a parameter-free pathway to predicting how advanced materials behave, was published in Scripta Materialia.

"Of course, at the end of the day, the experiments are the ultimate test, but we found that zentropy can provide a quantitative prediction that can narrow down the possibilities significantly," Liu said. "You can design better experiments to explore ferroelectric material and the research work can move much faster, and this means you save time, energy, and money and are more efficient."

While Liu and his team have successfully applied zentropy theory to predict the magnetic properties of a range of materials for various phenomena, discovering how to apply it to ferroelectric materials has been tricky. In the current study, the researchers reported finding a method to apply zentropy theory to ferroelectrics, focusing on lead titanate.

As an electric field reverses electric polarization reverses, the system transitions from ordered in one direction to disordered and then to ordered again as the system settles into the new direction. However, this ferroelectricity occurs only below a critical temperature unique to each ferroelectric material. Above this temperature, ferroelectricity — the ability to reverse polarization — disappears and paraelectricity — the ability to become polarized — emerges. The change is called the phase transition. The measurement of those temperatures can indicate critical information about the outcome of various experiments, Liu said. However, predicting the phase transition prior to an experiment is nearly impossible.

This is due to a defect in the material known as “mirror twins.” Mirror twin boundaries form from opposite-oriented tungsten diselenide crystals on the sapphire wafers. This defect scatters electrons as they move through the 2D layer, which in turn reduces the performance of the nanosheet transistor.

In the study published in Nature Nanotechnology, the researchers turned to metal organic chemical vapor deposition (MOCVD), a technology that is used to deposit ultra-thin, single crystal layers onto a substrate, in this case a sapphire wafer. 2DCC-MIP researchers pioneered the use of this technique for the synthesis of wafer-scale transition metal dichalcogenides like tungsten diselenide.

To solve this issue and get most of the tungsten diselenide crystals to align with the sapphire crystals, the researchers took advantage of “steps” on the sapphire surface. The sapphire single crystal that makes up the water is highly perfect in physics terms; however, it is not perfectly flat at the atomic level. There are steps on the surface that are a mere atom or two tall with flat areas between each step. The researchers made an interesting and significant discovery about these steps.

The step on the sapphire crystal surface is where the tungsten diselenide crystals tended, but not always, to attach and the crystal alignment when attached to the steps tended to be in all one direction.

The researchers found that by controlling the MOCVD process conditions, most of the crystals could be made to attach to the sapphire at the steps. And during the experiments, they made a bonus discovery: If the crystals attach at the top of the step, they align in one crystallographic direction, if they attach at the bottom, they align in the opposite direction.

This in turn led to researchers in the 2DCC-MIP Theory/Simulation/Data facility lead by Dr. Nadire Nayir, a postdoctoral scholar in Prof. Adri van Duin’s group, to develop a theoretical model of the atomic structure of sapphire surface to explain why the tungsten diselenide attached to the top or bottom edge of the steps. If the surface of the sapphire was covered with selenium atoms, then they would attach to the bottom edge of the steps, if the sapphire is only partially covered so that the bottom edge of the step lacks selenium atom, then the crystals attached to the top.

To confirm this theory, the Penn State 2DCC-MIP researchers worked with Krystal York, a graduate student in Prof. Steven Durbin’s group at Western Michigan University, who contributed to the study while a visiting scholar as part of the 2DCC-MIP Resident Scholar Visitor Program (RSVP). York learned how to grow tungsten diselenide thin films via MOCVD while using 2DCC-MIP facilities for her Ph.D. thesis research. Her experiments helped confirm that indeed, this method worked. ■

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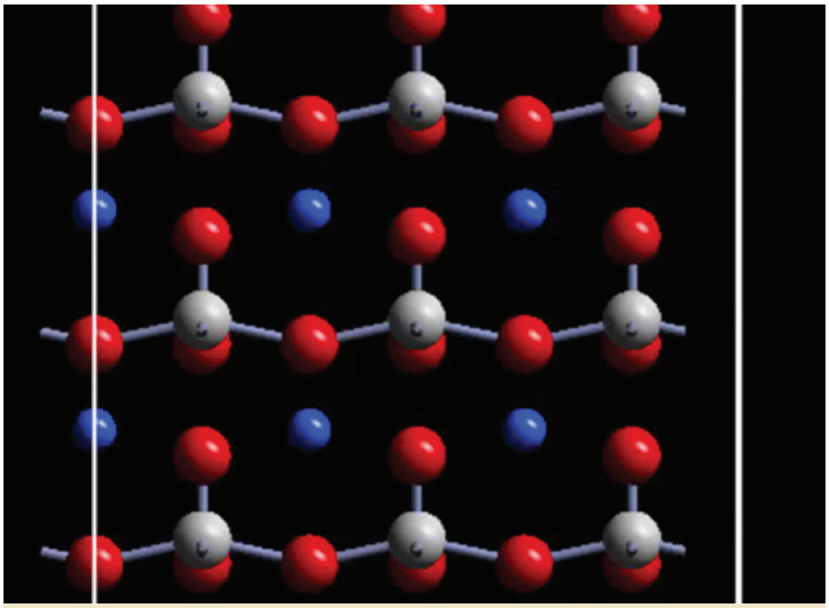
“No theory and method can accurately predict the free energy of the ferroelectric materials and the phase transitions prior to the experiments,” Liu said. “The best prediction of transition temperature is more than 100 degrees away from the experiment’s actual temperature.”

In ferroelectrics, the configuration of electric dipoles in the material can change the direction of polarization. The researchers applied zentropy to predict the phase transitions in lead titanate, including identifying three types of possible configurations in the material.

The predictions made by the researchers were effective and in agreement with observations made during experiments reported in the scientific literature, according to Liu. They used publicly available data on domain wall energies to predict a transition temperature of 776 degrees Kelvin, showing a remarkable agreement with the observed experimental transition temperature of 763 degrees Kelvin. Liu said the team is working on further reducing the difference between predicted and observed temperatures with better predictions of domain wall energies as a function of temperature.

This ability to predict transition temperature so closely to the actual measurements can provide valuable insights into the physics of ferroelectric material — and help scientists to better their experimental designs, Liu said.

"This basically means you can have some intuitions and a predictive approach on how a material behaves both microscopically and macroscopically before you conduct the experiments,” Liu said. “We can start predicting the outcome accurately before the experiment.” ■



A snapshot of the ab initio molecule dynamics simulations at 753 degrees Kelvin, showing the polarized titanium oxide bonding with local tetragonal structures in various orientations, which depict the local 90 and 180 degree domain walls. Credit: Zi-Kui Liu

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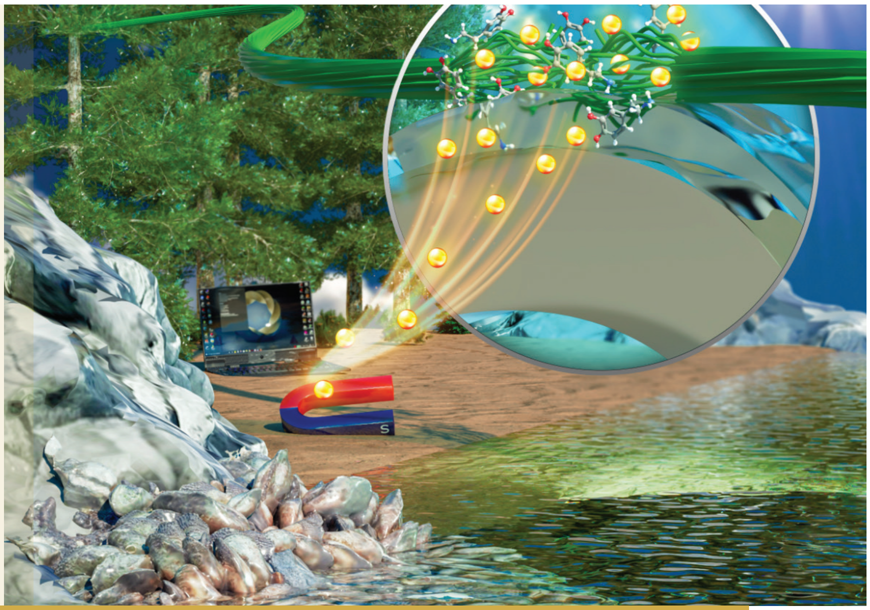

Mussels' unique and remarkable ability to stick to underwater surfaces such as rocks has inspired a new, more efficient, and environmentally friendly way to extract critical rare earth elements. Credit: Provided by the Sheikhi Lab/Penn State

Mussels inspire an eco-friendly way to extract critical rare earth elements

By Jamie Oberdick

THERE IS A conundrum around rare earth elements (REE). They play a key role in clean energy, vital to the production of lightweight, efficient batteries and essential components in wind turbines. Conversely, conventional extraction of these elements raises environmental concerns ranging from habitat destruction to water and air pollution to the high amount of energy needed to extract and process these elements.

To solve this quandary, Penn State researchers found inspiration under the sea: mussel stickiness. By mimicking this natural glue, the researchers developed a new mussel-inspired nanocellulose coating (MINC) that has demonstrated what they call a “remarkable, even surprising” ability to recover REEs from secondary sources such as industrial wastewater without using a high amount of energy.

They published the work on July 31 in ACS Applied Materials and Interfaces.

Mussels have a remarkable ability to adhere to surfaces underwater thanks to the adhesive properties of catechol-based molecules found in mussel proteins. The MINC mirrors this by consisting of ultra-tiny hairy cellulose nanocrystals with uniquely sticky properties. The MINC is applied to a substrate via a technique called dopamine-mediated ad-layer formation. A chemical reaction enables the MINC to form a thin layer of molecules on a surface, making it capable of sticking to a broad range of substrates.

