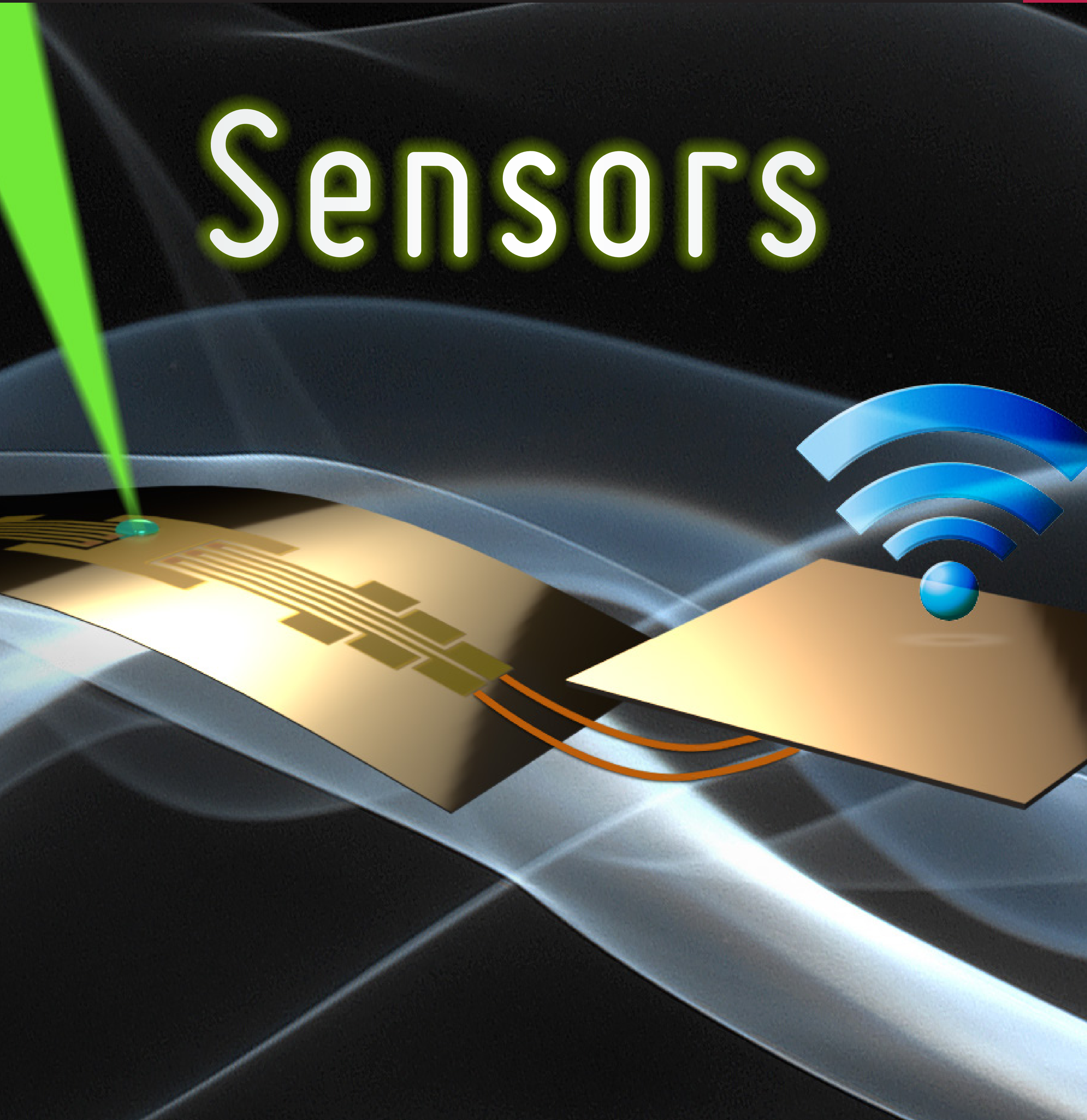
PennState
Materials Research
Institute

FOCUS on MATERIALS

MATERIALS RESEARCH INSTITUTE BULLETIN

FALL 2020



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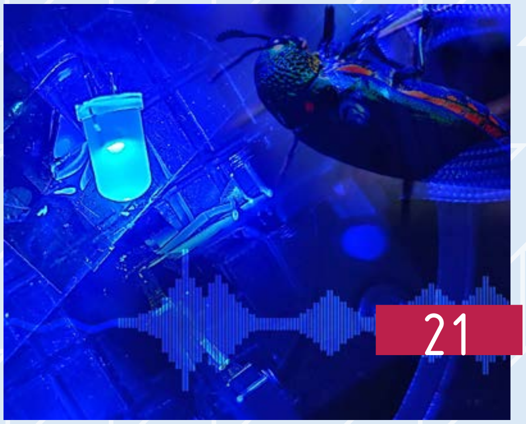
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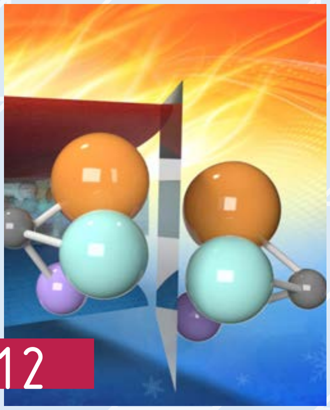

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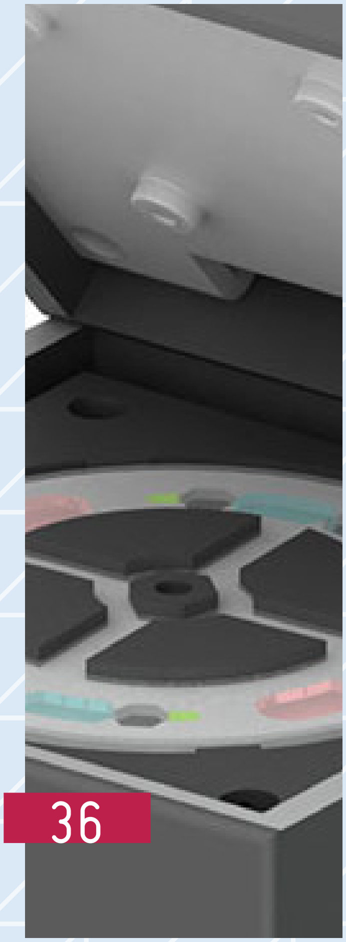

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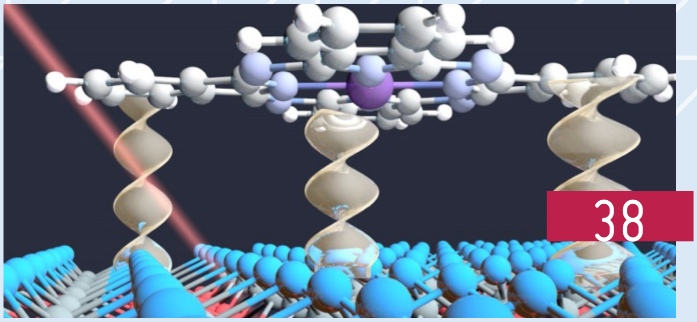

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Focus on Materials is a bulletin of the Materials Research Institute at Penn State University. Visit our web site at **www.mri.psu.edu**.

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U. Ed. RES 20-28

From the Editor

This year marks the 15th anniversary of MRI's Focus on Materials research bulletin. That first issue also was on sensors, as is this issue, but more on that later. I was hired in 2005 as MRI's first full-time writer/editor. This issue will be my last as I transition into retirement. I believe that Focus will carry on strongly with a new hand at the helm. There is too much great research in materials going on at Penn State to stop telling our story in every way we can.

One of the prime considerations when launching our magazine was to tell our stories to our industry partners, both current and future. From its beginnings, MRI has had a mission to go beyond fundamental research in order to provide societal benefits through collaborations with companies that can translate our ideas into products. We also provide expertise and major laboratory capabilities beyond the reach of small and most mid-size companies. By highlighting individual faculty expertise, we try to connect the knowledge at the university with the needs outside Penn State. And importantly, we connect faculty researchers with each other across colleges and institutes. In a campus this huge, it is not easy to know what the colleague down the hall is working on, much less those in other departments.

I was hired by MRI director Carlo Pantano and managing director Bob Cornwall when science communications on campus was in a much less prominent place. The entire day-to-day communications team at University Park consisted of three writers, all women as it happens, and a couple of veteran writers in the College of Agriculture. There was also the award-winning research magazine Research Penn State and magazines in the College of Engineering, Eberly College of Science, and the College of Agriculture. If I am leaving anyone out, I apologize. Many of these magazine features were repurposed news releases or outsourced to freelancers.

As the university's research portfolio grew to nearly $1 billion, the administration saw the value in greatly expanding science communications. Today, around a dozen new positions have been added in colleges and in the institutes overseen by the vice president for research. After a few years' absence, Research Penn State has been revived. The future of science communications seems bright.

When the first sensors issue of this magazine came out, it was thin. There was not a lot of work in this area at the time and for a decade after. Recently, sensor research has exploded. The demand for sensors in medicine, environmental monitoring, and manufacturing has surged. This issue catalogues some of this activity, and does it, in many cases, through the voices of those new science communicators across University Park.

I want to thank MRI director Clive Randall for his support of our science communications and especially for his desire to capture and preserve the rich history of materials research at Penn State. This led to our Pioneers of Materials historical poster project, which hangs in the north wing of the Millennium Science Complex. When campus is open to visitors again, I urge you to check out how Penn State became the number one materials university in the nation. You can also view the posters online at mri.psu.edu.

Sincerely,

Walt Mills

From the Director

First, I wanted to congratulate and thank all of our materials community for their efforts in these difficult and challenging times, for their dedication, resilience, sense of community, and creativity. The collective hard work of faculty, students, and our invaluable staff have been quite extraordinary, and it should fill each of you with Penn State pride. The collective response to drive our mission forward has been humbling to witness. Although we still have a long way to go, we can allow ourselves to see that what we are doing is working and leading to success.

Our faculty and staff have continued to submit highly creative and competitive proposals. In this issue of Focus on Materials, we highlight some large awards, but across the board there has been an increase in success. In the section called Funding in the News, there is a special call-out to Doug Wolfe, Vin Crespi, and Susan Trolier-McKinstry and their teams. The efforts that it takes to win these large, highly competitive, multi-university grants, requires enormous attention to detail, in addition to technical excellence. Thank you!

In addition, we are back in laboratories, working hard and safely. Please remain vigilant in our commitments to keep all safe and productive. If we do this right, we will drive innovative benefits to society, contribute to knowledge, and enable the educational mission for our graduate students and postdoctoral scholars. Their future is our mutual responsibility. As in a finely refined complex mechanical system, each part, however large or small, is essential for the operation; each screw, cog, and gear has to play its role.

This Focus on Materials issue is dedicated to sensor technology. Efforts are quite extensive in this research area at Penn State, and we are sorry that not all activities are reflected by any means. However, I think that this gives a flavor of the important technological trends in sensors. Sensors address the information that permits efficient control and understanding of physical, chemical, or biological systems. Sensors are needed everywhere and within every industry. Sensors are a central aspect that enables the realization of the internet of things (IoT). Sensor technology is not new, but it is aggressively advancing to support the IoT. Our MRI community is addressing all the aspects of sensing technology with new materials, new diagnostic techniques, miniaturization of devices, innovation to enhance signal to noise, and integrating sensing arrays to aid smart detection. We are also integrating energy harvesting strategies for different environments, a technology enabled by functional materials. Energy harvesting and transient storage provide the energy for wireless sensing and communication.

We also highlight some of the sensing technologies in which we invested in February and March of this year via seed grants with our partners, led by the Huck Institutes of the Life Sciences, to address testing and diagnostics of the virus SARS-CoV-2. However, the basic platform strategies are flexible to other pathogens and hence provide important new strategies with a long-term perspective. As I mentioned in the letters that I wrote to our MRI community, we have to learn from crisis, and this virus will not be the last virus to threaten a pandemic or our food security. In this regard, sensing offers us so much in monitoring of all the ecosystems that we need to monitor to understand threats and maintain quality of life. Please enjoy the ideas that are discussed.

Lastly, but not least, I want to thank Walt Mills for all his efforts in communicating the materials community discoveries and inventions. He has been an important part of MRI's success. We wish him well in a well-deserved retirement. Walt you are a star!

Sincerely,

C A Randall

Director, Materials Research Institute

Penn State to Lead $30 Research Alliance

THE DEPARTMENT OF Defense's Defense Threat Reduction Agency (DTRA) has awarded a combined total of $51.1 million to two university research alliances to counter threats of destruction, with a specific focus on improving current and developing future warfighter technology. Penn State is leading the Interaction of Ionizing Radiation with Matter University Research Alliance, which was awarded $30 million for the next five years, with the potential of extending the alliance for a total of nine years and $54 million of funding with additional funding opportunities available.

Led by Doug Wolfe, head of the Department of Metals, Ceramics and Coatings Processing in the Applied Research Laboratory (ARL), professor of materials science and engineering, professor of nuclear engineering by courtesy, and professor of engineering science and mechanics, Penn State's efforts are focused in ARL, the College of Engineering,

> "We have a very strong, multidisciplinary group who proposed transformative research addressing DTRA's needs," Wolfe said. "Our collaboration consists of extremely talented investigators from a variety of institutions and disciplines with a wide range of technical expertise."

Million University

and the College of Earth and Mineral Sciences. The alliance includes three other permanent members: the University of Michigan (UM), Massachusetts Institute of Technology (MIT) and the University of Florida (UF). The rest of the alliance includes eight other universities and several national laboratories and industry partners.

Primary Penn State contributors include Meghan Flannery Hayes, head of the Department of Complex Systems Monitoring at ARL; Marek Flaska and Azaree Lintereur, both of whom are assistant professors in the Ken and Mary Alice Lindquist Department of Nuclear Engineering; Aman Haque, professor of mechanical engineering and engineering science and mechanics; and Saptarshi Das, assistant professor of engineering science and mechanics..

The team is investigating how ionizing radiation interacts with matter. According to Wolfe, this research could lead to higher-resolution radiation detectors capable of identifying dirty bombs or concealed radiation materials. By understanding the material interactions, the researchers plan to design low-cost, high-efficiency room-temperature detectors that would eliminate the need for extreme temperatures to control detecting materials. They also plan to develop electronics and systems that would be secure against radiation damage.

“Current electronics, including banking and satellite systems, could not withstand a nuclear explosion,” Wolfe said. “We hope to develop devices and systems that would be insensitive to radiation. In the event of a bomb explosion, we would still be able to communicate with one another.”

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University Research Alliance team members are focusing on the basic research of ionizing radiation interactions over three research areas, with research area leads from MIT — materials, UM — devices and device integration, and UF — survival and response. The rotating alliance members will contribute via shorter-term projects that explore specific subgoals of the larger aims.

Beyond the primary research goals, the alliance has also established a workforce development program that gave the team their competitive edge, according to Wolfe.

“Fundamental to every stage of research is education,” Wolfe said.

The team aims to foster an inclusive academic community to recruit and train undergraduate students, graduate students, and postdoctoral fellows to become the next generation of researchers and engineers.

“This is a landscape-changing opportunity for nuclear engineering at Penn State,” said Jean Paul Allain, head of the Ken and Mary Alice Lindquist Department of Nuclear Engineering. “Our team has already demonstrated their collaborative research strengths through a variety of other projects, and now they are combining forces to elevate ionizing radiation interaction research in a way that will transform how we protect against radioactive threats, as well as how we innovate and design digital devices and radiation-hardened electronic systems. Scholars at all levels will come to Penn State to contribute to this project.” ■

Penn State Awarded an Research Center Grant

> "If you look at modern electronics, the memory is separate from the chip performing computation," she said. "It is a time and energy bottleneck getting the data back and forth between the processor and the memory."