“The MINC approach offers a sustainable and eco-friendly alternative to conventional extraction methods, minimizing the environmental footprint and contributing to the long-term availability of critical elements,” said lead author Amir Sheikhi, assistant professor of chemical engineering and of biomedical engineering, by courtesy.

The researchers focused on applying MINC to extract a particular REE, neodymium. The U.S. Department of Energy listed neodymium as a critical material due to supply shortages and its high impact on emerging sustainable technologies such as electric car batteries and magnets used in powering systems for electric vehicles and wind turbines. However, the “rare” part of rare earth elements is especially true with neodymium, as the lack of ready-to-extract supply of this critical element forces extraction of it from secondary sources such as industrial wastewater recycling. This can be both inefficient and energy intensive, according to Sheikhi.

“The limited global supply of neodymium and the environmental impact of current extraction methods necessitate the development of eco-friendly and sustainable approaches for REE recovery,” Sheikhi said, explaining that conventional extraction techniques use significant amounts of toxic chemicals, such as kerosene, to purify the target element. “Prior rare earth extraction methods have utilized adsorbents such as alginate gels, phosphorus sol-gel materials, nanotubes, and porous carbon, but these techniques demonstrate limited efficiency.”

The MINC coating is to neodymium what a magnet is to iron, pulling the REE out of water, even when the element is only present in amounts as limited as parts per million.

"The challenge in extracting neodymium lies in achieving efficient and selective removal of it at low concentrations,” Sheikhi said. “The MINC presented in this study offers improved selectivity and capacity for neodymium removal, overcoming limitations of previous methods.”

This selectivity allows MINC to avoid recovering undesired elements like sodium and calcium, which Sheikhi said would waste time and energy if they had to be filtered to further refine the neodymium. ■

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Thicker, denser, better: New electrodes may hold key to advanced batteries

By Jamie Oberdick

THE DEMAND FOR high-performance batteries, especially for use in electric vehicles, is surging as the world shifts its energy consumption to a more electric-powered system, reducing reliance on fossil fuels and prioritizing climate remediation efforts. To improve battery performance and production, Penn State researchers and collaborators have developed a new fabrication approach that could make for more efficient batteries that maintain energy and power levels.

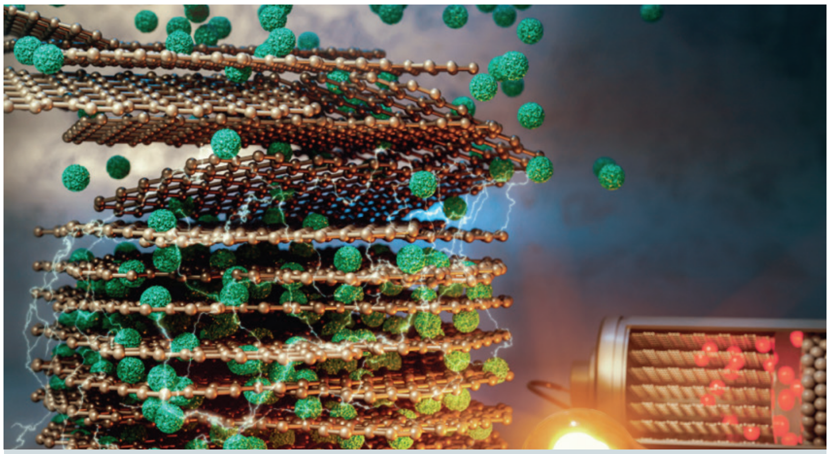
The improved method for fabricating battery electrodes may lead to high-performance batteries that would enable more energy-efficient electric vehicles, as well as such benefits as enhancing power grid storage, according to Hongtao Sun. Sun is an assistant professor of industrial and manufacturing engineering at Penn State, and the co-corresponding author of the study, which was published in and featured on the front cover of Carbon.

If an electric car maker wants to improve the driving distance of their vehicles, they add more battery cells, numbering in the thousands. The smaller and lighter, the better, according to Sun.

"The solution for longer driving distances for an electric vehicle is just to add compact batteries, but with denser and thicker electrodes," Sun said, explaining that such electrodes could better connect and power the battery's components, making them more active. "Although this approach may slightly reduce battery performance per electrode weight, it significantly enhances the vehicle's overall performance by reducing the battery package's weight and the energy required to move the electric vehicle."

More efficient electrodes — a kind of gateway for electricity in a battery — could help achieve a battery with a higher percentage of active components. Prior attempts to improve battery performance via better electrodes focused on only one metric, which was not as effective because the battery then performed poorly on other trade-off metrics. For instance, when a battery prioritizes high gravimetric performance (the amount of energy it can store relative to its weight), it may result in reduced areal metric performance (how much charge it can store per unit area) and/or diminished volumetric performance (the amount of charge delivered relative to the battery's size).

Sun and his research team focused on making thicker electrodes with optimized charge transport pathways, aiming to enable high performance across all three metrics: areal, volumetric, and gravimetric.



Electric field- and pressure-assisted fast sintering to control graphene alignment in thick composite electrodes for boosting lithium storage performance. Credit: Hongtao Sun/Penn State

To overcome the challenge of a thicker electrode having poor charge transport kinetics, the researchers developed a method to apply Spark Plasma Sintering (SPS) to electrodes. SPS is an energy-efficient technique that uses heat and pressure to compact and densify materials into a solid object, such as an electrode.

"SPS enabled us to fabricate a very thick and dense electrode," Sun said. "The typical thickness of the battery electrode is only about 50 microns to 100 microns but now, in this work, we are talking about 300 microns, 500 microns. That is five times higher than the proportion of mass of the electrode in a real battery device."

This technique achieves vertically aligned carbon networks and pore channels in the electrodes, enabling cathodes with high electrode density for high volumetric performance and high mass loading (amount of active material present) for high areal metric performance, while demonstrating rapid charge transports.

Using the researchers' newly designed thicker electrodes with fast charge transport capability would increase the percentage of active components and enhance the energy capacity normalized by the total weight of the battery package, Sun said. They also make the batteries compact due to the high density of the electrodes, which enables packing more electrode active materials within the same space. ■

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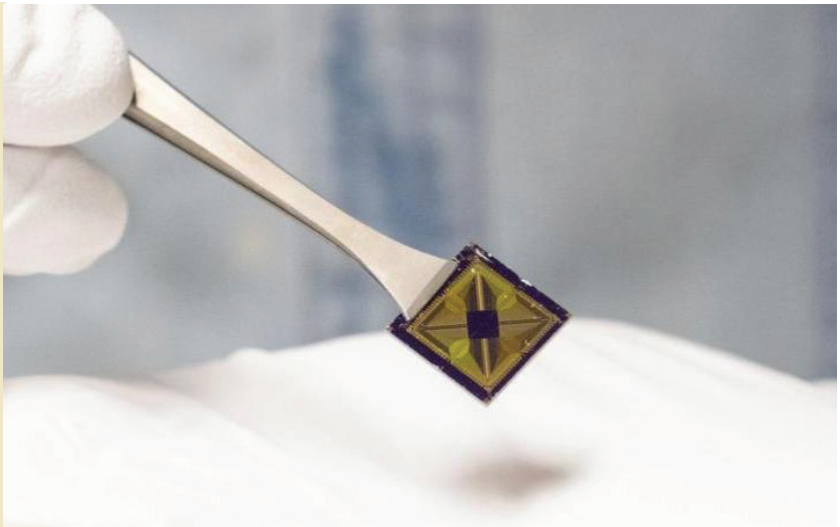
research SNAPSHOTS



Penn State researchers developed a graphene-based electronic sensor that can "taste" flavor profiles such as sweet and salty.
Credit: Das Research Lab/Penn State

Can AI crave a favorite food?

'Electronic tongue' holds promise as possible first step to artificial emotional intelligence

CAN ARTIFICIAL INTELLIGENCE (AI) get hungry? Develop a taste for certain foods? Not yet, but a team of Penn State researchers is developing a novel electronic tongue that mimics how taste influences what we eat based on both needs and wants, providing a possible blueprint for AI that processes information more like a human being.

Human behavior is complex, a nebulous compromise and interaction between our physiological needs and psychological urges. While artificial intelligence has made great strides in recent years, AI systems do not incorporate the psychological side of our human intelligence. For example, emotional intelligence is rarely considered as part of AI.

"The main focus of our work was how could we bring the emotional part of intelligence to AI," said Saptarshi Das, associate professor of engineering science and mechanics at Penn State and corresponding author of the study published this week (Sept. 27) in Nature Communications.

Das noted that our eating habits are a good example of emotional intelligence and the interaction between the physiological and psychological state of the body. What we eat is heavily influenced by the process of gustation, which refers to how our sense of taste helps us decide what to consume based on flavor preferences. This is different than hunger, the physiological reason for eating. Anyone who has felt full after a big lunch and still was tempted by a slice of chocolate cake at an afternoon workplace party knows that a person can eat something they love even when not hungry.

While there are still many questions regarding the neuronal circuits and molecular-level mechanisms within the brain that underlie hunger perception and appetite control, Das said, advances such as improved brain imaging have offered more information on how these circuits work in regard to gustation.

Taste receptors on the human tongue convert chemical data into electrical impulses. These impulses are then sent through neurons to the brain's gustatory cortex, where cortical circuits, an intricate network of neurons in the brain shape our perception of taste. The researchers have developed a simplified biomimetic version of this process, including an electronic "tongue" and an electronic "gustatory cortex" made with 2D materials, which are materials one to a few atoms thick. The artificial tastebuds comprise tiny, graphene-based electronic sensors called chemitransistors that can detect gas or chemical molecules. The other part of the circuit uses memtransistors, which is a transistor that remembers past signals, made with molybdenum disulfide. This allowed the researchers to design an "electronic gustatory cortex" that connect a physiology-drive "hunger neuron," psychology-driven "appetite neuron" and a "feeding circuit."

The process is versatile enough to be applied to all five primary taste profiles: sweet, salty, sour, bitter, and umami. Such a robotic gustatory system has promising potential applications, Das said, ranging from AI-curated diets based on emotional intelligence for weight loss to personalized meal offerings in restaurants. The research team's upcoming objective is to broaden the electronic tongue's taste range.

"We are trying to make arrays of graphene devices to mimic the 10,000 or so taste receptors we have on our tongue that are each slightly different compared to the others, which enables us to distinguish between subtle differences in tastes," Das said. "The example I think of is people who train their tongue and become a wine taster. Perhaps in the future we can have an AI system that you can train to be an even better wine taster." ■

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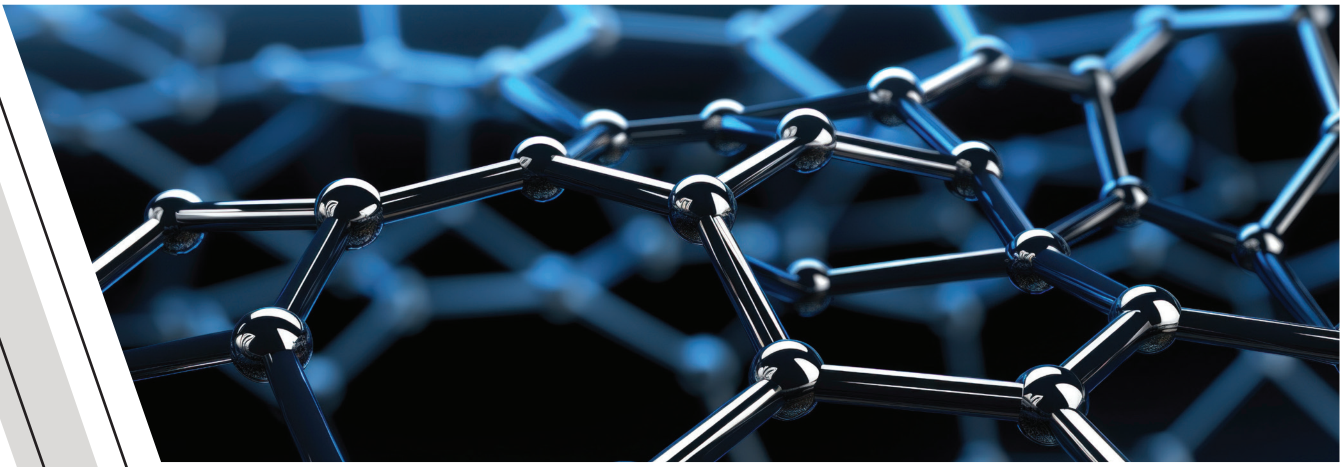
The Many Dimensions of Two-Dimensional Material Research at Penn State

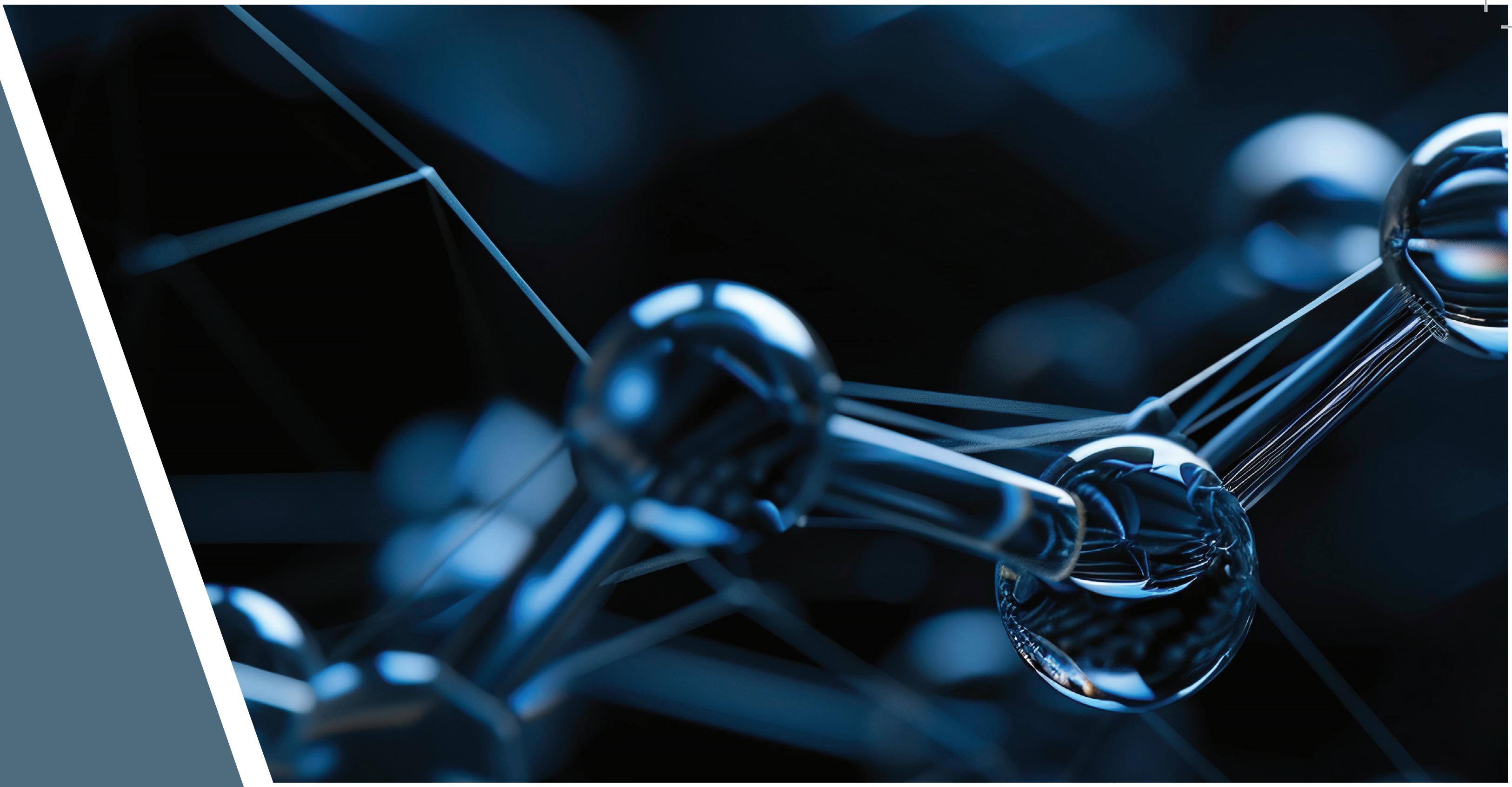


Credit: Adobe Stock

LIKE SO MUCH in science and engineering, the history of two dimensional (2D) materials begins with a theory.

In the mid-20th Century, the existence of 2D materials were theorized as possible, and potentially could exhibit useful and unique electronic and mechanical properties. However, most also theorized that such a material would be impossible to maintain at room temperature, as they would not be stable in such thermal conditions.

In 2004, physicists Andre Geim and Konstantin Novoselov at the University of Manchester changed all that when they successfully isolated graphene with a method that is almost ridiculous in its simplicity: They mechanically exfoliated graphene using adhesive tape. Since then, two-dimensional (2D) materials have revolutionized the field of material science, offering new possibilities for technology and research. And Penn State has played a pivotal role in advancing the study and application of these materials.



Graphene's remarkable properties, such as its exceptional electrical conductivity, mechanical strength, and flexibility, set the stage for the exploration of other 2D materials. Researchers began investigating materials like hexagonal boron nitride (h-BN), transition metal dichalcogenides (TMDs) such as molybdenum disulfide (MoS_2), and phosphorene. Each of these materials brought unique characteristics, expanding the potential applications in electronics, photonics, and energy storage.

Penn State has been at the forefront of this research, contributing significantly to both fundamental science and practical applications. The Material Research Institute's (MRI) Center for 2-Dimensional and Layered Materials (2DLM), established in 2012, has become a hub for interdisciplinary research in this field. This in turn led to the development of two other organizations within MRI, including one of four National Science Foundation-funded Materials Innovation Platforms, the Two-Dimensional Crystal Consortium (2DCC), and the Center for Atomically Thin Multifunctional Coatings (ATOMIC), which also includes sites at Boise State University and Rice University.

Credit: Adobe Stock

Among Penn State's notable contributions in 2D materials in the area of material synthesis and characterization. Researchers at the University have developed advanced techniques for producing high-quality 2D materials, including chemical vapor deposition (CVD) and molecular beam epitaxy (MBE). These methods enable the controlled growth of large-area 2D materials with precise thickness and composition, essential for scalable device fabrication.

Penn State's researchers have also made significant strides in understanding the fundamental properties of 2D materials. Their work on the electronic, optical, and mechanical properties of materials like MoS2 and h-BN has provided valuable insights into their potential applications. Furthermore, the University's collaborative approach, involving partnerships with industry and other research institutions, has accelerated the translation of these findings into practical technologies.

Where do we go from here? Well, 2D material research is still in its infancy. Penn State's ongoing research and commitment to advancing the field of 2D materials ensure that it will remain a key player in this dynamic area of science. The University's efforts to bridge the gap between fundamental research and practical applications highlight the transformative potential of 2D materials in shaping the future of technology. ■

Better health through sensors built with 2D materials

SENSORS HAVE MADE great strides in recent years, and at the heart of this revolution lies 2D materials. These atom-to-few-atoms thick materials enable an entirely new class of sensors that are especially laden with potential for uses in healthcare.