THE DEPARTMENT OF Energy has awarded an Energy Frontier Research Center Award to Penn State, one of 10 awards announced in 2020, and the second EFRC awarded to Penn State researchers.

The topic of this large center grant is 3D ferroelectric microelectronics, according to principal investigator Susan Trolier-McKinstry, Evan Pugh University Professor and the Steward S. Flaschen Professor of Ceramic Science and Engineering, and professor of electrical engineering.

The von Neumann bottleneck posits that the speed and efficiency of computation is limited by the time it takes to transfer data between chips, and in the meantime the much faster computational chip remains idle. The goal of this project is to prepare materials that will serve as memory to stack in the third dimension above the processor chip enabling seamless communication between memory and computation to mitigate this bottleneck.

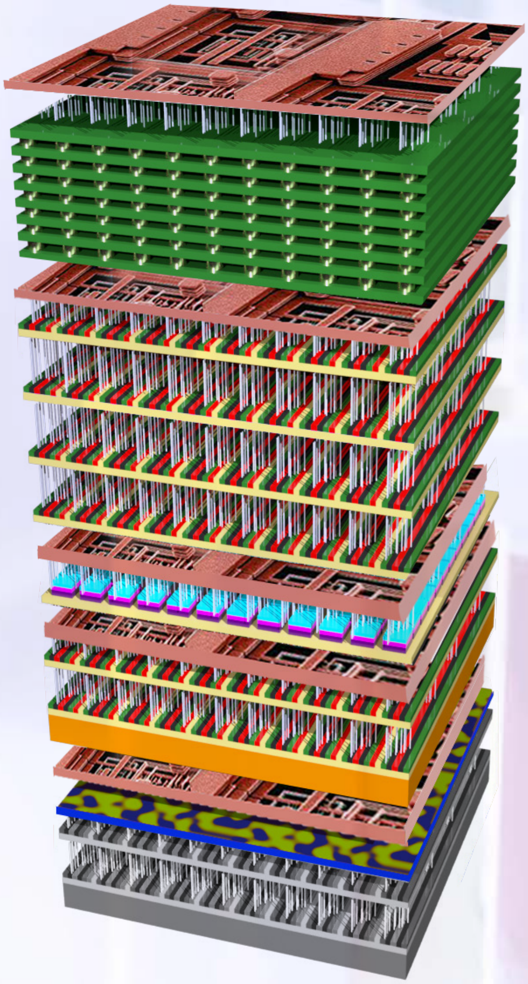
The breakthrough technology, she says, is their ability to prepare the ferroelectric memory materials at very low temperatures. Previously, it was not possible to stack memory on

Energy Frontier Worth Over $10 Million

the processor chip because the interconnects on the processor chip could not take temperatures higher than 400 degrees C. Without being able to lay the ferroelectric material down at a lower temperature, it is not possible to put memory on top of computational logic on the same chip. The research in the center will focus on discovery of new ferroelectric materials, probing the origins of ferroelectricity, developing tools to control the functional properties, growing tailored ferroelectrics at low temperatures, integrating the new materials into a variety of memory devices, and developing processes that allow these materials to be stacked in 3D memory arrays.

Along with Trolier-McKinstry, who is the new center's director, others in the leadership team include associate director Vijay Narayanan, from Computer Science and Engineering, and thrust leaders Jon-Paul Maria, from Materials Science and Engineering, and Tom Jackson, from Electrical Engineering. Other Penn State faculty include Saptarshi Das, Engineering Science and Mechanics; Nasim Alem, Venkat Gopalan, Roman Engel-Herbert, Ismaila Dabo, and Shashank Priya, all from Materials Science and Engineering; Abhronil Sengupta from the Department of Electrical Engineering and Computer Science; and Qi Li and Ying Liu from the Department of Physics. Other institutional partners are Sandia National Laboratory and Oak Ridge National Laboratory, Purdue University, University of Pennsylvania and University of Virginia.

The four-year grant began August 1 and is funded at between $10 million and $15 million with possibility of renewal. The other EFRC, the Center for Lignocellulose Structure and Formation, was renewed for an additional four years in 2018. ■



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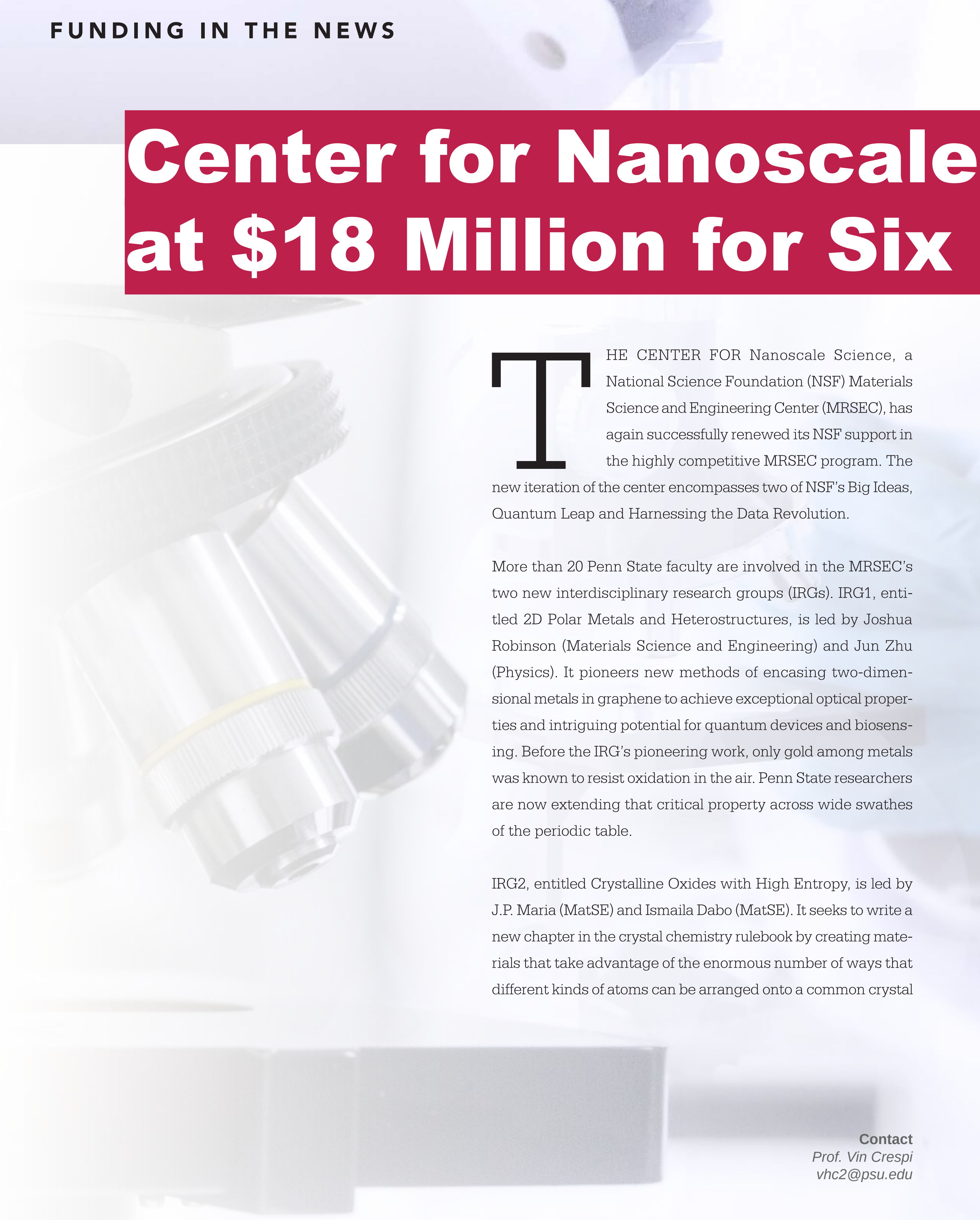

Center for Nanoscale at $18 Million for Six

THE CENTER FOR Nanoscale Science, a National Science Foundation (NSF) Materials Science and Engineering Center (MRSEC), has again successfully renewed its NSF support in the highly competitive MRSEC program. The new iteration of the center encompasses two of NSF's Big Ideas, Quantum Leap and Harnessing the Data Revolution.

More than 20 Penn State faculty are involved in the MRSEC's two new interdisciplinary research groups (IRGs). IRG1, entitled 2D Polar Metals and Heterostructures, is led by Joshua Robinson (Materials Science and Engineering) and Jun Zhu (Physics). It pioneers new methods of encasing two-dimensional metals in graphene to achieve exceptional optical properties and intriguing potential for quantum devices and biosensing. Before the IRG's pioneering work, only gold among metals was known to resist oxidation in the air. Penn State researchers are now extending that critical property across wide swathes of the periodic table.

IRG2, entitled Crystalline Oxides with High Entropy, is led by J.P. Maria (MatSE) and Ismaila Dabo (MatSE). It seeks to write a new chapter in the crystal chemistry rulebook by creating materials that take advantage of the enormous number of ways that different kinds of atoms can be arranged onto a common crystal

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Science Renewed Years

lattice. This innovative technique enables Penn State researchers to put atoms into environments that they normally do not assume, with potential applications across a wide domain, from new energy materials to new quantum devices, guided by a close interplay of theory, computation, data, and experiment.

The MRSEC also provides career development opportunities for dozens of graduate students with a focus during this renewal on sustainability in research practice and outcomes. A recently launched educational website, Mission: Materials Science, will expand its content and reach out to youth audiences through a new partnership with the local Discovery Space museum. Outreach through participation in summer science camps, STEM programs for students who are blind or visually impaired, and partnerships with universities that serve underrepresented students will remain core to the Center's mission.

Program Director for Education and Outreach Kristin Dreyer says, "The best and most effective messengers for communicating important science concepts to youth and public audiences and inspiring the next generation of materials scientists are current researchers themselves. My colleague, Tiffany Mathews, and I get to help make those opportunities happen and provide the necessary support for our members to do it successfully."

The Center for Nanoscale Science is among eight MRSECs successfully renewing their funding along with three new centers. NSF says, "The US economy and its competitiveness depend on innovation, an essential part of which is fueled by technological breakthroughs in basic research. Our comfort, work, and wellbeing depend on the development of new materials for anything ranging from smart electronics to implantable medical devices." The Center for Nanoscale Science has been funded continuously since 2000. ■

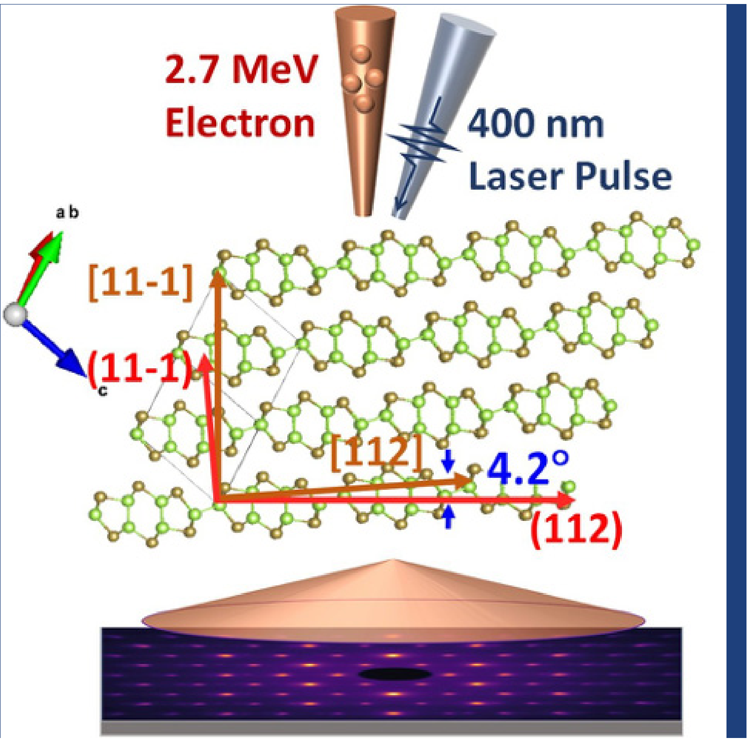
"These two intriguing research directions define new materials platforms— whole classes of new materials — that are being pioneered here at Penn State," says Vin Crespi, the Director of the Center for Nanoscale Science research SNAPSHOTS

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

New Insights Into van der Waals Materials Found

LAYERED van der Waals materials are of high interest for electronic and photonic applications, according to researchers at Penn State and SLAC National Accelerator Laboratory, in California, who provide new insights into the interactions of layered materials with laser and electron beams.

Two-dimensional van der Waals materials are composed of strongly bonded layers of molecules with weak bonding between the layers.



The lattice dynamics of monoclinic gallium telluride (GaTe) is studied by ultrafast electro diffraction (UED). This study provides a generalized understanding of Friedel's law and a comprehensive explanation of the lattice dynamics.
Image: Qingkai Qian, Penn State

The researchers used a combination of ultrafast pulses of laser light that excite the atoms in a material lattice of gallium telluride, followed by exposing the lattice to an ultrafast pulse of an electron beam. This shows the lattice vibrations in real time using electron diffraction and could lead to a better understanding of these materials.

“This is a quite unique technique,” said Shengxi Huang, assistant professor of electrical engineering and corresponding author of a paper in ACS Nano that describes their work. “The purpose is to understand fully the lattice vibrations, including in-plane and out-of-plane.”

One of the interesting observations in their work is the breaking of a law that applies to all material systems. Friedel’s Law posits that in the diffraction pattern, the pairs of centrosymmetric Bragg peaks should be symmetric, directly resulting from Fourier transformation. In this case, however, the pairs of Bragg peaks show opposite oscillating patterns. They call this phenomenon the dynamic breaking of Friedel’s Law. It is a very rare if not unprecedented observation in the interactions between the beams and these materials.

“Why do we see the breaking of Friedel’s Law?" she said. "It is because of the lattice structure of this material. In layered 2D materials, the atoms in each layer typically align very well in the vertical direction. In gallium telluride, the atomic alignment is a little bit off.”

When the laser beam shines onto the material, the heating generates the lowest-order longitudinal acoustic phonon mode, which creates a wobbling effect for the lattice. This can affect the way electrons diffract in the lattice, leading to the unique dynamic breaking of Friedel’s law.

This technique is also useful for studying phase change materials, which absorb or radiate heat during phase change. Such materials can generate the electrocaloric effect in solid-state refrigerators. This technique will also be interesting to people who study oddly structured crystals and the general 2D materials community.

The lead author on the article, titled “Coherent Lattice Wobbling and Out-of-Phase Intensity Oscillations of Friedel Pairs Observed by Ultrafast Electron Diffraction” is Huang’s postdoctoral scholar Qingkai Qian. Additional Penn State authors in her group are graduate students Kunyan Zhang and Lanxin Jia, and research scholar Yu Zhou. Xijie Wang, accelerator physicist at the Department of Energy’s SLAC National Accelerator Laboratory, led the ten-member SLAC team.