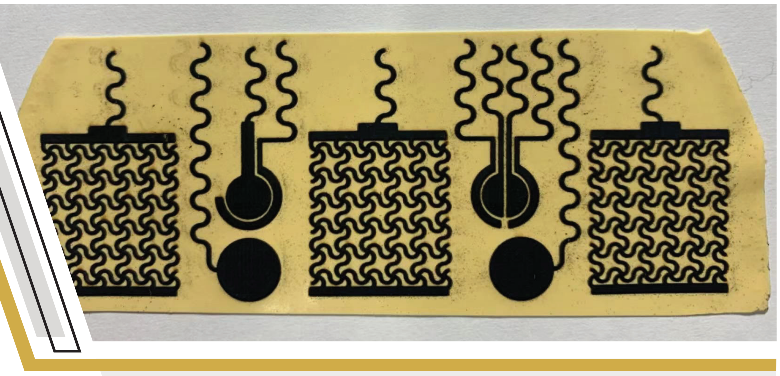
The properties of 2D materials make them ideal for use in sensors. They have a high sensitivity that enables them to detect subtle environmental changes, such as variations in biomarker concentrations. Their flexibility allows them to conform to the irregular surfaces found on the surface and within the human body. Since they operate at lower voltages, they use much less power than traditional sensors, so they can work longer on a single battery charge. They also demonstrate strong biocompatibility, rapid response time, and the ability to fit specific healthcare applications which makes them a boon for personalized medicine.

Given Penn State's leadership in 2D materials research, it is not surprising that 2D healthcare sensors are a hot topic at the University. Two researchers blazing new trails in this world are Aida Ebrahimi, Roell Early Career Associate Professor of Electrical Engineering, and Huanyu "Larry" Cheng, James L. Henderson, Jr. Memorial Associate Professor of Engineering Science and Mechanics at Penn State.

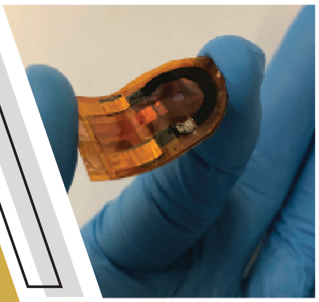
Ebrahimi's research fits into the Material Research Institute's (MRI) philosophy of interdisciplinary research by incorporating varied disciplines including electrical engineering, device physics, electrochemistry, materials, data science, applied physics and chemistry, and microbiology. One example of her work is an ultra-sensitive sensor for detecting dopamine levels, which can be an early warning indicator for Parkinson's disease, Alzheimer's disease, and other neurological disorders.

> "We have been researching sensors based on 2D materials to detect neurotransmitters involved in neurological diseases as well as the brain-gut microbiome dialogues, such as dopamine, serotonin, epinephrine, norepinephrine, and so on," Ebrahimi said. "For dopamine, for example, when it is low in the human body, it's one of the symptoms of Parkinson's disease. So, you must give such patients certain drugs to treat it, and this can help a doctor determine that early on."

Ebrahimi's group is exploring different functionalized 2D materials to develop sensors for neurotransmitters. In one work, they explored engineering graphene ink and developed fully printed sensors with record low detection limit. In another work, the sensors are based on doping the two-dimensional layered material molybdenum disulfide with manganese. This allows the sensor to detect dopamine



Sensor. Credit: Larry Cheng



From left: Keren Zhou, Vinay Kammarchedu, Derrick Butler, and Aida Ebrahimi

in human sweat or saliva, so it would give researchers a non-invasive method to monitor dopamine levels. Ebrahimi's group also showed that the performance of conventional electrochemical sensors can be significantly boosted by combining material functionalization methods (such as doping) with advanced analytical methods for data collection and analysis.

Another example of innovative healthcare sensor research is Cheng's work in a unique 2D material, porous graphene.

"We utilize a unique 2D material known as porous graphene, distinct from conventional graphene," Cheng said. "The synthesis involves a laser scribing process, akin to toasting bread into carbon black but with a precision akin to a laser printer. This process tunes the graphene into a high defect level, resulting in a 3D graphene composed not of a single flake but a multitude of flakes assembled into a 3D porous structure with a cellular framework. The mescoscale pore structure exhibits pore sizes ranging from a few microns to several tens of microns. It is actually a multiscale porous structure, with nanoporous structures on the cellular walls of the mescoscale microporous structures."

This highly porous structure enhances the transport of ions, electrolytes, and biomarkers through the material, consequently augmenting the specific surface area not just within a graphene flake but also across the thickness direction, which is how thick or thin a graphene layer is from one side to another.

One example of applications of this research is the development of a non-invasive glucose sensor using porous graphene nanocomposites to detect glucose levels through sweat samples. Cheng and his fellow researchers are working on incorporating materials like nickel and gold into graphene to enhance its properties for highly sensitive/selectivity and rapid glucose detection, which could help manage diseases like diabetes.

Cheng also envisions that the sensor could be powered by energy harvested from the environment. They are developing graphene-based sensors and wireless devices that are energy efficient by using graphene rectennas and triboelectric nanogenerators to harvest electromagnetic energy from the environment and kinetic energy from the human motion. This harvested energy can be stored in graphene-based micro-supercapacitor arrays and used to power the devices without the need for batteries or extend the lifetime of batteries/supercapacitors, making the systems self-sustaining through ambient energy harvesting and conversion.

Thanks to the work of Ebrahimi, Cheng, and others involved in 2D sensor research at MRI, we soon may be able to extensively monitor our health in real time, and both give doctors a better idea how to treat maladies and help us avoid them in the first place. ■

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The 2DCC-MIP's key role in driving 2D materials research at Penn State

IN THE 20 years since the first 2D material, graphene, was discovered, Penn State has established itself as a global leader in the field. The existence of Penn State's Two-Dimensional Crystal Consortium Materials Innovation Platform (2DCC-MIP) is proof of that and is part of the effort to build on that reputation in what looks like a bright future for Penn State 2D materials research.

In 2015, the National Science Foundation (NSF) initiated the Materials Innovation Platforms program, calling for funding of proposals for facilities specializing in the synthesis of inorganic materials. Applicants were asked to propose specific inorganic material systems and design facilities to efficiently synthesize these materials.

"When that call came out, it seemed to us like a broad topic," said Joan Redwing, distinguished professor of materials science and engineering and electrical engineering and director of the 2DCC-MIP. "But at the same time, we felt like we were ahead of the game. Mauricio Terrones and Joshua Robinson had recently established the Center for 2D and Layered Materials (2DLM) at Penn State which brought together faculty from a variety of departments and facilitated collaborations."

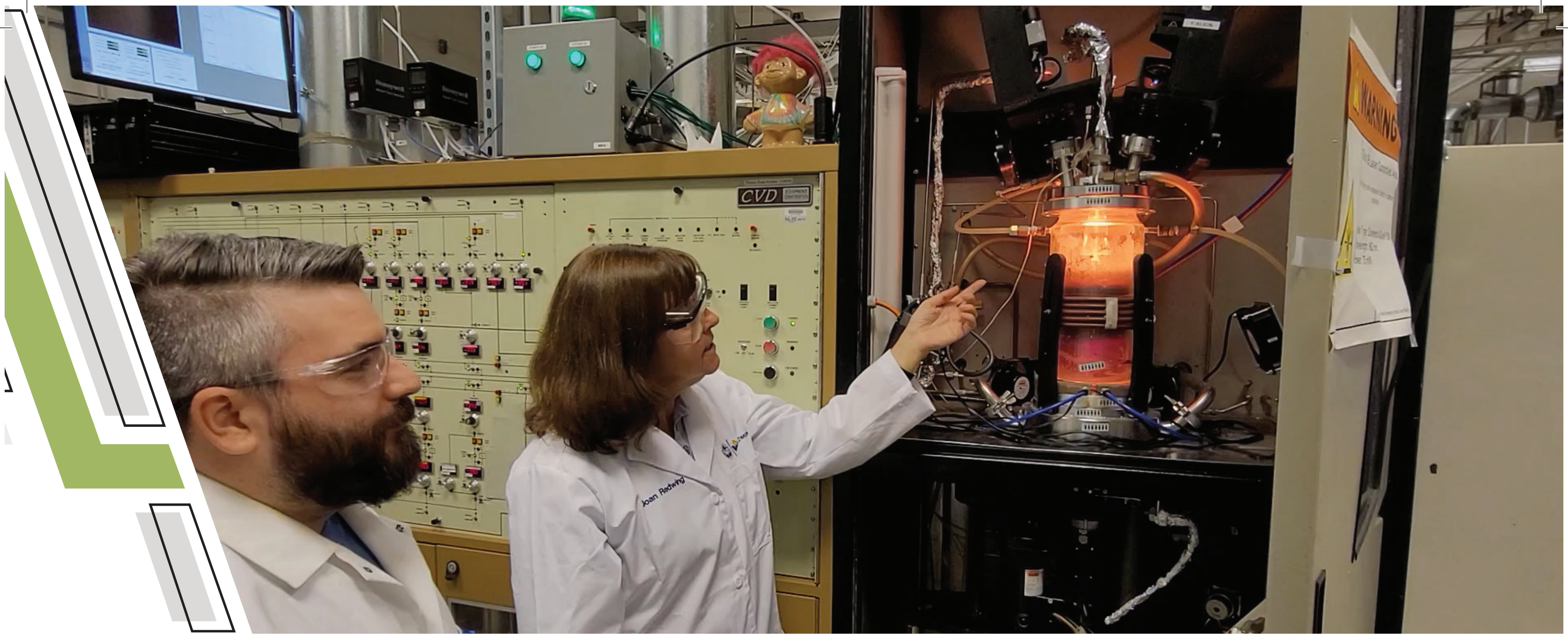
With such a track record in a field that was only around for a little over 10 years at the time, Penn State was a logical place for the NSF to fund an MIP center. Redwing reached out to her colleague Nitin Samarth, Verne M. Willaman Professor of Physics, professor of materials science and engineering, and associate director of the 2DCC-MIP, about submitting a proposal that leveraged the wealth of expertise in materials synthesis and facilities like those housed in the Millennium Science Complex.