The National Science Foundation supported this work. The Department of Energy supports SLAC. ■

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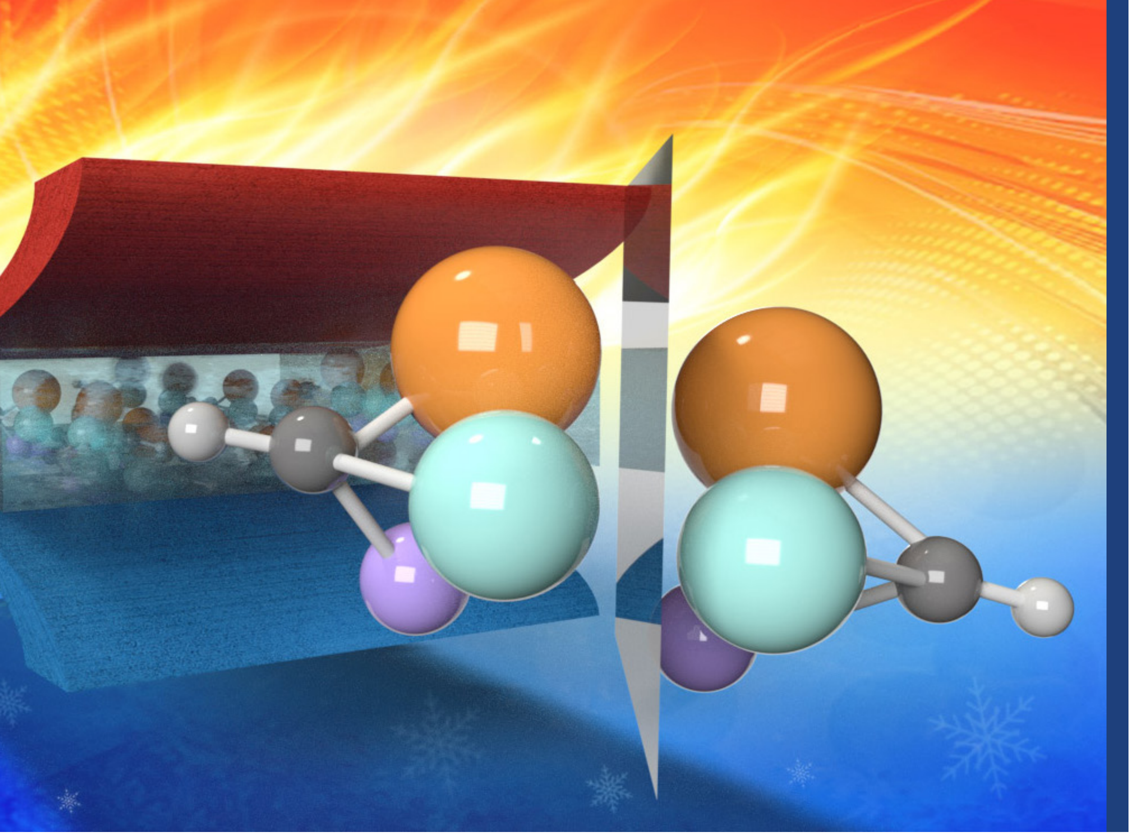
Full articles on all snapshots can be read at **mri.psu.edu/news**



Chiral (mirror) molecules give relaxor ferroelectrics their amazing properties.
Credit: MRI/Penn State

An Understanding Of Relaxor Ferroelectric Properties Could Lead To Advances In Multiple Fields

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A NEW FUNDAMENTAL UNDERSTANDING of the behavior of polymeric relaxor ferroelectrics could lead to advances in flexible electronics, actuators and transducers, energy storage, piezoelectric sensors, and electrocaloric cooling, according to a team of researchers at Penn State and North Carolina State.

The theory behind the mechanism of relaxor ferroelectrics has been debated for more than 50 years, says Qing Wang, professor of materials science and engineering, Penn State. While relaxor ferroelectrics are well-recognized fundamentally fascinating and technologically useful materials, they have been commented as heterogeneous, hopeless messes by Nature in 2006. Without a fundamental understanding of the mechanism, little progress has been made in designing new relaxor ferroelectric materials. The new understanding, which relies on both experiment and theoretical modeling, shows that relaxor ferroelectricity in polymers comes from chain conformation disorders induced by chirality. Chirality is a feature of many organic materials in which molecules are mirror images of each other, but not exactly the same. The relaxor mechanism of polymers is found to be vastly different from the mechanism proposed for ceramics whose relaxor behavior originates from chemical disorders.

“Different from ferroelectrics, relaxors exhibit no long-range large ferroelectric domains but disordered local polar domains,” Wang explains. “The research in relaxor polymeric materials has been challenging owing to the presence of multiple phases such as crystalline, amorphous and crystalline-amorphous interfacial area in polymers.”

In energy storage capacitors, relaxors can deliver a much higher energy density than normal ferroelectrics, which have high ferroelectric loss that turns into waste heat. In addition, relaxors can generate larger strain under the applied electric fields and have a much better efficiency of energy conversion than normal ferroelectrics, which makes them preferred materials for actuators and sensors.

Penn State has a long history of discovery in ferroelectric materials. The first relaxor ferroelectric polymer was discovered by Penn State electrical engineering professor Qiming Zhang in 1998, when he used an electron beam to irradiate a ferroelectric polymer and found it had become a relaxor. Zhang along with Qing Wang also made seminal discoveries in the electrocaloric effect using relaxor polymers, which allows for solid state cooling without the use of noxious gases and uses much less energy than conventional refrigeration.

“The new understanding of relaxor behavior would open up unprecedented opportunities for us to design relaxor ferroelectric polymers for a range of energy storage and conversion applications”, says Wang.

Their work, titled “Chirality-induced relaxor properties in ferroelectric polymers,” appears in the June journal Nature Materials. The lead author is Yang Liu, a postdoctoral scholar in Wang’s group. Co-authors Wenhan Xu and Aziguli Haibibu are former graduate students in Wang’s group. Zhubing Han is Wang’s current graduate student. Bing Zhang is a graduate student in Professor J. Berholc’s group at NC State. And Wenchang Lu is a research associate in Berholc’s group.

This research was funded by the U.S. Air Force Office of Scientific Research and the US Office of Naval Research. The supercomputer time at the National Center for Supercomputing Applications was provided by the National Science Foundation. ■

New Advances In Superconductivity

THE GOAL OF room temperature superconductivity took a small step forward with a recent discovery by a team of Penn State physicists and materials scientists.

The surprising discovery involved layering two-dimensional materials called molybdenum sulfide with another material called molybdenum carbide. Molybdenum carbide is a known superconductor, which means that electrons can flow through the material without any resistance. Even the best of metals, such as silver or copper, lose energy through heat. This loss makes long distance transmission of electricity more costly.

"Superconductivity occurs at very low temperatures, close to absolute zero or 0 Kelvin," said Mauricio Terrones, corresponding author on a paper in Proceedings of the National Academy of Sciences published this week. "The alpha phase of Moly carbide is superconducting at 4 Kelvin."

When layering metastable phases of moly carbide with moly sulfide superconductivity occurs at 6 Kelvin, a 50 percent increase. Although this is not remarkable in itself – other materials have been shown to be superconductive at temperatures as high as 150 Kelvin-- it was still an unexpected phenomenon that portends a new method to increase superconductivity at higher temperatures in other superconducting materials.

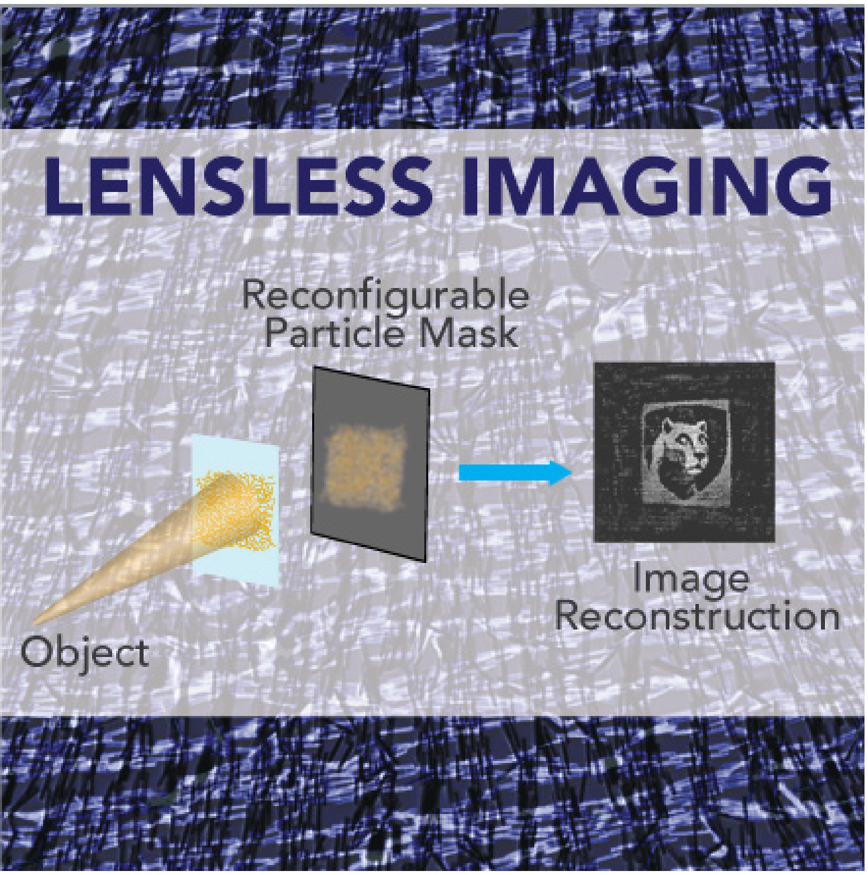
The team used modeling techniques to understand how the effect was achieved experimentally. According to materials scientist Susan Sinnott, "Calculations using quantum mechanics as implemented within density functional theory assisted in the interpretation of experimental measurements to determine the structure of the buried molybdenum carbide/molybdenum sulfide interfaces. This work is a nice example of the way in which materials synthesis, characterization, and modeling can come together to advance the discovery of new material systems with unique properties."

According to Terrones, "It's a fundamental discovery, but not one anyone believed would work. We are observing a phenomenon that to the best of our knowledge has never been observed before."

The team will continue experimenting with superconductive materials with the goal of someday finding materials combinations that can carry energy through the grid with zero resistance.

In addition to Terrones and Sinnott, authors on the PNAS paper, titled "Superconductivity enhancement in phase-engineered molybdenum carbide/sulfide vertical heterostructures," are Ph.D. students or graduated Ph.D. students Fu Zhang, Yanfu Lu, Lavish Pabbi, Anna Binion Tomota Granzier-Nakajima, Tiany Zhang, Zhong Lin, and postdoctoral scholars Kazunori Fujisawa and Yu Lei, Professor Eric Hudson and former Research Assistant Professor Laura Elias, all of Penn State, and Wenkai Zhang and Luis Balcas of Florida State.

This work was funded by a grant from the Department of Energy, which was recently renewed to continue their research. ■



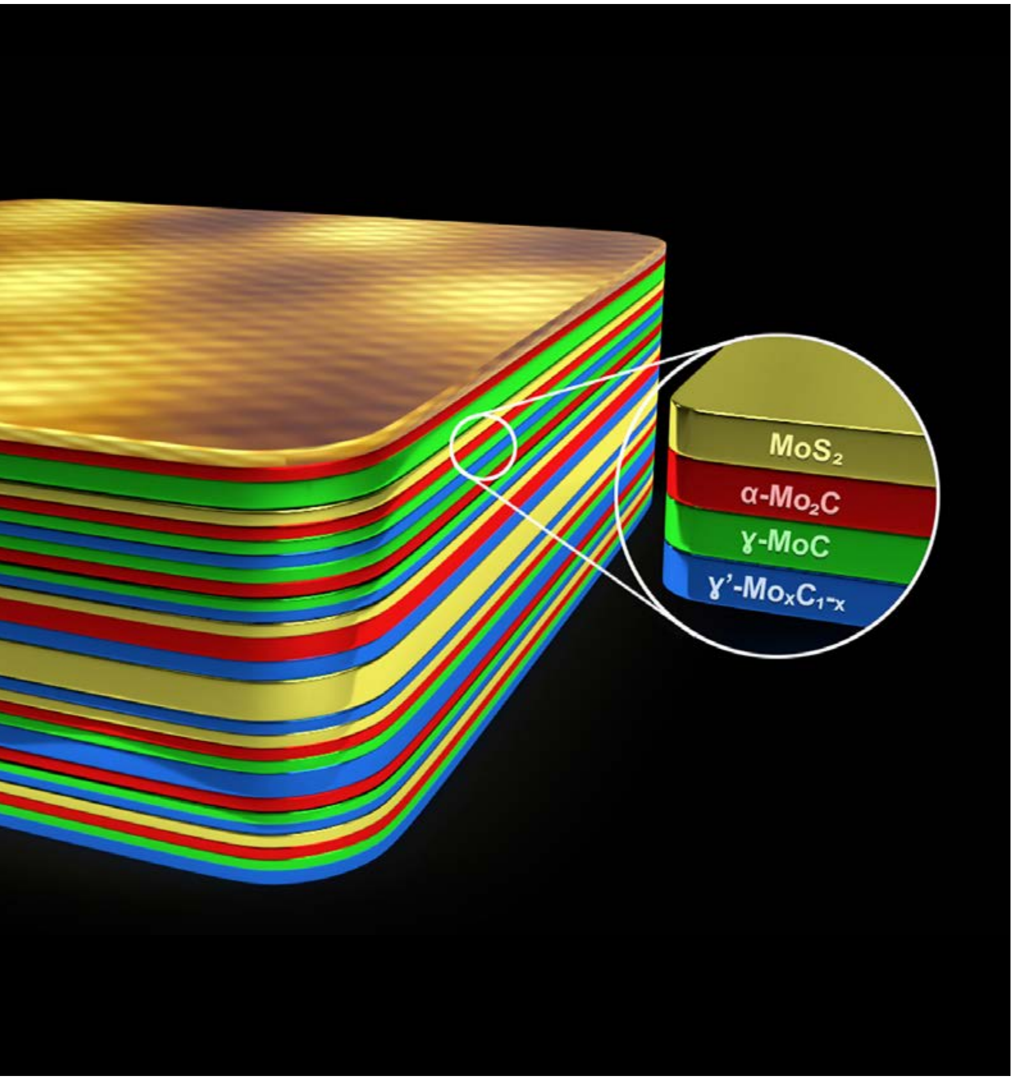
Schematic of a lens-free camera. Credit: Jennifer Miller / Penn State

A Multishot Lensless Camera Could Aid Disease Diagnosis

A NEW TYPE OF imaging that does not require a lens and uses reconfigurable particle-based masks to take multiple shots of an object is being developed by researchers at Penn State. The electric-field directed self-assembling mask technology is expected to have uses in lower-cost and faster disease diagnosis, the enhancement of optical microscopy and may even lead to thinner cell phone technology.

How it works

A mask made of microscopic gold wires is placed near the object that will be imaged. The mask scatters the light reflected off the object and the light is collected by an image sensor. The particles in the mask are then rearranged by an electric current, giving a new mask with every iteration, and the new image is recorded. The scattered light can then be computationally reconstructed into the original object image using the multiple light captures, resulting in highly improved resolution and quality.



Layers of molybdenum carbide and molybdenum sulfide allow superconductivity at 50 percent higher temperatures. Credit: Elizabeth Flores-Gomez Murray / Penn State

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"We are not the only group to do lens-free imaging," explains Jennifer Miller, a doctoral candidate in chemistry and a first author on a paper published online this week in ACS Nano. "What is different about our work is that typically you would need to make multiple masks and physically move them around to get multiple images. This becomes bulky and expensive and negates some of the simplicity that is the advantage of lens-free imaging."

Adds co-first author Cheng-Yu Wang, doctoral candidate in electrical engineering, "Traditional masks are passive. We can add functionalization to our microwire, like polarization, selectivity and plasmonic effects, that make our imaging system more powerful."

In typical microscopy, there exists a trade-off between the field of view and the power of the resolution, so a 10x field is wider than a 100x field. By using a lens-free imaging technology, it is possible to combine a wide field of view with high magnification for lower-cost images and faster diagnosis of disease. This could be especially useful in developing countries where high-end microscopes are not available.

In the case of cell phones, one major contributor to their bulk is due to the camera lens needing to be a certain distance to the detector. A lens-free camera could help minimize the space requirement. Likewise, a lens-free system added to a cell phone could turn the cell phone into a low-power microscope.

Along with Miller and Wang, senior authors on the ACS Nano paper, titled "Particle-based reconfigurable scattering masks for lensless imaging," are Christine Keating, Distinguished Professor of Chemistry, and Zhiwen Liu, professor of electrical engineering.

This work was funded by the Penn State Materials Research Science and Engineering Center, Center for Nanoscale Science, and by the National Science Foundation. ■

Penn State has filed a patent application for this technology.

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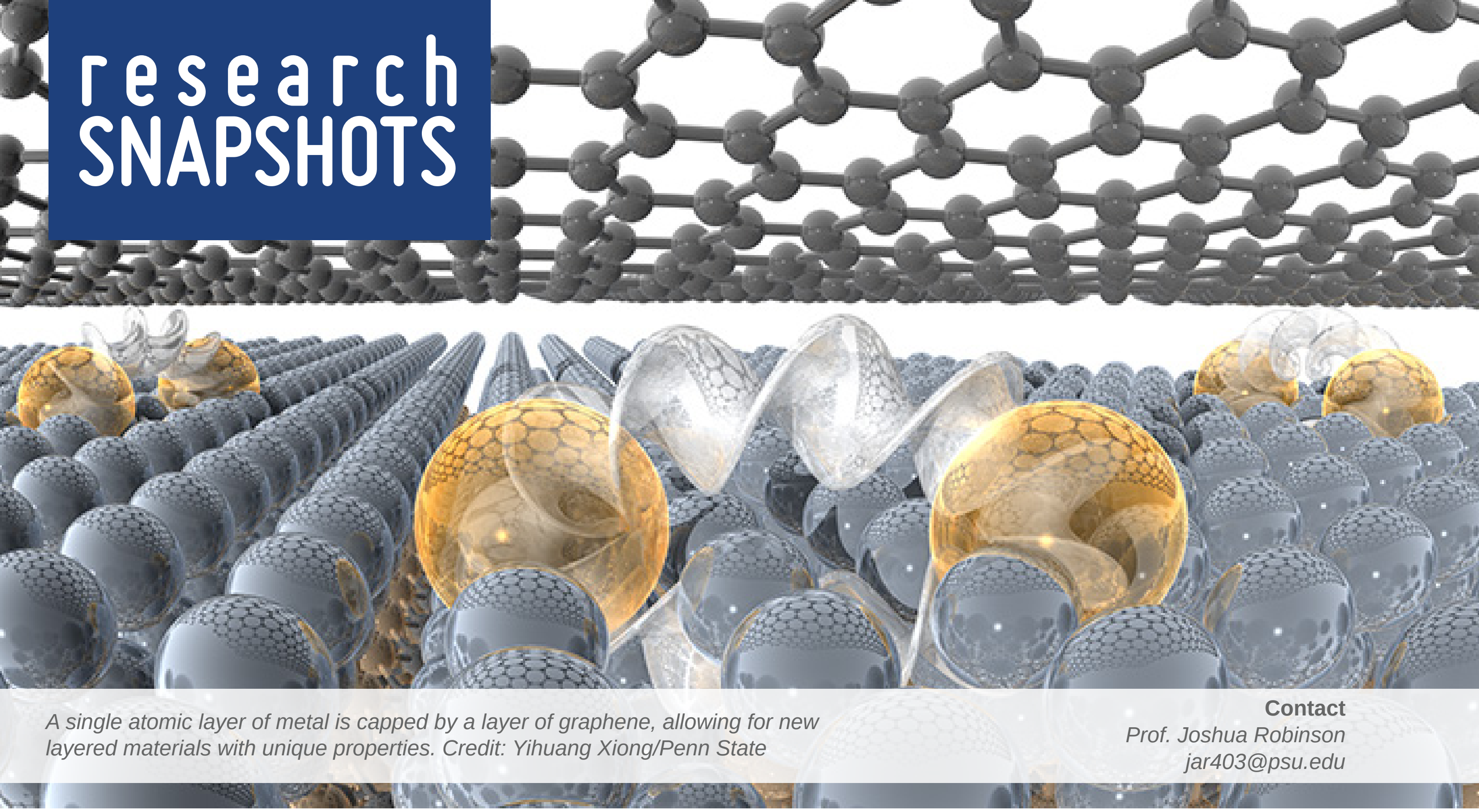
Full articles on all snapshots can be read at **mri.psu.edu/news**



A single atomic layer of metal is capped by a layer of graphene, allowing for new layered materials with unique properties. Credit: Yihuang Xiong/Penn State

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Two-Dimensional Metals Open Pathways to New Science

A NEW, ATOMICALLY THIN materials platform developed by Penn State researchers in conjunction with Lawrence Berkeley National Lab and Oak Ridge National Lab will open a wide range of new applications in biomolecular sensing, quantum phenomena, catalysis, and nonlinear optics.

“We have leveraged our understanding of a special type of graphene, dubbed epitaxial graphene, to stabilize unique forms of atomically thin metals,” says Natalie Briggs, a Ph.D. candidate and co-lead author on a new paper in the journal Nature Materials. “Interestingly, these atomically thin metals stabilize in structures that are completely different from their bulk versions, and thus have very interesting properties compared to what is expected in bulk metals.”

Traditionally, when metals are exposed to air they rapidly begin to oxidize, or rust. In as short as one second, metal surfaces can form a rust layer that would destroy the metallic properties – and in the case of a 2D metal, this is the entire layer. Furthermore, if you were to combine a metal with other 2D materials via traditional synthesis processes, the chemical reactions during synthesis would ruin the properties of both the metal and layered material. To avoid these reactions, the team exploited a method that automatically caps the 2D metal with a single layer of graphene while creating the 2D metal.

The team starts with silicon carbide that they heat to a high temperature. The silicon leaves the surface, and the remaining carbon reconstructs into epitaxial graphene. Importantly, the graphene/silicon carbide interface is only partially stable and is readily passivated by nearly any element, if the element has access to this interface. The team provides this access by poking holes in the graphene with an oxygen plasma, and then they evaporate pure metal powders onto the surface at high temperatures. Incredibly, the metal atoms migrate through the holes in the graphene to the graphene/silicon carbide interface, creating a sandwich structure of silicon carbide, metal, and graphene. The process to create the 2D metals is called confinement heteroepitaxy, or CHet. “We call it CHet because of the confined nature of the metal, and the fact that it is epitaxial – the atoms all line up – to the silicon carbide, an important aspect to the unique properties we see in these systems,” notes Joshua Robinson, senior author and associate professor of materials science and engineering, Penn State.

“In this paper, the focus is on the fundamental properties of the metals that are going to enable a new set of research topics,” says Robinson. “It shows that we are able to develop novel 2D materials systems that are applicable in a variety of hot topics such as quantum, where graphene is a key link that allows us to think about combining very different materials that normally could not be combined to form the basis for superconducting or photonic qubits.”

Next steps in their studies will involve proving out the superconducting, sensing, optical and catalytical properties of these unique layered materials. Beyond creating unique 2D metals, the team is continuing to explore new 2D semiconducting materials with CHet that would be of interest to the electronics industry in future electronics beyond silicon.

Additional authors from Penn State include former Ph.D. student in the Robinson group and co-lead author Brian Bersch, Ph.D. student Yuanxi Wang, and professors Cui-Zu Chang, Jun Zhu, Adri van Duin and Vincent Crespi.

The Nature Materials paper is titled “Atomically Thin Half-van der Waals Metals via Confinement Heteroepitaxy.”

Primary funding was provided by the Northrop Grumman Corp., with additional funding from the Semiconductor Research Corporation, the National Science Foundation, and the Alfred P. Sloan Research Fellowship. ■

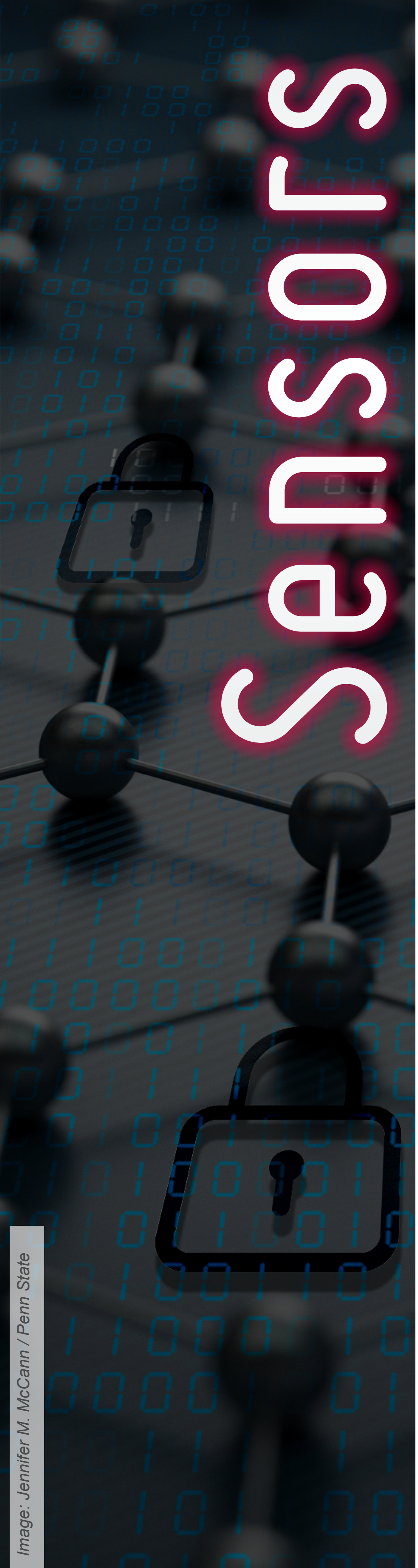

Image: Jennifer M. McCann / Penn State

SENSORS: AN OVERVIEW

"A sensor is a device used to measure a property, such as pressure, position, temperature, or acceleration, and respond with feedback." - TE Connectivity

TE Connectivity is one off the world's largest makers of sensor devices and a company that has worked with Penn State Harrisburg extensively and recently developed a relationship with the main campus at University Park. TE makes 2,744 different sensors, from temperature sensors to ultrasonic sensors to speed and distance sensors.

We are living in a world where sensors are ubiquitous and growing exponentially. The much talked about internet of things (IoT), in which sensors talk to humans and to other machines, is based on millions, even billions of different types of reliable and cost-effective sensors.

At Penn State, sensor research is in a kind of renaissance. In fact, this is the first Focus on Materials to have a theme issue on sensors in 15 years.

Why now? Fundamental research in areas such as nanotechnology and two-dimensional materials over the past decade is now leading to applications. A new spirit of entrepreneurship fostered by university President Eric Barron is making start-ups based on university research more appealing. Some of those young companies will be featured here. And, as is often the case, funding agencies and the needs of society shape the direction of research.

You will recognize that a number of the articles included here are a response to the Covid pandemic. A fast, reliable test for Covid is still a number one priority in containing the spread of the disease. Sensing the Covid particles in the air is also a priority, especially as people return to business as usual and meet face-to-face. Both of these technologies are being developed at Penn State.

This university is unique or at least unusual in the breadth of expertise and the interdisciplinary approach to research. We find physicists collaborating with data scientist and biologists, biomedical researchers teaming with veterinary scientists, electrical engineers with clinicians at Penn State College of Medicine. Facilitating the cross-cutting research is the strength of the university-wide interdisciplinary research institutes, including the Materials Research Institute. These institutes sprang into action when the threat of the Covid pandemic became clear.

Beyond the current crisis, sensors are still required for other medical conditions, for environmental monitoring, for the early detection of plant diseases that can affect the worldwide food supply. All of those applications are discussed in the articles you will read in this issue. Submitted for your consideration, the MRI Focus on Materials Sensor issue. ■

A Spectroscopic Sensor Battles Deadly

Credit: Adobe Stock

By Walt Mills

CITRUS GREENING IS a disease that has cost billions of dollars statewide and wiped out many of Florida's citrus groves. Caused by a disease imported from China shortly after the turn of the current century, it is spread by an insect and attacks the roots of the citrus trees, either killing them or causing the fruit to drop off prematurely. This is the disease a technology developed in the laboratory of Zhiwen Liu is targeting for early detection.

Liu, professor of electrical engineering, and his then Ph.D. student Perry Edwards developed a miniaturized version of a full-size spectrometer for applications in mobile settings and in the field. After Edwards' graduation, they formed a company together called Atoptix to commercialize the spectrometer. As they searched for a more specific application, they focused in on sensing diseases in plants. The new company became Croptix.

"What Croptix has done is utilize that technology to identify diseases in plants," said Edwards, who is the president of the company. "We look at what happens within a leaf and diagnose changes in a leaf's structure and see how those changes correlate with disease progression, nutrient and water deficiency, basically any problems within the plant."

Citrus Greening

A worker uses the Croptix device to check for Citrus Greening.
Image: Croptix

Their technology is a field-deployable system run through a smart phone app. The user takes a spectroscopic measurement of the leaf and send the data to the cloud where Croptix accesses and analyzes it. It takes four to six leaves to assess the condition of the tree. This takes just a few minutes, much faster than sending the leaves off to a lab to analyze.

"This is a big deal," Liu said. "Because every day they can measure thousands of spectra. We are not talking about just a spectrometer. We are talking about an entire system. You have to have the source, the fiber optic configuration, and the way to transfer the data into the cloud server and process it. ▸ ▸ ▸

In addition, you also have all of this GPS information recorded. You have a time stamp and a space stamp, so you can take a measurement in the field and know when and where it was taken. We use big data analysis and machine learning, which is all based on having lots of data to analyze. This is the enabling technology."

They first started out testing at Penn State's agricultural station at Rock Springs, looking at diseases in potatoes. Then they moved on to studying corn and soybeans at the greenhouse on campus near the Berkey Creamery. They were looking at nutrient deficiency and water stressors.

"We had interesting results from that," Edwards said, "but from a company standpoint, it was hard to see a way forward."

That's when they started looking at citrus greening. They took their technology to Florida and got good preliminary results. They then began working with a USDA lab in Maryland where they began studying the disease in detail.

Plants are stressed by three things: nutrient deficiencies, over or under watering, and disease. Their sensors are capable of measuring all three. Currently their sensors are made in-house. They will make a small batch, test them, then improve the design. Now that the design is optimized, they feel ready to outsource the manufacturing. They are being financed these days by a National Science Foundation Phase II SBIR award. It's a two-year grant with some follow-up funding. They also had seed funding from Ben Franklin Technology Partners. They also have projects in California and Texas, the latter of which is being funded by a USDA grant.

Rather than selling the sensors outright, they plan to provide the grower with the sensors and the equipment to upload the data to the cloud, where Croptix will analyze the data and send the results to the growers, usually within a couple of days. The planter will pay a monthly or annual fee, and if anything breaks or technology improves, they will replace the equipment.

"We have had some collaborations early on with David Hughes and Plant Village," Liu said. Hughes is a Penn State researcher who co-founded Plant Village, a database of plant disease images that can help farmers identify problems with their crops using a smart phone. "We gave him some of our early sensors to study and do some tests on cassava melons, but now we're laser focused on citrus greening."

The Stage I SBIR grant was awarded to prove the efficacy of their technology. Now, in Phase II, they are focusing on proving its ability to target citrus greening. They had been setting up for a substantial commercial launch this year, but they are unsure how the recent national events will impact that. "We'll see how that pans out," Edwards said. ■

Gathering data in the field. Image: Croptix

> "Citrus is a great crop to work with," added Edwards, "a lot of interest, a lot of concern about this disease. Once we have everything working in that area, we can transfer all the infrastructure to other crops."