"We had the right group of people with the right expertise working on the right topic at the right time," Redwing said. "That's how these things go, right? We were fortunate to have a great group of people and a timely topic."

Penn State was awarded one of the two inaugural MIPs in 2016 under NSF cooperative agreement DMR-1539916 and subsequently renewed in 2021 under NSF cooperative agreement DMR-2039351, with a team from Cornell and Johns Hopkins receiving the other. Redwing noted that the Cornell-Johns Hopkins and Penn State's specific areas of expertise complemented each other.

"Cornell's focus topic was different," Redwing said. "It's more focused on oxide materials and material interfaces. Whereas ours was specifically focused on 2D materials."

Once funded, a core group of faculty formed the organization which has expanded over the years. Along with Redwing and Samarth who head up the thin films facility, there is Vincent Crespi, distinguished professor of physics, who leads the theory/simulation facility. Zhiqiang Mao, professor of physics, heads up the bulk crystal growth facility. Joshua Robinson, professor of materials science and engineering, serves as the director of user programs and Stephanie Law, associate professor of materials science and engineering, is the director of education and training programs. Additional faculty include Adri van Duin, distinguished professor of mechanical engineering; Wes Reinhart, assistant professor of materials science and engineering; and Jun Zhu, professor of physics. Kevin Dressler serves as operation manager and director of user facilities while Kelsey Maxin serves as the director for user engagement and training.



Credit: Seana Wood

> "The fact that we were one of only two MIPs that were funded back in 2016, really raised awareness of our capabilities and helped put Penn State on the map in the area of 2D materials," Redwing said. "There were a number of other universities that also submitted proposals, but we had the right combination of people, research expertise, and a strong track-record of user facility operation in the Materials Research Institute."

Since the birth of the 2DCC-MIP in 2016, the center has established itself in several main areas. One is topological insulators, which are unique materials that conduct electricity on their surfaces but act as insulators in their bulk. This unique characteristic makes them promising for next generation devices such as quantum computing, because their surface states may enable more stable qubits that make them less susceptible to disruption.

"Given that these materials have these unique surface states, there's a lot of interest in them for quantum computing approaches in the future," Redwing said. "In that area, we're one of the leading groups worldwide in synthesizing topological insulators heterostructures and magnetically-doped topological insulators. We've also developed unique intrinsic magnetic topological insulators in our bulk crystal growth facility. We produce samples and provide them to researchers outside of Penn State. We've become a center known for producing high-quality samples of these topological insulators."

Another area of expertise for the 2DCC-MIP is the synthesis of wafer-scale 2D semiconductors, materials such as molybdenum disulfide and tungsten diselenide.

"When we received funding from NSF, we made a point to get equipment that would enable us to deposit these films on large area substrates, anticipating that people who are making devices would want large area 2D films to work with," Redwing said. "An important outcome of the 2DCC-MIP is the development of these wafer scale, high quality transition metal dichalcogenides which has enabled faculty like Saptarshi Das (associate professor of engineering science and mechanics) to use our material for the development of 2D devices for advanced memory and logic and bio-inspired computing. We also send a lot of these samples to other device groups in academia, government labs, and industry."

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Another area where the 2DCC-MIP has unique expertise is in theory and simulation. One example of this is the work of Adri van Duin, distinguished professor of mechanical engineering. Van Duin developed the ReaxFF reactive force field technique, which is a bond order-based force field method and is a powerful computational tool that enables reactive simulations on complex materials such as few-atom thick 2D materials.

Credit: Seana Wood

"ReaxFF can be used to simulate chemical reactions, such as reactions of molecules on a surface, which is basically the process that we use to deposit the 2D layers," Redwing said. "Adri has the expertise to simulate those reactions which enables us to understand what's going on at the atomic level on the surface leading to the formation of 2D crystals."

In addition, the 2DCC-MIP has a bulk growth facility led by Zhiqiang Mao, professor of physics, material science, and engineering, and chemistry.

"Zhiqiang is a master of synthesizing bulk crystals of all of these layered materials, in particular for topological insulators that are of interest for quantum applications," Redman said. "This is yet another example of how we have clear expertise that's unique, not just in synthesis and experimental work, but also in theory and modeling."

This myriad of expertise has helped to build a portfolio of accomplishments that has grown Penn State's already strong reputation as a leader in 2D materials research. The researchers at 2DCC-MIP are working to build on this and produce even more advancements in 2D materials.

This includes delving into data management and data science. Their web-based database called the Lifetime Sample Tracking database, or LiST was developed by full stack software developer Konrad Hilse. LiST efficiently organizes the vast volumes of experimental data produced in the 2DCC-MIP facility, providing an invaluable resource for materials synthesis and characterization for not only data curation and sharing but also for research. This repository's novelty lies in its potential to be used in combination with machine learning to develop algorithms that can predict growth conditions for synthesis of new materials and material combinations.

Additionally, 2DCC-MIP aims to expand its prowess in 2D semiconductors, aligning with industry interests in next-generation logic circuits to transcend the limitations of Moore's Law. Their capacity for wafer-scale films and 2D device development creates a bridge between fundamental research and real-world applications. This dual focus on industry collaboration and innovative data-driven research propels 2DCC-MIP into a potential future ripe with groundbreaking discoveries and practical advancements.

"Those are the two areas where I see the 2DCC-MIP growing beyond our current core focus," Redwing said. "Interacting more with industry to transition some of our 2D materials synthesis capabilities and then also taking advantage of the LiST database to do unique, cutting-edge research." ■

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Blazing the 2D materials trail at Penn State

THE CENTER FOR 2D LAYERED MATERIALS WAS KEY IN DEVELOPING PENN STATE’S ROLE AS A LEADER IN 2D MATERIALS

THE FIRST 2D material, graphene, was discovered 20 years ago. And soon after the discovery, the search was on to find others.

Penn State researchers were part of that exploration for new 2D materials. This made sense, given Penn State’s long and accomplished history of materials research going back to the establishment in 1907 of the Department of Engineering Mechanics and Materials of Construction (now Department of Engineering Science and Mechanics).

Two of these 2D materials searchers were Josh Robinson, professor, materials science and engineering, and Mauricio Terrones, the George A. and Margaret M. Downsbrough Department Head of Physics, Evan Pugh University Professor, and professor of chemistry and of materials science and engineering. In 2012, Terrones and Robinson were looking to build on Penn State’s growing reputation as an early leader in 2D materials.

“I started at Penn State in 2012 and Mauricio had come on board just a little bit before that,” Robinson said. “At that point I had been doing graphene for several years. And Mauricio and I were trying to sort out how we could elevate Penn State in the world of 2D materials. So, we decided to pitch a new center at Penn State that would be the first one in the U.S. that focused on 2D materials beyond graphene.”

Terrones stated that “Although graphene research was taking off in Europe and South Korea, Penn State was building a reputation for seekers of other 2D materials such as transition metal dichalcogenides”.

> “We were hearing that since we are pioneers in the area of 2D materials in addition to graphene, we should start the first 2D Center beyond Graphene in the US,” Terrones said. “That was also due to our having very hot papers, papers that were the first ones in the field.”

In the summer of 2011, Penn State faculty led by Terrones and colleagues at Rice University led by Professor Pulickel Ajayan were awarded a U.S. Department of Defense Multidisciplinary University Research Initiative (MURI) grant to work on 2D systems beyond graphene. The grant became a seed effort to launch the first Penn State’s 2D materials center, the Center for Two-Dimensional and Layered Materials (2DLM).

A key achievement of the 2DLM was building a 2D community at Penn State. Prior to this, the burgeoning community of 2D materials researchers was rather dispersed.

“I think that the main way it started advancing the research part of it was just getting everyone in the community together,” Robinson said. “Before this, it was just very disparate. Everybody was just kind of out doing their own thing.”

A part of this community-building was the annual conference put on by the 2DLM, Graphene and Beyond since 2013.

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Credit: Rosemary Bittel

"2013 is when we did the first graphene and beyond," Robinson said. "We had only about 30-40 attendees, but we were able to get a lot of impactful faculty to come to this meeting. That we managed this with our first event made us realize that this event could really be something significant in the future, and it has lived up to that expectation."

This organization and community building helped supercharge 2D materials research at Penn State.

"Through the 2DLM early on we were able to focus our efforts and have Penn State faculty participating in nine NSF emerging frontiers in research and innovation (EFRI) grants that were in the neighborhood of $18 million combined," Robinson said. "I don't think we'd be near as successful if we hadn't been pulling faculty together to work on landing them. It's not about focusing on an individual project; it's about enabling others to work together."

Terrones added that via the 2DLM's efforts, Penn State's track record in landing NSF grants for materials research is very strong overall.

"We were involved in nine of the 20 EFRI research grants issued by NSF in 2015 and 2016 on 2D materials, which is a remarkable percentage," Terrones said. "And that's just the faculty affiliated with 2DLM landing these grants."

Along with research and community building, there is also a strong educational component to the 2DLM. This is not just for graduate students, but also for undergraduate students. The undergraduates receive opportunities through the center to do 2D materials research.

"The center advances undergraduate education at Penn State by offering opportunities for undergraduates, especially those in the Honors College, to work on 2D materials projects in faculty research groups," Terrones said. "Some undergraduates who have participated have gone on to top graduate schools. This helps attract students interested in 2D materials to Penn State, by offering this kind of hands-on research experience."

On the graduate student side, the 2DLM supports materials education in many ways.

> "From the grad student perspective, we give them a good tool belt of skills in next generation semiconductors, which is key right now given the importance of the CHIPS Act," Robinson said. "That's where we see a big impact as far as the training aspect of the 2DLM."