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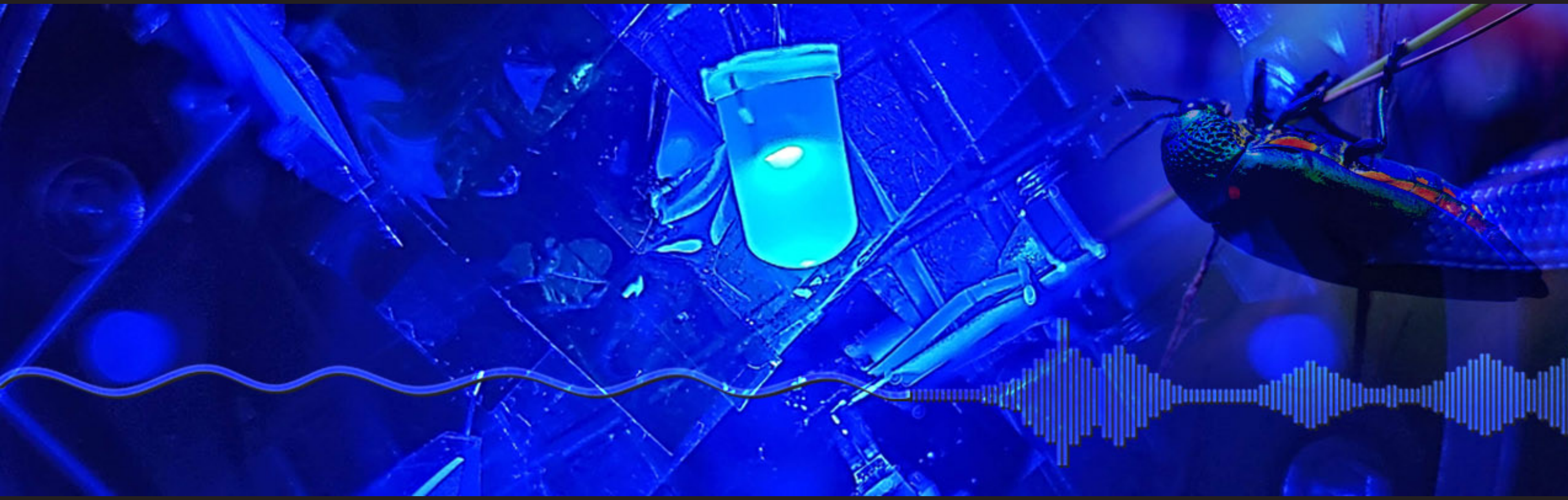
To Make a Better Sensor, Just Add Noise



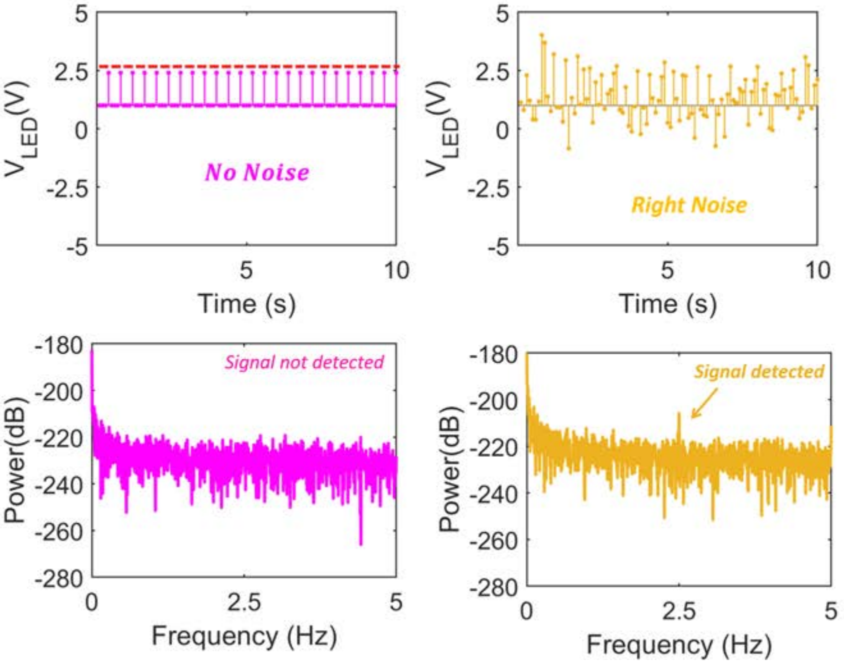
Above:
Artist's depiction of a phenomenon called stochastic resonance. Researchers studied this technique to apply it to sensors to detect signals too faint to otherwise capture. Image: Bessie Terrones / Penn State MRI

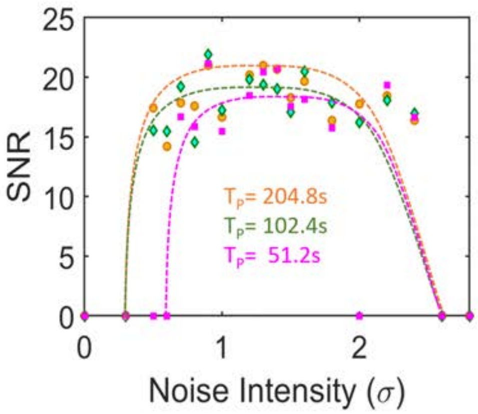
By Walt Mills

IN A SENSING phenomenon common in the animal world but unusual in man-made sensors, Penn State researchers have added a small amount of background noise to enhance very weak signals, in this case a light source too dim to sense.

In contrast to most sensors, for which noise is a problem that should be suppressed, they found that adding just the right amount of background noise can actually increase a signal too weak for sensing by normal sensors, to a level that can reach detectability. Although their sensor, based on a two-dimensional material called molybdenum disulfide, detects light, the same principle can be used to detect other signals, and because it requires very little energy and space compared to conventional sensors, could find wide adaptation in the coming internet of things (IoT). IoT will deploy tens of millions of sensors to monitor conditions in the home and factories, and low energy requirements would be a strong bonus.

"This phenomenon is something that is frequently seen in nature," says Saptarshi Das, an assistant professor of engineering science and mechanics. "For example, a paddlefish that lives in muddy waters cannot actually find its food, which is a phytoplankton called Daphnia, by sight. The paddlefish has electroreceptors that can pick up very weak electric signal from the Daphnia at up to 50 meters. If you add a little bit of noise, it can find the Daphnia at 75 meters or even 100 meters. This ability adds to the evolutionary success of this animal." ▸ ▸ ▸





Time:
White Gaussian noise of different standard deviations

Frequency:
Corresponding histogram of the LED voltage distribution.

Noise Intensity:
The SNR curves in this instance show the typical SR response found in biological species such as paddle fish, cray fish, etc.

"Stochastic resonance is a phenomenon where a weak signal which is below the detection threshold of a sensor can be detected in the presence of a finite and appropriate amount of noise," according to Akhil Dodda, a graduate student in engineering science and mechanics and co-first author on a new paper appearing in Nature Communications.

Another interesting example is the jewel beetle, which can detect a forest fire at 50 miles distance. The most advanced infrared detector can only detect at 10 to 20 miles. This is due to a phenomenon these animals use called stochastic resonance.

In their paper, the researchers demonstrate the first use of this technique to detect a subthreshold photonic signal.

One possible use being considered is for troops in combat. Army personnel in the field already carry very bulky equipment. It is unfeasible to add the heavy, power-hungry equipment required to enhance a subthreshold signal. As well as for soldier safety, their technique is applicable in resource-constrained environments or beneath the ocean where people want to monitor very weak signals. It could also be used in volcanic locations or to monitor earthquakes in time to give an alarm.

"Who would have thought that noise could play a constructive role in signal detection? We have challenged tradition to detect otherwise undetectable signals with miniscule energy consumption. This can reopen doors to a totally unexplored and ignored field of noise enhanced signal detection," said Aaryan Oberoi, a graduate student from the Department of Engineering Science and Mechanics and co-first author on the paper.

Their next step is to demonstrate this technique on a silicon photodiode, which make the device very scalable. Any state-of-the art sensor can be enhanced by this concept, Das says.

The team has filed a provisional patent application with a full patent to follow. ■

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Locust Swarm Could Improve Collision Avoidance

A collision detector for vehicles mimics an avoidance neuron in locusts that allows them to fly in swarms.
Image: Jennifer M. McCann / Penn State

By A'ndrea Messer

PLAGUES OF LOCUSTS, containing millions of insects, fly across the sky to attack crops, but the individual insects do not collide with each other within these massive swarms. Now a team of engineers is creating a low-power collision detector that mimics the locust avoidance response and could help robots, drones, and even self-driving cars avoid collisions.

"We are always looking for animals with unusual abilities, ones that do something better than humans," said Saptarshi Das, assistant professor of engineering science and mechanics. "Insect vision is something people use regularly to design automatic systems because they fly and don't collide, but then we found locusts are unique."

Locusts are unusual because they use a single, specialized neuron, called the Lobula Giant Movement Detector (LGMD), to avoid collisions. ▸ ▸ ▸

"So, we started looking at how it works and locusts are just incredible," said Das. "What these creatures can do is very humbling."

According to Darsith Jayachandran, graduate student in engineering science and mechanics, the neuron receives two different signals. An image of an approaching locust falls on the avoiding locust's eye. The closer the invading locust gets, the larger the image and the stronger this excitation signal becomes. The other input is the change in angular velocity of the invading locust with respect to the avoiding locust.

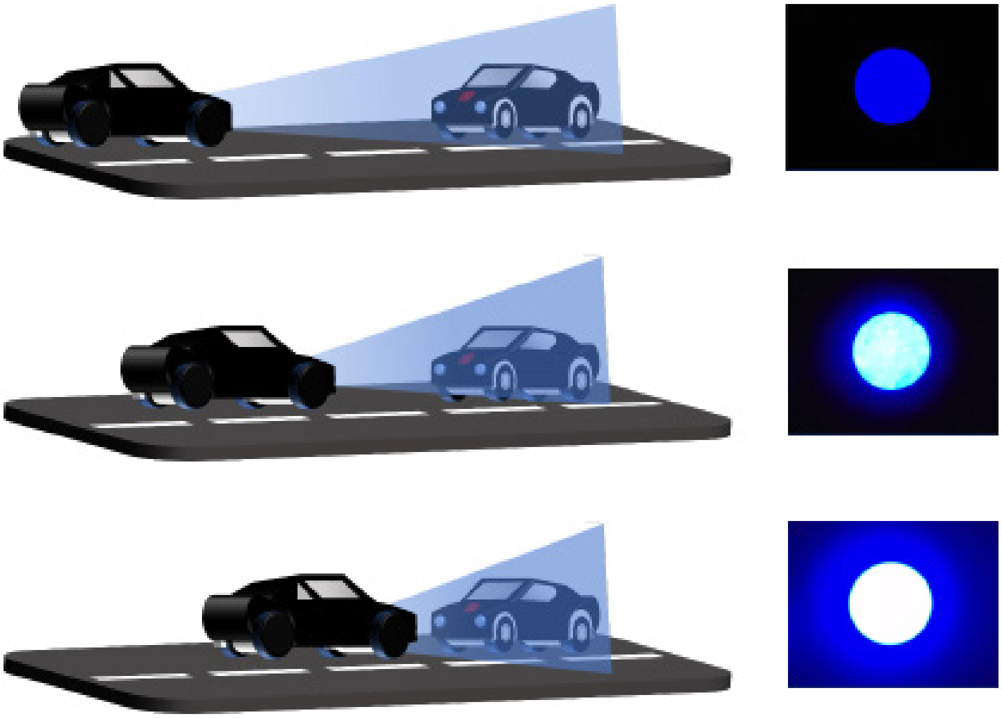
THE RESEARCHERS DEVELOPED a compact, nanoscale collision detector using monolayer molybdenum sulfide as a photodetector. They placed the photo detector on top of a programmable floating gate memory architecture that can mimic the locust's neuron response using only a tiny amount of energy.

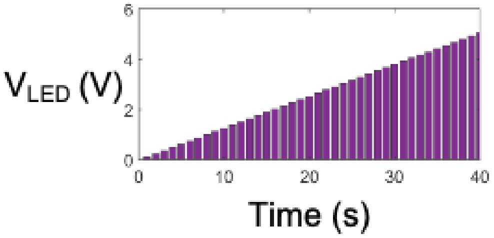
They report in Nature Electronics that this "is a leap forward towards the development of smart, low-cost, task-specific, energy efficient, and miniaturized collision-avoidance systems."

"Because the neuron has two branches, the locust computes the changes in these two inputs and realizes that something is going to collide," said Jayachandran. "So, the avoiding locust changes direction."

Das Research Group Members

Andrew Pannone, Yikai Zhang, Rahul Pendurthi, Thomas Schranghamer, Joseph Nasr, Tianlong Tang, Saptarshi Das, Akshay Wali, Sarbashis Das, Aaryan Oberoi, Andrew Arnold, Darsith Jayachandran, Akhil Dodda, Amritanand Sebastian





Left:
The collision detector in this car will perceive an increase in light intensity as the distance between the two cars reduces. This spatial visual stimuli can be converted to a temporal stimuli by ramping the LED voltage as shown here. A screen placed close to the LED during this experiment showed a very similar result as that of the moving car.

According to the researchers, locusts move at two to three miles per hour and make directional changes in hundreds of milliseconds. The decision to move employs non-linear mathematics and a miniscule energy expenditure.

This quick reaction and modest energy use is attractive for mechanized collision detectors. Current detectors for autonomous automobiles are very large and very heavy. The researchers' collision detector responds in two seconds. Also, rather than be a jack-of-all trades detector, the molybdenum sulfide-based sensor is task specific, but because it is so small and uses so little energy, that is acceptable, according to the researchers.

The photodetector causes an increase in device current in response to an oncoming object, the excitatory signal, while the underlying programmable memory stack always causes a decrease in the current, the inhibitory signal. When an object approaches, the excitatory signal is added to the inhibitory stimuli, causing a non-monotonic change in the device current, mimicking the escape response of the LGMD neuron found in locusts.

"While locusts can only avoid collisions with other locusts, our device can detect potential collisions of a variety of objects at varying speeds," said Das.

At this point, the researchers have only tested the device with objects on a direct collision path. They still need to optimize the responses for additional situations.

"We can't do every measurement, every situation," said Aaryan Oberoi, graduate student in engineering science and mechanics. "So, we developed a numerical model. We can also test if multiple devices on the same chip would work better. So far, it looks like a single device will be sufficient. However, a multi-pixel collision detector array can offer collision avoidance in 3D space."

Also working on this project from Penn State are Amritanand Sebastian, graduate student in engineering science and mechanics; Tanushree H. Choudhury, assistant research professor, 2D Crystal Consortium – Materials Innovation Platform; and Joan M. Redwing, professor of materials science and engineering, chemical engineering, and electrical engineering, and associate director of the Materials Research Institute.

Balakrishnan Shankar, associate dean for the School of Engineering, professor, head of the department, and the chairperson at the Department of Mechanical Engineering, Amritapuri campus of Amrita Vishwa Vidyapeetham, also participated in this work. ■

The researchers have filed a provisional U.S. patent on this technology.

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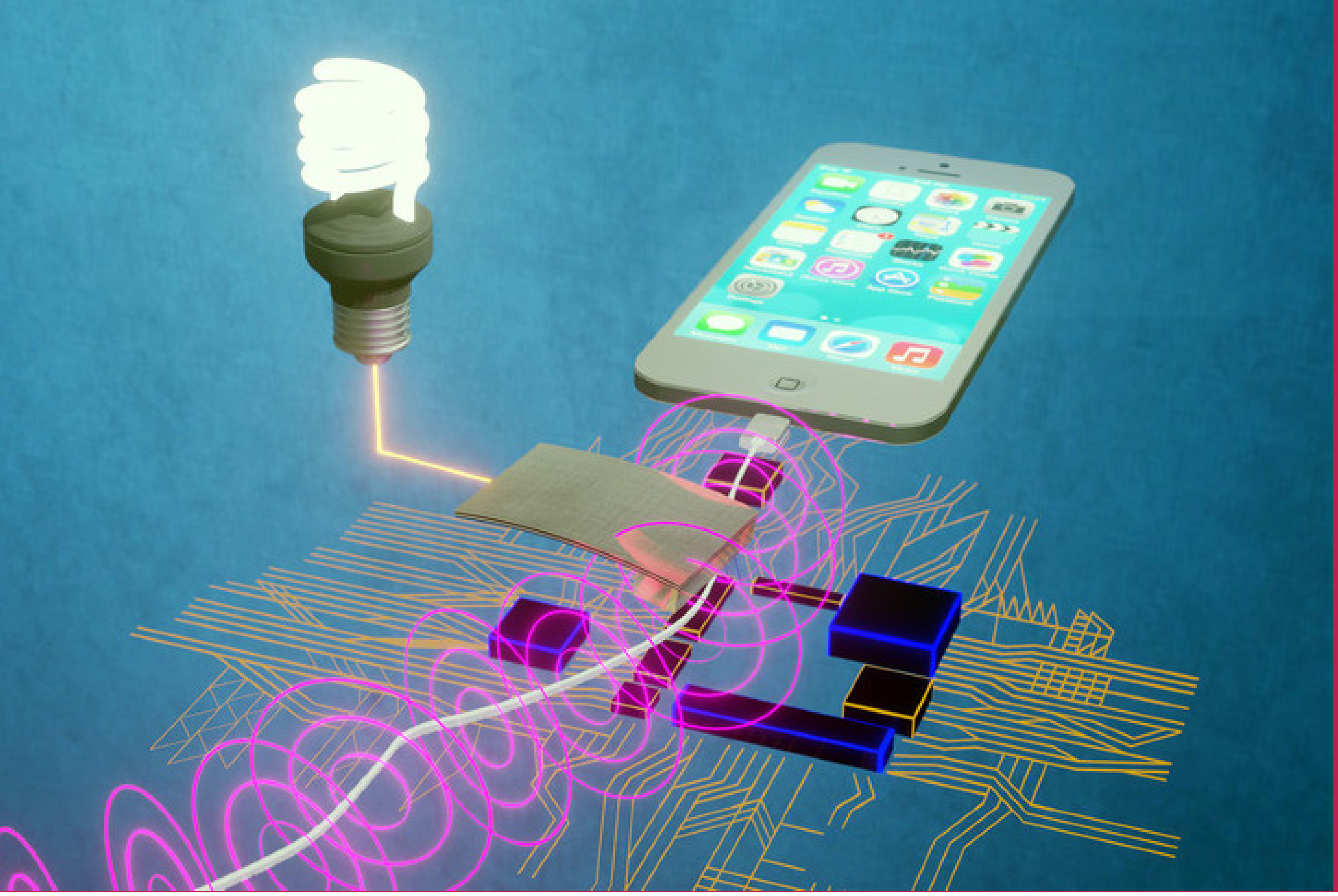

A team of scientists has developed a new mechanism to harvest stray magnetic fields all around us and convert the energy into useful, usable electricity. IMAGE: KAI WANG

By Matthew Carroll

THE ELECTRICITY THAT lights our homes and powers our appliances also creates small magnetic fields that are present all around us. Scientists have developed a new mechanism capable of harvesting this wasted magnetic field energy and converting it into enough electricity to power next-generation sensor networks for smart buildings and factories.

"Just like sunlight is a free source of energy we try to harvest, so are magnetic fields," said Shashank Priya, professor of materials science and engineering and associate vice president for research at Penn State. "We have this ubiquitous energy present in our homes, office spaces, work spaces, and cars. It's everywhere, and we have an opportunity to harvest this background noise and convert it to useable electricity."

A team led by Penn State scientists developed a device that provides 400 percent higher power output compared to other state-of-the-art technology when working with low-level magnetic fields, like those found in our homes and buildings.

The technology has implications for the design of smart buildings, which will require self-powered wireless sensor networks to do things like monitor energy and operational patterns and remotely control systems, the scientists said.

"In buildings, it's known that if you automate a lot of functions, you could actually improve the energy efficiency very significantly," Priya said. "Buildings are one of the largest consumers of electricity in the United States. So even a few percent drop in energy consumption could represent or translate into megawatts of savings. Sensors are what will make it possible to automate these controls and this technology in a realistic way to power those sensors."

Researchers designed paper-thin devices, about 1.5 inches long, that can be placed on or near appliances, lights, or power

Scientists Tap Unused Energy Source to Power Smart Sensor Networks

cords where the magnetic fields are strongest. These fields quickly dissipate away from the source of flowing electric current, the scientists said.

When placed 4 inches from a space heater, the device produced enough electricity to power 180 LED arrays, and at 8 inches, enough to power a digital alarm clock.

"These results provide significant advancements toward sustainable power for integrated sensors and wireless communication systems," said Min Gyu Kang, an assistant research professor at Penn State.

The scientists used a composite structure, layering two different materials together. One of these materials is magnetostrictive, which converts a magnetic field into stress, and the other is piezoelectric, which converts stress, or vibrations, into an electric field. The combination allows the device to turn a magnetic field into an electric current.

The device has a beam-like structure with one end clamped and the other free to vibrate in response to an applied magnetic field. A magnet mounted at the free end of the beam amplifies the movement and contributes toward a higher production of electricity, the scientists said.

"The beauty of this research is it uses known materials but designs the architecture for basically maximizing the conversion of the magnetic field into electricity," Priya said. "This allows for achieving high power density under low amplitude magnetic fields." ■

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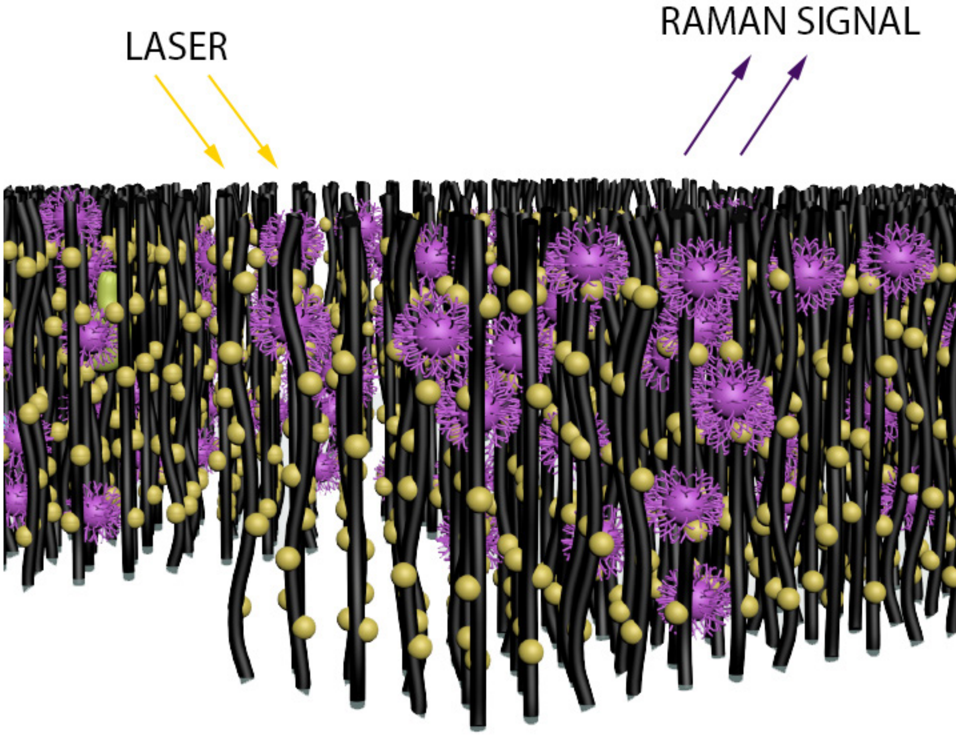
A fast and inexpensive device to Capture and Identify

By Walt Mills

A DEVICE TO QUICKLY capture and identify various strains of virus has been developed, according to researchers at Penn State and New York University.

Currently, virologists estimate that 1.67 million unknown viruses are in animals, a number of which can be transmitted to humans. Known viruses, such as H5N1, Zika and Ebola have caused widespread illness and death. The World Health Organization states that early detection can halt virus spread by enabling rapid deployment of countermeasures.

"We have developed a fast and inexpensive handheld device that can capture viruses based on size," said Mauricio Terrones, distinguished professor of physics, chemistry, and materials science and engineering at Penn State. "Our device uses arrays of nanotubes engineered to be comparable in size to a wide range of viruses. We then use Raman spectroscopy to identify the viruses based on their individual vibration."



An array of nanotubes decorated with gold nanoparticles captures virus molecules
Image: Terrones Lab/ Penn State

This device, called a VIRRION, has a wide range of possible uses. For farmers, for example, early detection of a virus in the field can save an entire crop. Early detection of a virus in livestock can save a herd from illness. Humans also will benefit by the detection of viruses in minutes rather than in days with current methods. Because of its size and low cost, such a device would be useful in every doctor's office as well as in remote locations when disease outbreaks occur.

"Most current techniques require large and expensive pieces of equipment," Terrones said. "The VIRRION is a few centimeters across. We add gold nanoparticles to enhance the Raman signal so that we are able to detect the virus molecule in very low concentrations. We then use machine learning techniques to create a library of virus types."

Viruses

According to Professor Elodie Ghedin, a virologist at NYU, "The VIRRION enables the rapid enrichment of virus particles from any type of sample — environmental or clinical — which jump-starts viral characterization. This has applications in virus emergence, virus discovery and in diagnosis. Eventually, we hope to use this device for the capture and sequencing of single virions, giving us a much better handle on the evolution of the virus in real time."

Added lead author Ying-Ting Yeh, an assistant research professor in the Terrones group, "We synthesized a gradient of aligned carbon nanotube forest arrays to capture different viruses according to their size and detect them in-situ using Raman spectroscopy. We designed and assembled a portable platform that enriches virus particles from several milliliters of clinical samples in a couple of minutes."

The work is published in the journal Proceeding of the National Academy of Science (PNAS). Titled “A rapid and label-free platform for virus capture and identification from clinical samples,” the paper’s coauthors are Ying-Ting Yeh, an assistant research professor in Terrones’ group, Kristen Gulino, Tsui-Wen Chou and Bin Zhou, all of NYU, and YuHe Zhang, Aswathy Sabestien, Zhong Lin, Istvan Albert, Huaguang Lu and Venkataranman Swaminathan, all of Penn State.

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Penn State Receives Five-year $3.7 Million Grant to Study Virus Evolution

An interdisciplinary team led by Penn State has received a five-year $3.7 million dollar grant from the National Science Foundation’s new program on convergence research. The grant is in two phases, depending on successful completion of phase one milestones.

Convergence brings together disciplines that have not worked together before to solve problems of high complexity with societal impact. Penn State is one of 11 universites to receive a convergence grant.

“Convergence is not the same as multidisciplinary research,” according to principal researcher Mauricio Terrones, Verne M. Willaman Professor of Physics. “Convergence is the deep dive into establishing communication pathways and new protocols that results in the emergence of a new field. In our project we have a virologist, an engineer, a physicist/chemist, a spectroscopist, and a data scientist.”

The team is trying to work on a very complicated problem, which is the evolution of viruses. They plan to do this by effectively capturing the viruses and by using a laser to record the vibrations of atoms and molecules that make up the surface of the viruses. As the virus mutates, their surface changes and the frequency of the vibrations change, thus leading to the evolution of new strains of contagious viruses.

Each year, one in five people around the globe are infected with epidemic strains of influenza, leading to half a million deaths. Early detection of new strains that can cause a pandemic is crucial, but current methodology requires extensive laboratory equipment housed in specialized centers with methods that are slow and costly. The Penn State/NYU team proposes to develop a handheld device that will quickly and cheaply detect evolving viruses in the field.

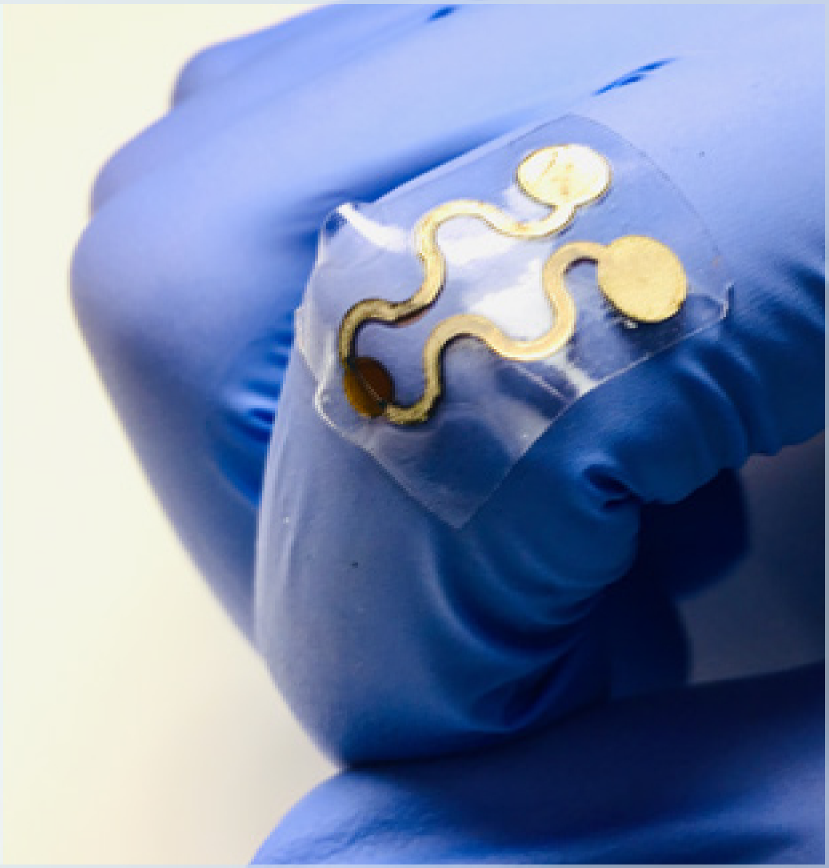
Because the changes in the virus surface are minute, the team will require data science and machine learning to create a database to differentiate between emerging strains. “Our virologist, Elodie Ghedin from NYU, is a leading expert on influenza and virus evolution, “said Terrones. “She will provide us with the viruses. She can track down viruses from the 1800s to now and see how the virus mutates over time.

“Five years from now we hope to create a center for viruses in plants, animals, and humans.”

In addition to Terrones and Ghedin, other members of the team included Sharon Huang, associate professor of information science and technology, Ying-Tin Yeh, assistant research professor of physics, and Shenxi Huang, assistant professor of electrical engineering and biomedical engineering. ■

Wearable for Environmental and

Sensors
Health Monitoring



Wearable gas sensors for environmental and human health.
Image: Cheng Lab/Penn State

By Walt Mills and Matt Swayne

A NEW ADVANCE IN wearable sensors is underway in the laboratory of Huanyu (Larry) Cheng, assistant professor in the Department of Engineering Science and Mechanics, and an associate in materials science and engineering and the Materials Research Institute.

A highly sensitive wearable gas sensor for environmental and human health monitoring may soon become commercially available, according to Cheng and his collaborators at Northeastern University.

The sensor platform is an improvement on existing wearable sensors because it uses a self-heating mechanism that enhances sensitivity and allows for quick recovery and reuse of the platform. Other sensor platforms require an external heater. In addition, other wearable sensors require an expensive and time-consuming lithography process under cleanroom conditions.