The graduate students also have multiple opportunities to present their research at events like Graphene and Beyond. These events also offer networking opportunities.

"The interacting with their grad student peers is so important," Robinson said. "They get to come to an event and hear what others are working on. This offers benefits beyond just your standard working in the lab and chatting with your colleagues kind of thing."

Terrones notes that this experience helps them greatly with their career, as they are not just building knowledge and research skills, but important interpersonal skills. These in turn, he points out, have given Penn State 2D materials graduate students a strong track record of success.

"Students who want to do 2D materials want to come to Penn State because of the reputation that we built," Terrones said. "I estimate around half or more of the graduate students who have worked with faculty groups and the 2DLM over the past 10-15 years have gone on to work in the semiconductor industry."

The future roadmap of the 2DLM is to not just build on what they have already achieved in community building, education, and research but also look to become more technology-based. This is especially important, Terrones and Robinson said, given the importance of the CHIPS Act.

"We are looking to partner with semiconductor companies who are exploring 2D materials," Terrones said. "Those who are interested like we are in taking 2D materials to the next level. And for 2D materials, that is developing them to be incorporated into new technologies and applications, such as coatings, semiconductors, sensors, and so on."

2DLM is the oldest 2D materials center at Penn State, having spawned two others, the Center for Atomically Thin Multifunctional Coatings (ATOMIC) and the NSF national user facility, the 2D Crystal Consortium- Materials Innovation Platform (2DCC). But as Robinson noted, they are not about to rest on their legacy.

"Because of the success of ATOMIC and the 2DCC, I think the 2DLM isn't talked about as much anymore," Robinson said. "But I think it is important to remember the history of 2D research at Penn State and remember that it was the 2DLM that kicked everything off back in 2012, 2013. It was because of the 2DLM's success that the other centers were possible. And we're still putting right along, and branching out." ■

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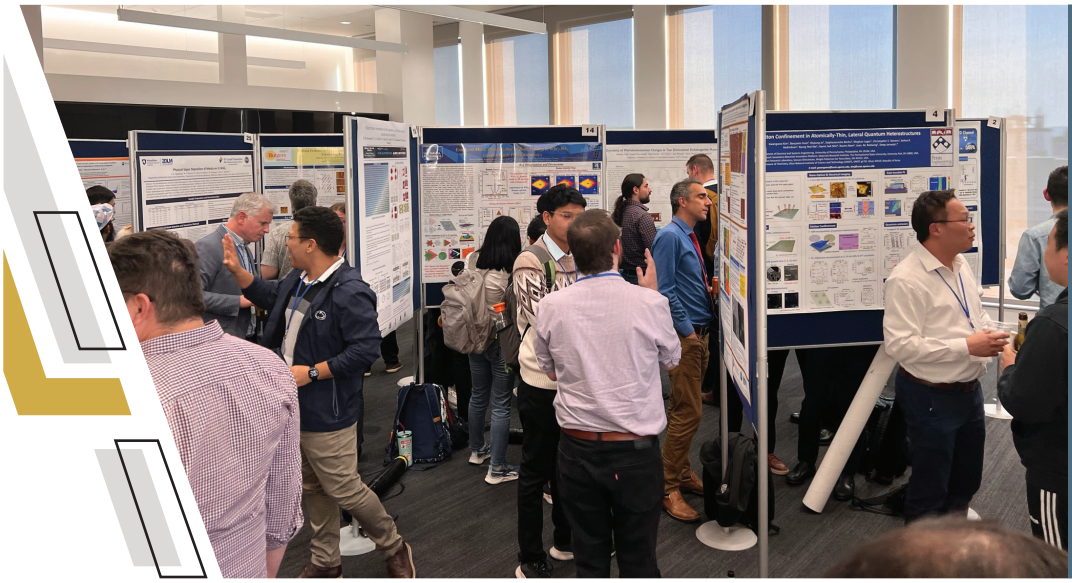

Credit: Rosemary Bittel

Credit: Rosemary Bittel

ATOMIC center builds industry relations, 2D materials workforce

SINCE ITS INITIAL funding and founding in 2015, the Center for Atomically Thin Multi-Functional Coatings (ATOMIC) has worked with Rice University and Boise State University to drive research in 2D materials and foster collaboration between academia and industry. Founded as a National Science Foundation (NSF) Industry-University Cooperative Research Center, ATOMIC operates on a unique model, uniting various stakeholders to address specific challenges and explore cutting-edge technologies.

ATOMIC's mission is multifaceted, with a primary focus on advancing the applications of 2D materials in functional coatings. These coatings, composed of atomically thin layers of materials, hold immense potential in revolutionizing various industries, from electronics to energy. Through collaborative efforts with member companies and national labs, ATOMIC conducts precompetitive research aimed at developing novel coatings with diverse functionalities.

> “ATOMIC is not just specific to electronic materials, it's much broader,” said Joshua Robinson, professor of materials science and engineering and co-director of ATOMIC. “It is about how can 2D materials enhance or augment current technologies. In addition, our mission is to address gaps in industry, and then try to understand how 2D research can help them solve a particular problem.”

The practical applications of ATOMIC's research are diverse and far-reaching, promising to benefit society in numerous ways. From advanced sensors for food safety and environmental monitoring to innovative coatings for corrosion protection and spacecraft applications, 2D materials offer a wide range of possibilities. ATOMIC's collaborative efforts with industry partners ensure that research outcomes are not confined to the laboratory but are translated into real-world solutions that address pressing societal needs.

"Right now, we're working with companies interested in mostly protective coatings, but we are expanding that to semiconductors," said Mauricio Terrones, co-director of ATOMIC, George A. and Margaret M. Downsbrough Department Head, Evan Pugh University Professor, and professor of chemistry and materials science and engineering. "We have found new data that tells us that we can help to make the material the industry requires for making the next generation of transistors. This is one unique aspect of ATOMIC, we can work with companies to do pre-competitive research to see if making the material is feasible as far as viability, reliability, scalability, and so on. If it is, then they can move forward, and if not, then explore if there are any innovative approaches to make it work."

Another key aspect of ATOMIC's mission is workforce development for industries related to advanced materials such as 2D materials. With a growing demand for skilled professionals in industries such as semiconductor manufacturing, ATOMIC plays a crucial role in training the next generation of talent. By offering opportunities for graduate and undergraduate students to engage in research projects spanning multiple universities, ATOMIC ensures that participants gain practical

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Credit: Rosemary Bittel

ATOMIC Partners: Daktronic

Nate Nearman is an engineering manager with Daktronics, a company based in South Dakota that designs, manufactures, sells, and services video displays, scoreboards, digital billboards, dynamic message signs, sound systems, and related products.

How did you get started working with ATOMIC?

We joined ATOMIC about two years ago, seeking research opportunities in environmental protection for our components. Our products must have 99.999% reliability, similar to high standards for LCD screens on your home TV but at the same time must operate in some pretty extreme real-world environments, such as very warm or very cold temperatures. What we found while looking around ATOMIC's website intrigued us, and after initial discussion with people like Dave Fecko (MRI's director of industry collaborations), we saw value in their work with 2D materials. Joining ATOMIC allowed us to influence projects, understand academia's advancements, and see common challenges across industries. This broadened our perspective, helping us anticipate and plan for future technologies, and seeing potential applications three to ten years ahead.

Can you give us an example of how your company has worked with ATOMIC to address an issue?

Penn State's ATOMIC network can hook you up with the right people with the right knowledge. We contacted Dave and asked about anti-graffiti coatings. We put digital signs in graffiti-prone areas and due to the technology involved they cannot be cleaned off easily. Dave and a Penn State faculty member, Christian Pester, offered valuable expertise, aligning ongoing research at Penn State with practical applications like our anti-graffiti coating project. Leveraging this network grants us access to specialized knowledge, enhancing our problem-solving capabilities at Daktronics and fostering potential innovations.

ATOMIC Partners: EMD Electronics

Ravi Kanjolia is a Technology Fellow at EMD Electronics, the Electronics Business of Merck KGaA, Darmstadt, Germany. The company's portfolio covers a broad range of products and solutions in life sciences, healthcare, and electronics, including high-tech materials and solutions for the semiconductor industry, liquid crystals, and OLED materials for displays, and advanced pigments for coatings and cosmetics.

What issues were you hoping that a partnership with ATOMIC could help you address?

When we first contacted David Fecko (MRI director of industrial collaborations) and Mauricio Terrones (ATOMIC co-director), we were impressed by the amount of fundamental knowledge the organization has from its work in 2D materials. Several years ago, we had worked with collaborators to publish a few papers in this field but hadn't brought the technology in-house yet, so revisiting the topic was quite interesting.

Additionally, through this partnership, we were able to benefit from ATMOIC's ability to bring together academic institutions and the private sector together to look at problems from different angles and expertise. This approach is something we value greatly at EMD Electronics as we pride ourselves on collaborating across the industry to advance digital living.

Can you give us an example of the benefits of working with ATOMIC?

Over the years, we developed a manufacturing process around 2D materials. We develop new materials for microelectronics, and are always looking for that added advantage in a material that could make these films better. This is where ATOMIC comes in by adding value to our internal research efforts through your extensive partnership networks. For example, as we are looking at a specific material maybe we need a low temperature process. Boise State, an ATOMIC partner university, is exploring low temperature ALD processes for 2D materials for microelectronics applications, and they are located next to one of our key customers. That enabling component of ATOMIC to connect organizations is helpful for driving progress.

experience and industry-relevant skills. Additionally, internship programs and industry mentorship initiatives provide students with invaluable exposure to real-world challenges and opportunities, paving the way for seamless transitions into the workforce.

The significance of workforce development in the realm of 2D materials cannot be overstated. As industries increasingly rely on advanced materials and technologies, there is a growing demand for individuals with specialized skills in areas such as device fabrication, materials synthesis, and characterization techniques. ATOMIC's focus on equipping students with these skills not only addresses current industry needs but also prepares them for future challenges and innovations.