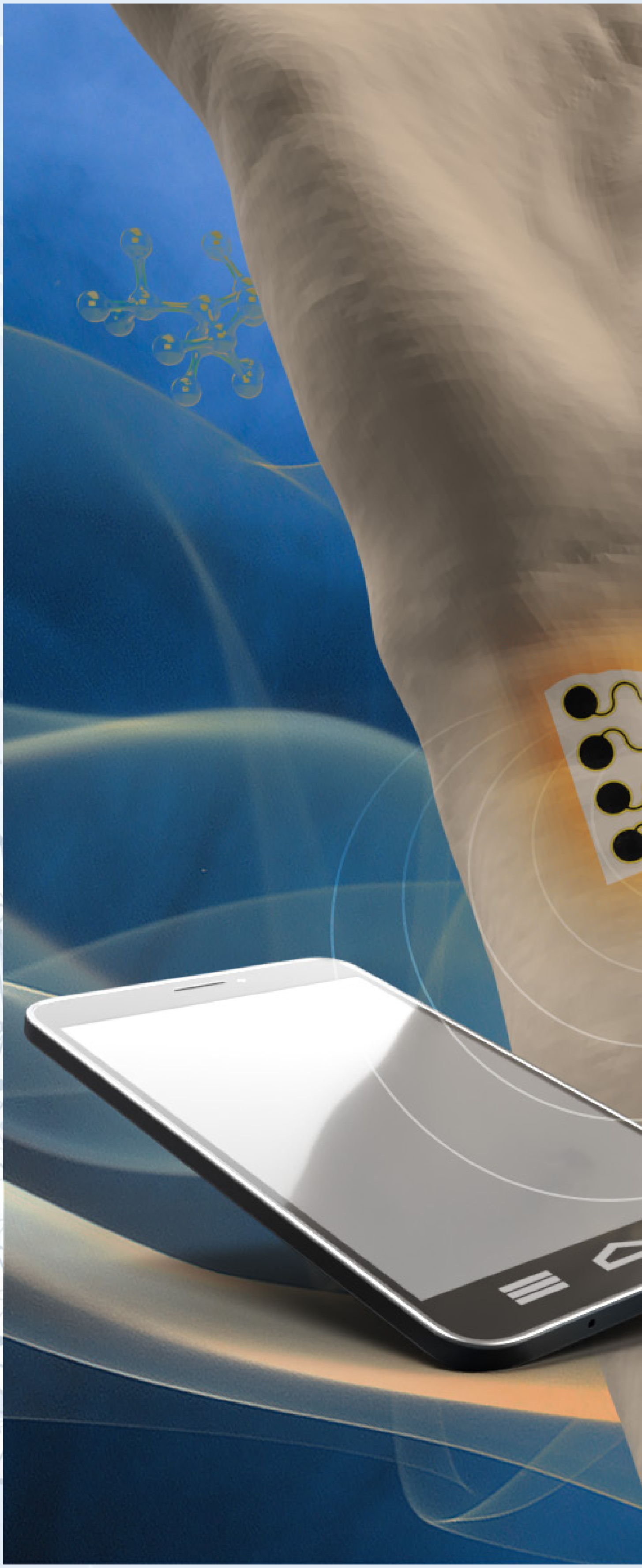
“People like to use nanomaterials for sensing because their large surface to volume ratio makes them highly sensitive,” said Cheng. “The problem is the nanomaterial is not something we can easily hook up to with wires to receive the signal, necessitating the need for something called interdigitated electrodes, which are like the digits on your hand.” ▸ ▸ ▸

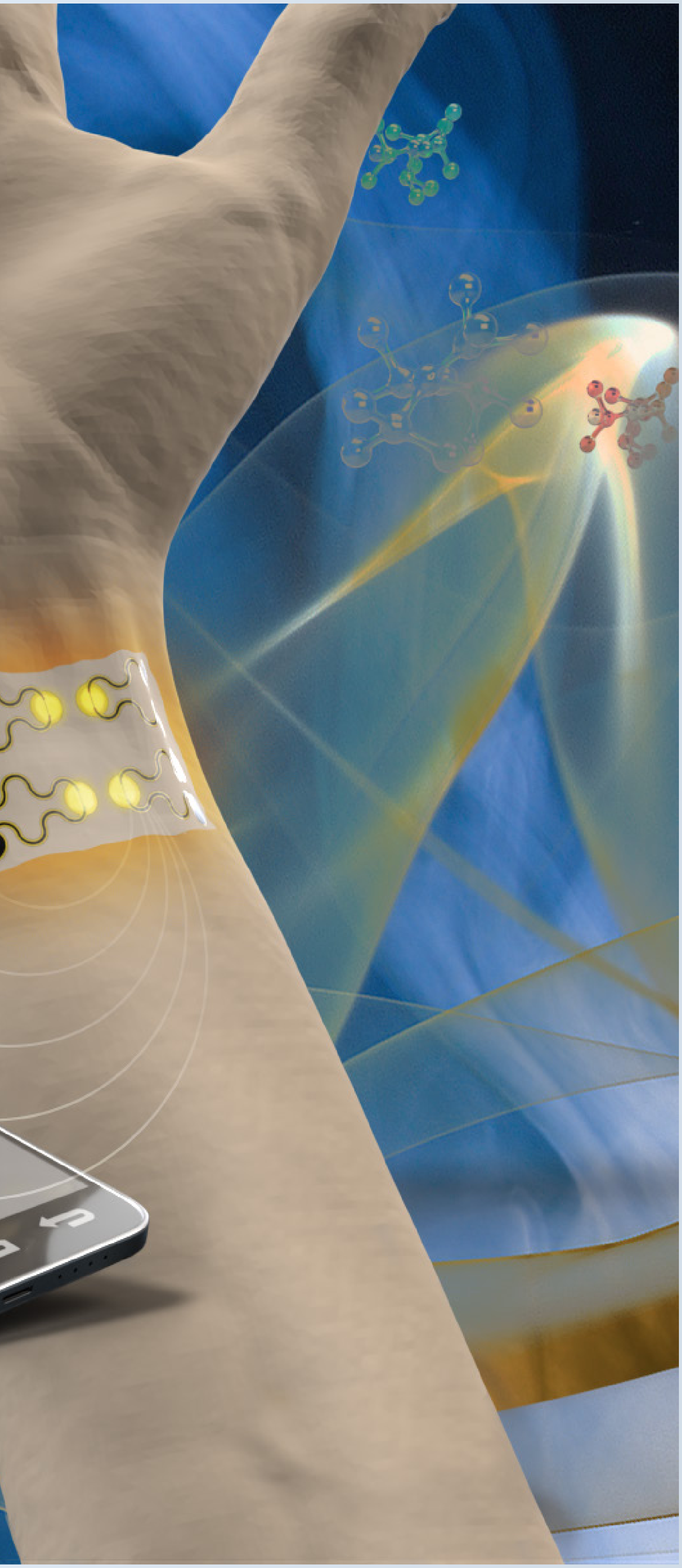
IN THEIR NEW work, Cheng and his team use a laser to pattern a highly porous single line of nanomaterial similar to graphene for sensing gas or biomolecules, and, in the future, for chemical sensing. In the non-sensing portion of the platform, they create a series of serpentine lines that they coat with silver. When they apply an electrical current, the gas sensing region will locally heat up due to its significantly larger electrical resistance, eliminating the need for a heater. The serpentine lines allow the platform to stretch like springs to adjust to the flexing of the body to allow for wearable sensors.

The nanomaterials used in this work are reduced graphene oxide and molybdenum disulfide, or a combination of the two, or a metal oxide composite consisting of a core of zinc oxide and a shell of copper oxide. These materials represent the two classes of widely used gas sensor materials (i.e., low-dimensional and metal oxide nanomaterials). "Using a CO2 laser, often found in machine shops, we can easily make multiple sensors on our platform," Cheng said. "We plan to have tens to a hundred sensors, each selective to a different molecule, like an electronic nose, to decode multiple components in a complex mixture."

The U.S. Defense Threat Reduction Agency (DTRA) is interested in this wearable sensor to detect chemical and biological agents that could damage the nerves or lungs. A medical device company is also working with the team to scale up production for patient health monitoring, including gaseous biomarker detection from the human body and environmental detection of pollutants that can affect the lungs.

Ning Yi, a Ph.D. student in Chen's lab and co-lead author of a new paper posted online in the Journal of Materials Chemistry A, said, "In this paper, we showed that we could detect nitrogen





A wearable gas sensor can monitor environmental and medical conditions. IMAGE: Jennifer M. McCann/Penn State

dioxide, which is produced by vehicle emissions. We can also detect sulfur dioxide, which, together with nitrogen dioxide, causes acid rain. All these gases can be an issue in industrial safety."

Their next step is to create high-density arrays and try some ideas to improve the signal and make the sensors more selective. This may involve using machine learning to identify the distinct signals of individual molecules on the platform.

A CALL FOR COMPUTATIONAL POWER

The Penn State engineers are also using computational power and data sciences to develop their stretchable, flexible, and wearable devices.

The team believes that computational power is a key to technology for smart bandages, health tattoos, and artificial organs.

Monitoring a patient's health status is often an invasive and uncomfortable process at best, and a dangerous process at worst. Cheng's team wants to change that and make biosensors that could make health monitoring less bulky, more accurate, and much safer.

The key is to make sensors that are so stretchable and flexible that they can easily integrate with the human body's complex, changing contours.

If biosensors that are both energy efficient and stretchable can be achieved at scale, the researchers suggest that engineers can pursue — and, in some cases, are already pursuing — a range of options for sensors that can be worn on the body, or even placed inside the body. The payoff would be smarter, more effective, and more personalized medical treatment and

▸ ▸ ▸

improved health decision-making — without a lot of bulky, buzzing, and beeping pieces of monitoring equipment.

Some of the ideas that researchers at Penn State and around the world are investigating include stretchable textiles that can incorporate biosensors. Paper-based sensors could also potentially be used to create smart bandages that can monitor the status of wounds. Temporary tattoos could even incorporate biosensors for health monitoring. For example, a biosensor-enabled tattoo could provide diabetes patients with instant estimates of their glucose levels.

MORE COMPUTATIONAL POWER

An antenna that can transmit data is the key element for these biosensor ideas, said Cheng. But it can't be an ordinary antenna. An antenna in the human body would require it to not just be durable, withstanding the extreme conditions of the body, but it also needs to be stretchable, so it can fit the contours of various organs and tissues in the body.

Creating those stretchable antennas require complex computations to model all of the different variations the design of the sensors can take in order to determine the best designs. And that means the design process alone requires lots of computational power.

"We explore a lot of different patterns and designs when we are investigating these ideas," Cheng said. "This can become a problem because it's difficult to find the right design with all of the different parameters. That's why we need more computational power. This additional computational power can help us play with the different parameters and find out the effect of each one. Then we can figure out how to optimize them."

The team also wants to see how mechanical and electromagnetic properties are changed as the device changes shape.

> "We need to leverage the computational resources to design this efficient antenna that can be stretchable, but, more importantly, with this stretchable antenna, we can do a lot of things because if we want to get the place where these sensors are transmitting data, this antenna is the key element that you can't get around," he said.

POWERING SENSORS

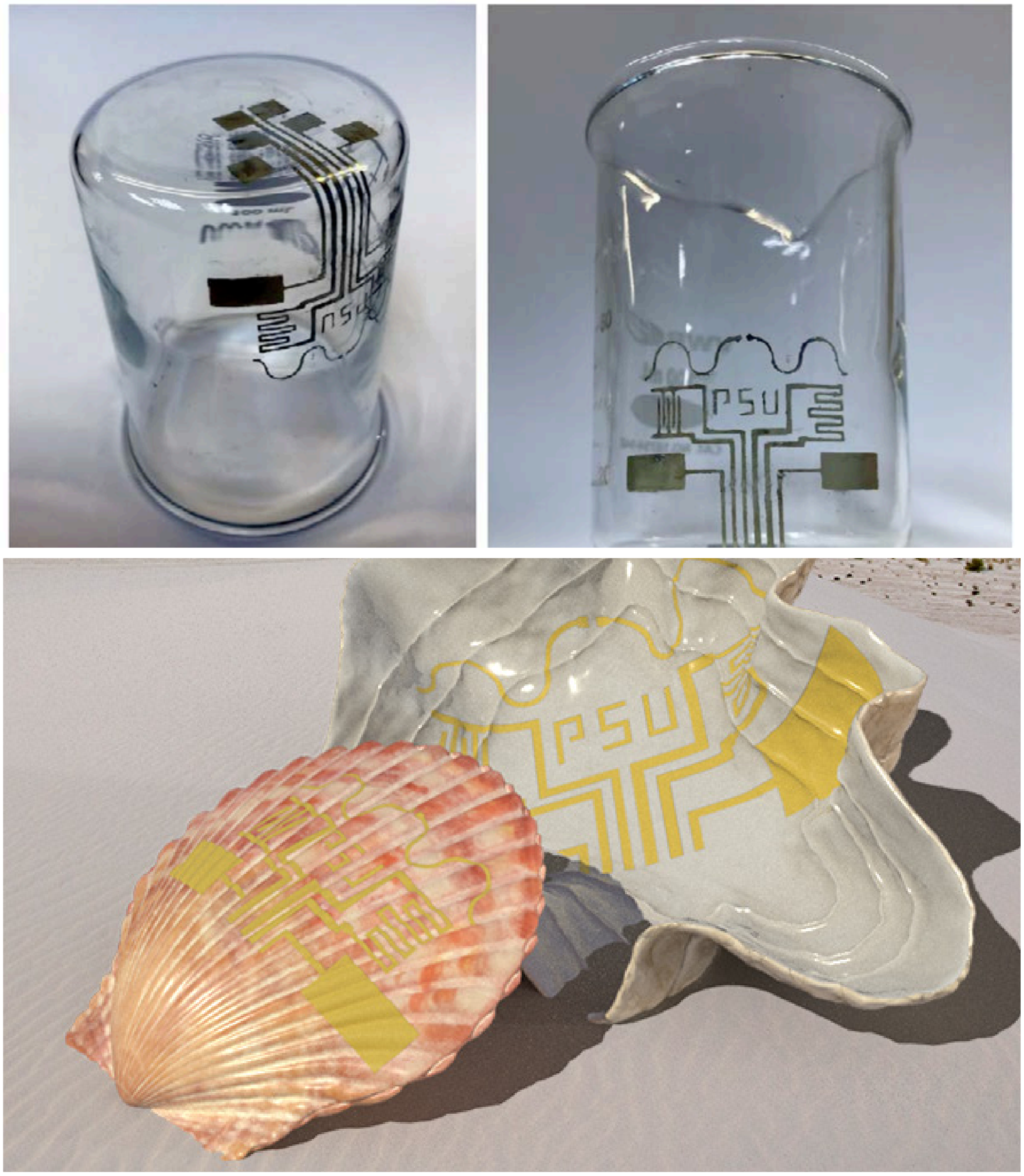
The next step is finding ways to power the sensors. Current batteries may be too big and rigid to power a sensor that can operate on or in a human body, said Cheng. His lab is now investigating new ways to power biosensors.

While people might think that we have to plug the sensor into an energy source, Cheng realized that we are actually surrounded by natural and human-made sources of energy, called ambient energy.

"Our work now is also focused on harvesting the ambient energy, which can include Wi-Fi, either 3-G, 4-G, or 5-G, or even microwave sources," said Cheng. "With ambient energy, it's always on, no matter whether you're using it or not, it's always there. Even when you go to sleep, it's there. If we don't harvest that energy, it just gets wasted."

The researchers' design calls for a stretchable rectifying antenna, or rectenna, that can convert electromagnetic energy into direct current. Cheng said that might be able to power the device or charge up a battery outside the body as a power source.

Because the device has access to a broader range of available energy, the initial results show that the researchers' design is about 10 to 100 times better than existing models.



A) and B) Images of a flexible, wearable sensor demonstrated on the curve of beakers. IMAGES: H. Cheng Group C) Sensors show their flexibility to curve on varying textures IMAGE: Jennifer M. McCann/Penn State

"If we only harvested the energy at a single frequency, it will, of course, minimize the amount of energy we can use, but by harvesting the energy over a wide band around the device, it will compound the efficiency," said Cheng.

FUTURE DIRECTIONS: POP-UPS AND ORGANOIDS

In the future, Cheng expects his team will continue to work on biosensors, but they are also investigating the potential integration of biosensors with organoids, which are human-cultured, organ-specific tissues designed to mimic the function of natural organs. Cheng said that organoids could be used for medical testing.

"Animal testing is used quite often in medical research, but testing in organoids would give us a much more ethical option," he said.