"One of the neat things about ATOMIC is we have graduate students that are working on projects involving different companies across all three member universities," Robinson said. "We also have undergraduate students, such as those in our REU (Research Experience for Undergraduates) program with Boise State. There are also internships we set up with partner companies, where the students get practical research experience and a lot of mentoring. There is a direct connection to industry that our students receive through ATOMIC."

The practical applications of ATOMIC's research are diverse and far-reaching, promising to benefit society in numerous ways. From advanced sensors for food safety and environmental monitoring to innovative coatings for corrosion protection and spacecraft applications, 2D materials offer a wide range of possibilities. ATOMIC's collaborative efforts with industry partners ensure that research outcomes are not confined to the laboratory but are translated into real-world solutions that address pressing societal needs.

Looking ahead, ATOMIC remains committed to pushing the boundaries of 2D materials research and fostering collaboration with industry partners. Planned projects include the development of next-generation coatings for anti-corrosion applications, advancements in 2D semiconductor devices, and engagement with companies to better understand the potential of 2D materials in various industries. One example Terrones gave is a vision of where the recently passed CHIPS and Science Act, a law that is designed to return America to prominence in the global semiconductor industry.

> “It seems like 2D materials could be CHIPS Act 2.0, not the CHIPS Act as it is currently, but rather CHIPS in 5-10 years," Terrones said. “That's where ATOMIC can really make an impact. So, we start with a completely new 2D materials technology that we develop from scratch. We aim to innovate and ATOMIC and Penn State could become leaders, in this thing that could be called CHIPS 2.0. So, that is the vision.”

Companies or government labs who are interested in learning more about ATOMIC membership can contact Dave Fecko, ATOMIC Industry Liaison Officer at dlf5023@psu.edu. ■

ATOMIC Partners: Idaho National Laboratory

Kiyo Fujimoto is a chemical engineer with the Idaho National Laboratory, a leading research facility specializing in nuclear energy, national security, environmental science, and advanced materials.

What opportunities are there for workforce development for ATOMIC's partners?

There's a significant opportunity for workforce development, which is one of the most attractive aspects of being part of the Center for Atomically Thin Multifunctional Coatings. We're focused on building and diversifying our talent pipeline. Although we haven't fully leveraged this opportunity yet, we're exploring ways to do so. The biannual meetings, where students present their updates and participate, provide a chance for us to interact and mentor them. Even though it's not a formal internship, we can still guide and train them in ways that align with our organization.

How does ATOMIC help the Idaho National Laboratory with its research?

Exploring 2D materials is a new area for Idaho National Laboratory (INL). Our focus is on developing and investigating 2D materials for extreme environments, such as radiation, high temperature, and high pressure—conditions beyond normal life. We aim to create materials suitable for these challenging settings. This includes radiation shielding materials, sensors and electronic components developed from the materials studied within the ATOMIC Center.

By collaborating with the ATOMIC Center, we can work with leaders in the field, such as Boise State, Penn State, and Rice University, who are pioneers in printed electronics and 2D materials. This partnership enhances INL's capabilities in advanced manufacturing and materials development, which is very exciting. INL brings a unique perspective that helps align some projects with national priorities and offers the opportunity to leverage government resources that might not otherwise be available.

2D materials may have future impact on CHIPS Act

THE CHIPS ACT, also known as the Creating Helpful Incentives to Produce Semiconductors for America Act, is a bipartisan initiative passed in 2022 to strengthen domestic semiconductor production. It was implemented in response to mounting apprehensions regarding the country's dependence on foreign suppliers for semiconductor chips, which given our constantly growing reliance on technology, is important.

The act offers financial incentives to foster investment in semiconductor research, development, and manufacturing. Penn State has contributed to these efforts by founding the Mid-Atlantic Semiconductor Hub (MASH), a partnership of nine founding universities designed to combine expertise to promote workforce development, develop technologies such as digital twinning, packaging, and commercialization of these technologies. This will be achieved through collaboration with relevant industry/companies of all sizes and government partners.

Given 2D materials and their role in cutting-edge semiconductor research, one might think that these materials could play a big role in the CHIPS Act. However, not yet, given how 2D materials research is still in the early stages despite Penn State's multiple advances in its development.

“Because of the newness of 2D materials, the CHIPS Act has some focus on 2D materials but it is limited for now,” said Daniel Lopez, Liang Professor of Electrical Engineering and Computer Science, director of the Nanofabrication Lab, and the founding director of MASH. “For example, the Department of Commerce considers 2D materials to be too far away as far as practical, widespread application.”

While 2D materials may not be ready for prime time now, they do hold a great deal of promise for the future. In fact, the CHIPS Act includes the following under “Initial list of key technology focus areas”:

“Advanced materials science, including composites 2D materials, other next-generation materials, and related manufacturing technologies.”

So, the CHIPS Act not only is looking at upping America's semiconductor game now, it is also looking to the future and developing important technologies like 2D materials. One example is in the use of 2D materials to develop artificial neural networks, one of the research focuses of Saptarshi Das, associate professor of engineering science and mechanics. Das, like many researchers today, are looking to nature to come up with inspiration for biomimetic breakthroughs. In his case, he looks to the human brain's ability to do rather complex computing and yet, use very little energy relative to artificial computing.

In 2020, the global information and communication technology sector, covering data centers, networks, and user devices, used approximately 915 TWh of electricity, accounting for 4-6% of global electricity consumption, akin to the energy use of 86 million average American homes. By 2030, this demand could surge to 3,200 TWh.

"Back in say the 1960s and 70s people didn't really care about energy efficiency from any electronic devices,” Das said. “There were not too many around and the chips then did not consume much power. Now, these devices have more and more transistors, so they are more powerful, consuming more energy, and there are so many more of them, from sensors to our sophisticated smartphones. This is where the problem originates: How can we make our devices more energy efficient?”

Unlike traditional computers that separate processing and memory, neuromorphic chips are designed to mimic the brain's architecture where computation and storage occur together in neurons and synapses. This integrated design avoids the energy wasted by constantly transferring data between separate processing and memory units. Das explained that the brain can process vast amounts of sensory data with just 20 watts of energy consumption, from the food we consume - far more efficient than today's power-hungry systems.

> "The brain's exceptional energy efficiency has sparked interest in its architecture, leading to the development of neuromorphic chips inspired by neural networks,” Das said. “These chips mimic the brain's structure, where neurons serve as computing units and synapses as storage units, with no physical separation between computation and storage.”

Das’s group is working to develop solid-state neuromorphic devices that can achieve similar low-power operation by detailed modeling of neural behavior down to the individual neuron. Beyond just copying the human brain, Das's biomimetic approach draws inspiration from specialized sensory systems found throughout the animal kingdom.

Certain insects, fish, and birds possess senses that far surpass human abilities, like an octopus's polarized vision or a catfish's highly sensitive chemical detection. By understanding these natural designs, Das and his team hope to create novel bio-inspired sensors and computing architectures for applications like environmental monitoring, medical diagnostics, and more.

Where do 2D materials come in? They have emerged as a promising platform for realizing these bio-inspired concepts. As naturally thin nanoscale materials, 2D semiconductors avoid the scaling limitations of conventional silicon and can endow devices with multiple functionalities like sensing and low-power operation. With support from the National Science Foundation, Das is working to develop 2D-material-based neuromorphic chips through a collaborative "Futures in Semiconductor Research" grant.

This aligns with goals of the CHIPS Act to revitalize U.S. leadership in semiconductor manufacturing and research. As Das notes, bridging the gap from lab concepts to industrial production has been challenging. The Act's investments in shared research facilities and workforce training seek to address this by fostering partnerships between universities and companies. Das sees these public-private collaborations as critical to transitioning bio-inspired ideas into real-world technologies.

“The CHIPS Act is crucial for maintaining U.S. technological leadership,” Das said. “My research aims to develop newer, low-power, cost-effective technologies, with chipsets being a key enabler due to their reliance on semiconducting materials. While past focus was on silicon, there's growing recognition of the need to invest in newer materials. Bridging the gap between academic research (TRL 1-3) and industrial production (TRL 7-9) is essential for translating innovative ideas into viable technologies, and the CHIPS Act could enable this.”

By following nature's example of extreme efficiency, neuromorphic devices could unlock applications from remote sensors to personalized health monitors while reducing the environmental impact of ever-growing digital systems. The CHIPS Act moves the nation closer to these benefits through domestically developed energy-efficient chips inspired by nature's blueprint for intelligent computing. Das and his research team already has a head start . ■

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Partnership focuses on 2D material research, STEM diversity

A PARTNERSHIP BETWEEN PENN STATE and Florida International University (FIU) is managing to do two very important things at once: achieving significant advancements in two-dimensional (2D) materials research while championing diversity and inclusion within the scientific community.

This partnership, forged through shared expertise and a commitment to excellence, exemplifies the transformative impact of collaborative research initiatives. The beginnings of this research relationship can be traced back to 2016. At Penn State, the partnership is centered at the 2D Crystal Consortium Materials Innovation Platform (2DCC-MIP), a national user facility supported by the National Science Foundation. The 2DCC-MIP is focused on advancing the synthesis of 2D layered chalcogenides for next generation electronics and quantum technologies. It includes state-of-the-art equipment for bulk crystal growth, thin film deposition, and in situ characterization as well as expertise in theory and simulation which was of interest to FIU.

The partnership started small and quickly grew, according to Daniela Radu, Associate Professor of Materials Science and Engineering at FIU's College of Engineering and Computing. Radu is also a Diversity Mentor Professor at FIU which is a distinction for promoting women and minorities in STEM.

"I initially submitted a user proposal to the 2DCC facility for theory assistance related to our group's research in nanomaterials synthesis," Radu said. "It became apparent from that collaboration that there was complementary expertise and interests at FIU and 2DCC in the field of 2D materials synthesis and characterization and that it would be beneficial to both institutions to look for ways to increase our interactions in research."

FIU and the 2DCC teamed at first in a proposal for the NASA Minority University Research and Education Project (MUREP) Institutional Research Opportunity (MIRO). The proposal, successfully awarded in 2019, led to the establishment of the CRE2DO (Center for Research and Education in 2D Optoelectronics) based at FIU. The NASA project is dedicated to research and training for space-related applications involving 2D materials. Building on this success, FIU and 2DCC extended their collaboration to focus on research and education in 2D materials for applications in quantum technologies. This expanded effort led to the Partnership for Research and Education in Materials (PREM) award from NSF.

"Our growing Materials Science Program at FIU benefits tremendously from access to the educational and training resources available within MRI," Radu said. "FIU faculty and students in materials research benefit from having access to state-of-the-art equipment and techniques in the user facilities at Penn State, particularly the 2DCC and the Materials Characterization Laboratory, as well as the expertise of the technical staff and faculty."

For Penn State and the 2DCC, the advantages of the partnership include diverse perspectives that help advance the research.

> “Penn State benefits from FIU’s faculty expertise in 2D materials synthesis in solution phase as well as the advanced characterization pertaining to these materials, and also in having access to talented FIU students who come from diverse backgrounds, given that FIU is a Hispanic-serving institution,” said Joan Redwing, director of the 2DCC and synthesis lead, and Distinguished Professor of Materials Science and Engineering and Electrical Engineering.

Several impactful research projects have emerged from this partnership, showcasing the power of collaboration in driving scientific innovation. For instance, Daniela Radu's collaboration with Distinguished Professor Vincent Crespi's group at 2DCC elucidated fundamental mechanisms underlying the synthesis of sulvanite nanomaterials, uncovering novel pathways for transforming 3D crystals into 2D sheets. Additionally, collaborative efforts facilitated access to state-of-the-art transmission electron microscopy (TEM) equipment at Penn State for FIU researchers, enabling groundbreaking studies on nanomaterials’ structure and composition.

Moreover, collaborative research initiatives have provided invaluable opportunities for student participants. Through programs like the Research Experiences for Undergraduates (REU) and Resident Scholar Visitor Program (RSVP), FIU students gain hands-on experience with cutting-edge equipment and interact with peers and mentors from diverse backgrounds. Similarly, Penn State students benefit from mentoring roles, broadening their networks, and nurturing future leaders in materials science.

Beyond academic circles, this partnership holds significance by promoting diversity in STEM and advancing materials research. The NSF's PREM program aims to increase diversity in materials research by fostering formal partnerships between minority-serving institutions and research centers, aligning with the ethos of the FIU/Penn State collaboration. By nurturing such partnerships and advancing scientific inquiry, this collaboration contributes to a more inclusive and innovative scientific community.

“We are continually looking for new ways to strengthen the connections between FIU and Penn State through collaborative proposals and student recruitment,” Redwing said. “We hope to recruit several FIU undergrads to grad school at Penn State if we can convince them that the snow and cold in winter is not all that bad.” ■

2D materials hold promise for sustainable, climate-friendly electronics

GIVEN OUR RELIANCE on electronics is ever-growing, developing low-energy devices becomes increasingly crucial.

The percentage of electric consumption by information and communication technology (ICT) is steadily increasing. It is currently estimated to be anywhere from 5% to 9% of total electricity consumption worldwide. According to the energy data research company Enerdata, by 2030, the percentage of energy used by ICT could rise to 20% by 2030.

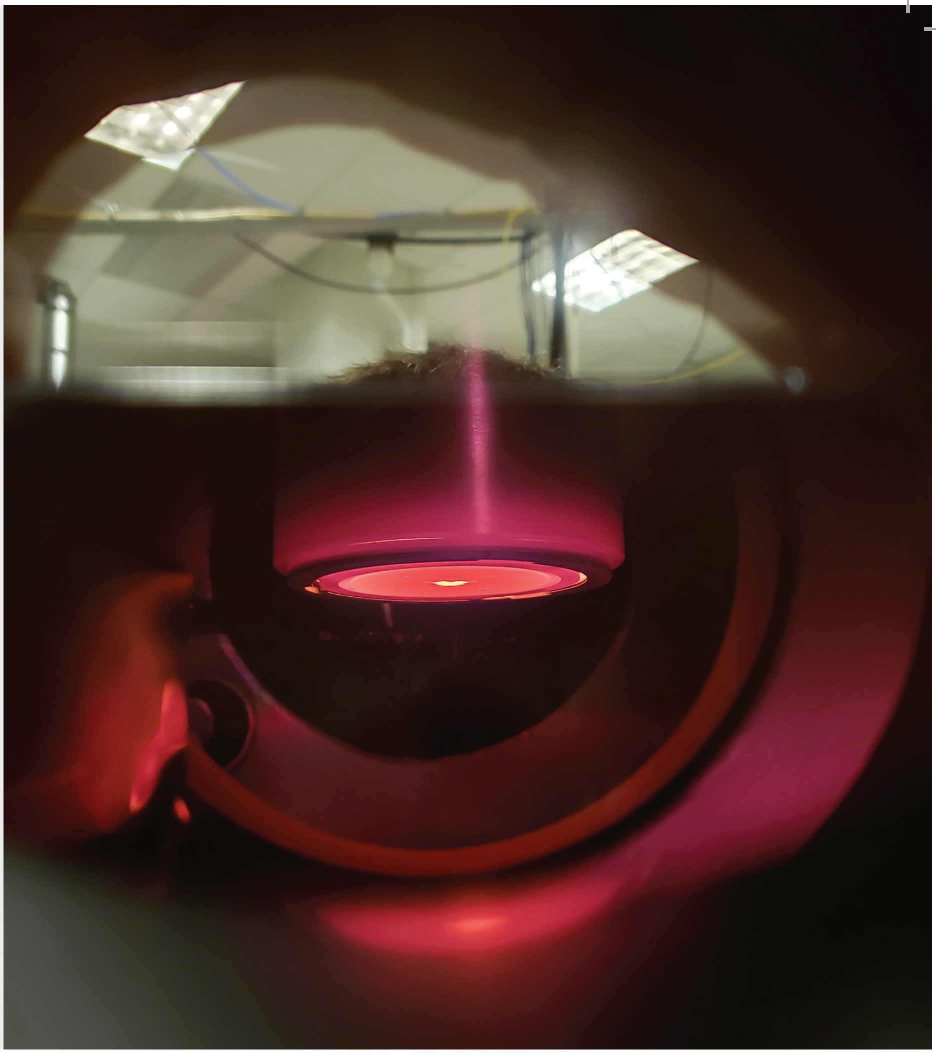
With the need for climate change remediation and greener energy sources, this increase in ICT energy use offers both an issue and, an opportunity. The opportunity is developing semiconductors that are both energy efficient and provide multifunctionality. One of the researchers in the Materials Research Institute leading the effort to find new semiconductor materials that revolutionize how ICTs are powered while minimizing environmental impact is Maria Hilse, assistant research professor, working in thin films-MBE.

Hilse's expertise is in 2D materials, especially inorganic thin films, with a focus on semiconductors and quantum materials. She employs a cutting-edge technique called molecular beam epitaxy (MBE) to fabricate precise and clean films. Two of the 2D materials she works with are tin selenide and tin telluride, which hold promise for high-performance ultra-low power and functional electronics.

> “Tin selenide and tin telluride have slight differences, and they are both interesting. In terms of their internal quantum properties,” Hilse said. “Tin selenide has ferroelectric properties, which is a good addition to just a plain semiconductor. Tin telluride has unique topological properties, including topological non-triviality, which gives it a unique way of conducting electrical current in the material. This is also a very intriguing property to study and learn how to use that because it could potentially conduct electrical current with much less energy dissipation.”

The minimal energy dissipation property holds tremendous potential for reducing power consumption in electronic devices, ultimately aiding in the fight against climate change. This property is rooted in the topological non-triviality, which is a different path of conducting electrons in a material that involves much less friction, and therefore, uses less energy.

“We could lower the power consumption if we could design our normal computers and chips with those materials,” Hilse said.



Credit: Maria Hilse

In addition, these materials could enable semiconductors to not just be low energy, but also energy harvesters.

“These materials also have thermoelectric properties, enabling them to become mini electric generators,” Hilse said. “Imagine an automobile engine, you could use that dissipation heat and feed it back into the 2D material device to gain electrical current which you could then use to say power your lights or something else.”

Hilse is at the forefront of several groundbreaking projects around further developing these 2D materials, collaborating with institutions like Georgia Tech and Ohio State University. Her work spans from exploring the ferroelectric properties of tin selenide to unraveling the spin quantum coupling mechanisms in manganese, and tin telluride. Each project brings her research closer to practical applications that could reshape the electronics industry.

But challenges remain, especially when working with two-dimensional materials like tin selenide. These materials lack strong bonding between layers, making precise growth and thickness control difficult. However, Hilse's innovative approach, utilizing metal organic precursors in hybrid MBE techniques, holds promise in overcoming these obstacles.

Looking ahead, Hilse is optimistic about the potential of hybrid MBE to revolutionize semiconductor research. By manipulating growth kinetics, she aims to coax two-dimensional materials into more organized structures, opening new avenues for sustainable electronics.

"If we can take the typical semiconductor and replace it with a more multifunctional device or material,” Hilse said. "That would add more capabilities to those transistors, meaning eventually we might use one transistor to do more operations simultaneously. All these innovations could lead to alternative semiconductors that could mitigate the environmental impact of our technology-driven society.” ■

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In the Next Issue:

Transformative Research Facilities

Labs and Beyond

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