Cheng added that designing materials that can assume three-dimensional shapes is yet another area of future research exploration for the group. These "pop-up" designs could be inserted to a target area as a flat surface, but then morph into a 3D shape. These could be used in future applications in the health and medical fields, among others. ■

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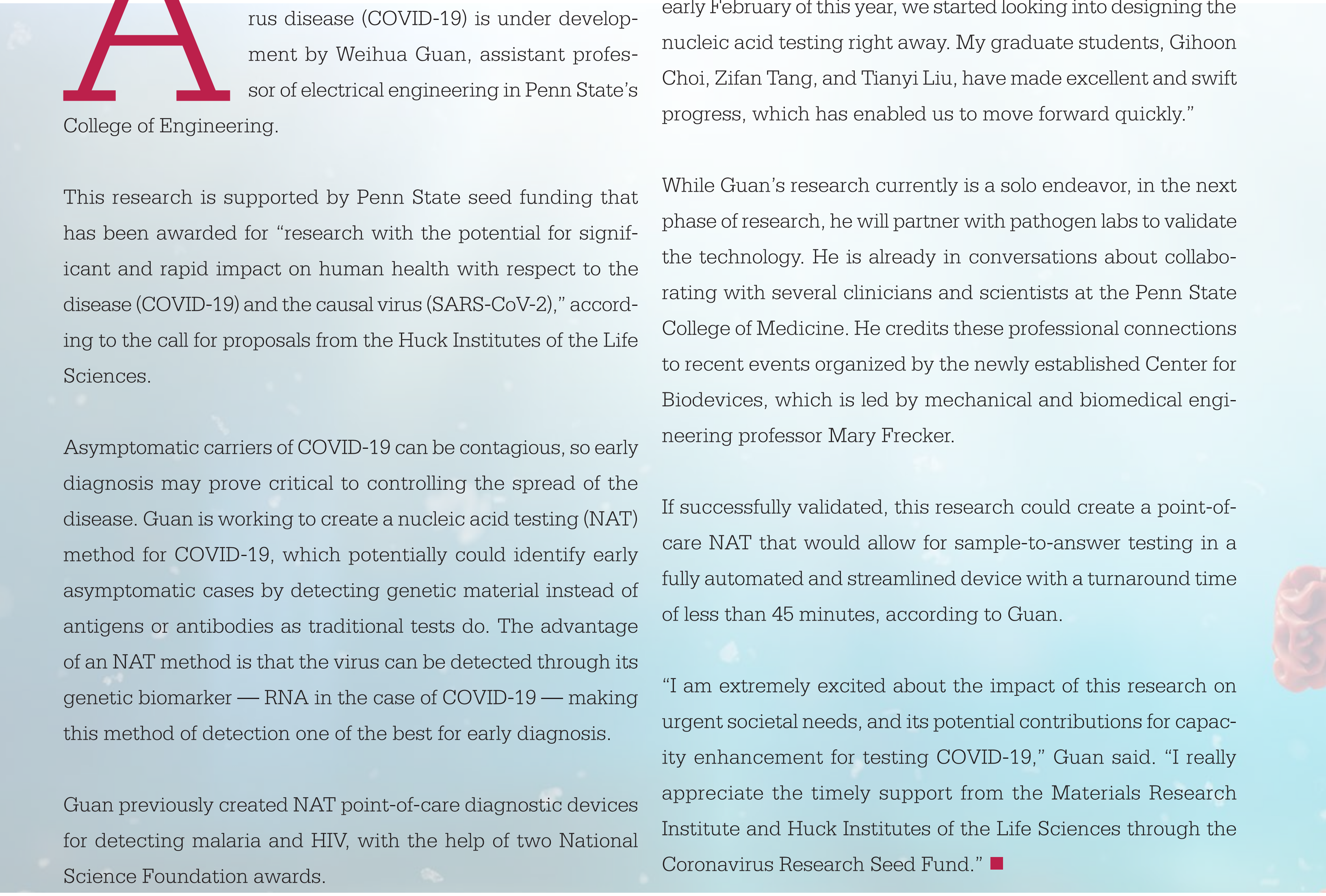
Penn State Engineer May Be Able to Test

By Sarah Small



A POINT-OF-CARE TESTING DEVICE that may help diagnose the novel coronavirus disease (COVID-19) is under development by Weihua Guan, assistant professor of electrical engineering in Penn State's College of Engineering.

This research is supported by Penn State seed funding that has been awarded for "research with the potential for significant and rapid impact on human health with respect to the disease (COVID-19) and the causal virus (SARS-CoV-2)," according to the call for proposals from the Huck Institutes of the Life Sciences.

Asymptomatic carriers of COVID-19 can be contagious, so early diagnosis may prove critical to controlling the spread of the disease. Guan is working to create a nucleic acid testing (NAT) method for COVID-19, which potentially could identify early asymptomatic cases by detecting genetic material instead of antigens or antibodies as traditional tests do. The advantage of an NAT method is that the virus can be detected through its genetic biomarker — RNA in the case of COVID-19 — making this method of detection one of the best for early diagnosis.

Guan previously created NAT point-of-care diagnostic devices for detecting malaria and HIV, with the help of two National Science Foundation awards.

"The technology is essentially a platform technology that can be extended toward an array of infectious diseases," Guan said. "When we learned the genomic sequence of the SARS-CoV-2 in early February of this year, we started looking into designing the nucleic acid testing right away. My graduate students, Gihoon Choi, Zifan Tang, and Tianyi Liu, have made excellent and swift progress, which has enabled us to move forward quickly."

While Guan's research currently is a solo endeavor, in the next phase of research, he will partner with pathogen labs to validate the technology. He is already in conversations about collaborating with several clinicians and scientists at the Penn State College of Medicine. He credits these professional connections to recent events organized by the newly established Center for Biodevices, which is led by mechanical and biomedical engineering professor Mary Frecker.

If successfully validated, this research could create a point-of-care NAT that would allow for sample-to-answer testing in a fully automated and streamlined device with a turnaround time of less than 45 minutes, according to Guan.

"I am extremely excited about the impact of this research on urgent societal needs, and its potential contributions for capacity enhancement for testing COVID-19," Guan said. "I really appreciate the timely support from the Materials Research Institute and Huck Institutes of the Life Sciences through the Coronavirus Research Seed Fund." ■

Developing Device That for COVID-19

An illustration of a sample-to-answer nucleic acid testing device.
IMAGE: Gihoon Choi

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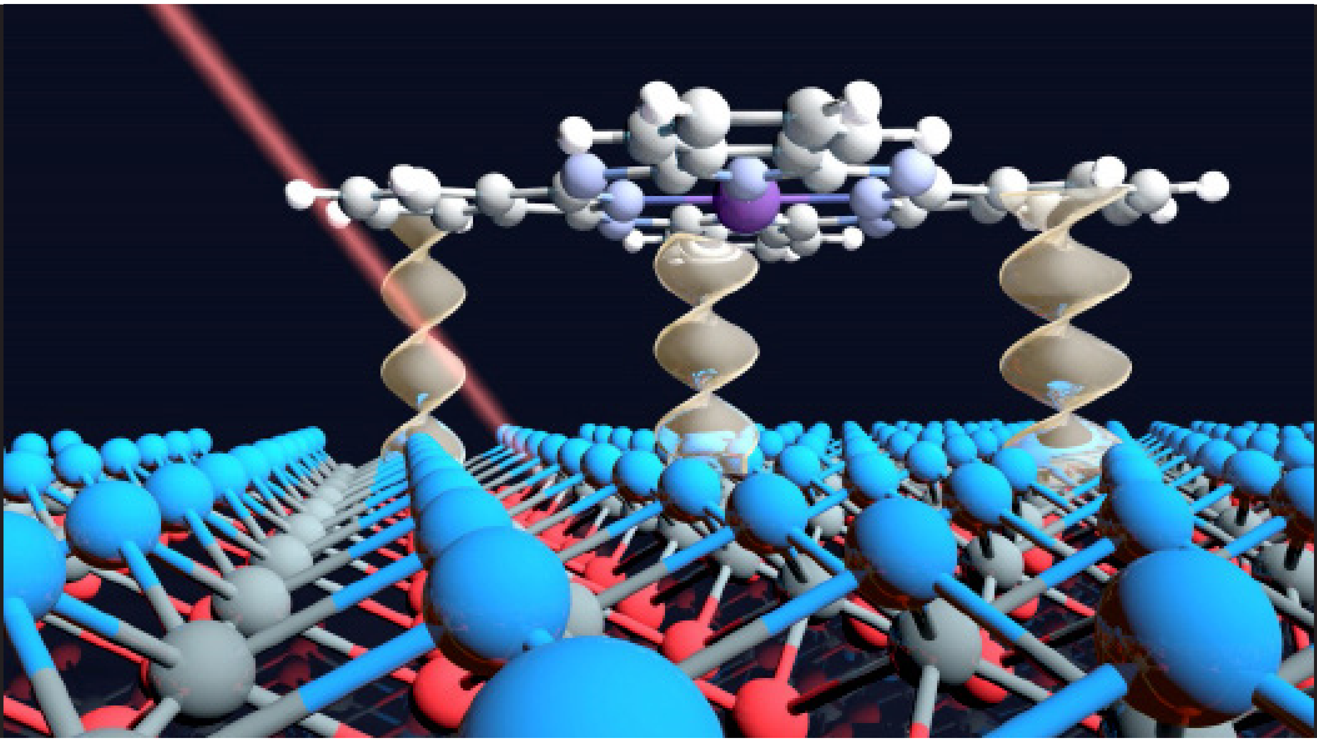
FOCUS ON SHENGXI HUANG:

Advancing 2D Mat



By Walt Mills

SHENGXI HUANG IS an assistant professor of electrical engineering. As a graduate student at MIT she worked in the group of Mildred Dresselhaus, a world-renowned carbon scientist. Her Ph.D thesis won the Jin Au Kong award for best thesis at MIT.

In Huang's SCOPE lab, she uses optical spectroscopy for studying low-dimensional materials and other nanostructures and applying nanomaterials in optoelectronics and sensing.

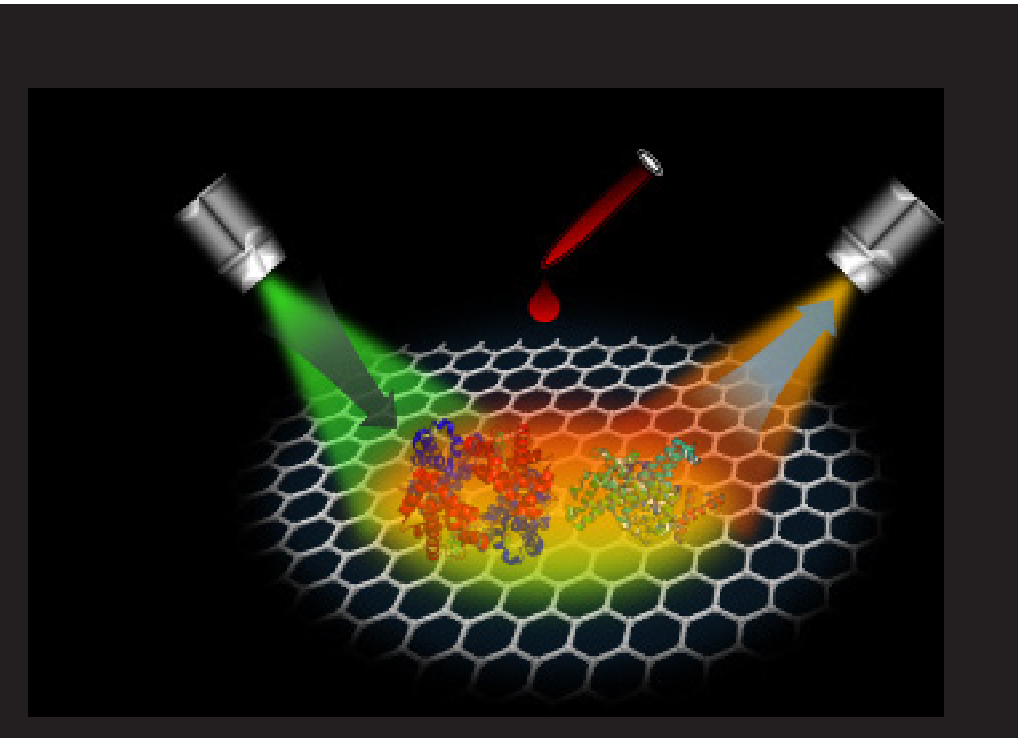
"We are working on a kind of optical spectroscopy that measures the vibrational mode of molecules," she said in a recent Zoom chat from her home in State College. "You can see a lot of peaks in the various molecules. These spectrums are fingerprints for the molecules."

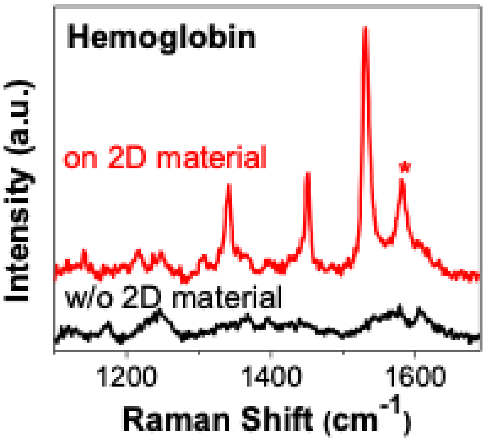
What her group is doing that is special is using 2-dimensional materials to enhance the sensitivity of the Raman signal. This can increase the detection limit so that they can detect lower concentrations of the molecule. They want to determine the mechanisms behind the enhancement and which 2D materials are best to use.

Their goal is to use the technique to study various disease proteins, such as the ones responsible for Alzheimer's. "When you are testing a real biological system, there are many types of molecules," she said. "Some might be very similar to each other, so we are seeing if we can make substrates specific to only a certain molecule."

In another project, she is working with Prof. Mauricio Terrones, in physics, and Sharon Huang in the College of Information

erials for Sensing





Opposite:
Molecule on 2D material surface, under Raman measurement.

Left:
Biomolecules (blood proteins) on 2D graphene surface, under Raman measurement.

Above:
Raman signal enhancement of hemoglobin when placed on 2D material.

Science and Technology to try to detect viruses, based on a large National Science Foundation grant. As the virus changes year-to-year, they want to try to detect small changes so that a flu vaccine can be developed to target that exact strain.

“IF WE CAN trace the evolution of these viruses, our collaborator in IST can use machine learning techniques to predict the next evolution. Very recently, because of the Covid-19 pandemic, we are trying to see if this platform can be used to predict coronaviruses. We are still trying to fabricate some substrates based on that.”

One of the benefits of their technique is that they can get results very quickly, in some cases in only a second, in others a couple of minutes. Currently they are using a tabletop Raman spectrometer, but there are some technologies available that can use a handheld Raman spectrometer, like a cell phone. But they are not as sensitive as the tabletop model. For that it will be necessary to enhance the signal effectively, she said.

“We are also working with Josh Robinson who makes a 2D metal that we find is very effective at enhancing the Raman signal,” she said.

The two-dimensional materials effort at Penn State is among the most advanced in the country. Whether for sensors, electronics, or quantum phenomena, 2D materials is a rapidly advancing new field in science and engineering. ■

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Penn State engineer aims to TACKLE COVID-19 from two angles

By Jamie Oberdick

TO COMBAT COVID-19 in both the treatment and testing arenas, Yong Wang, Penn State professor of biomedical engineering, has received two grants from the Huck Institutes of the Life Sciences COVID-19 multi-institute seed grant fund.

Wang will use the testing grant to look at the creation of a COVID-19 analysis potentially capable of producing results that could be easily read in minutes. Wang will serve as the primary investigator for the project.

"Our goal is to use a very high, strong signal to definitively display results to the person administering the test, even if they're not specifically trained," Wang said. "With this method, at a drive-up testing site, the testers could have the person pull over in their car and wait a few minutes to find out if they are COVID-19 positive."

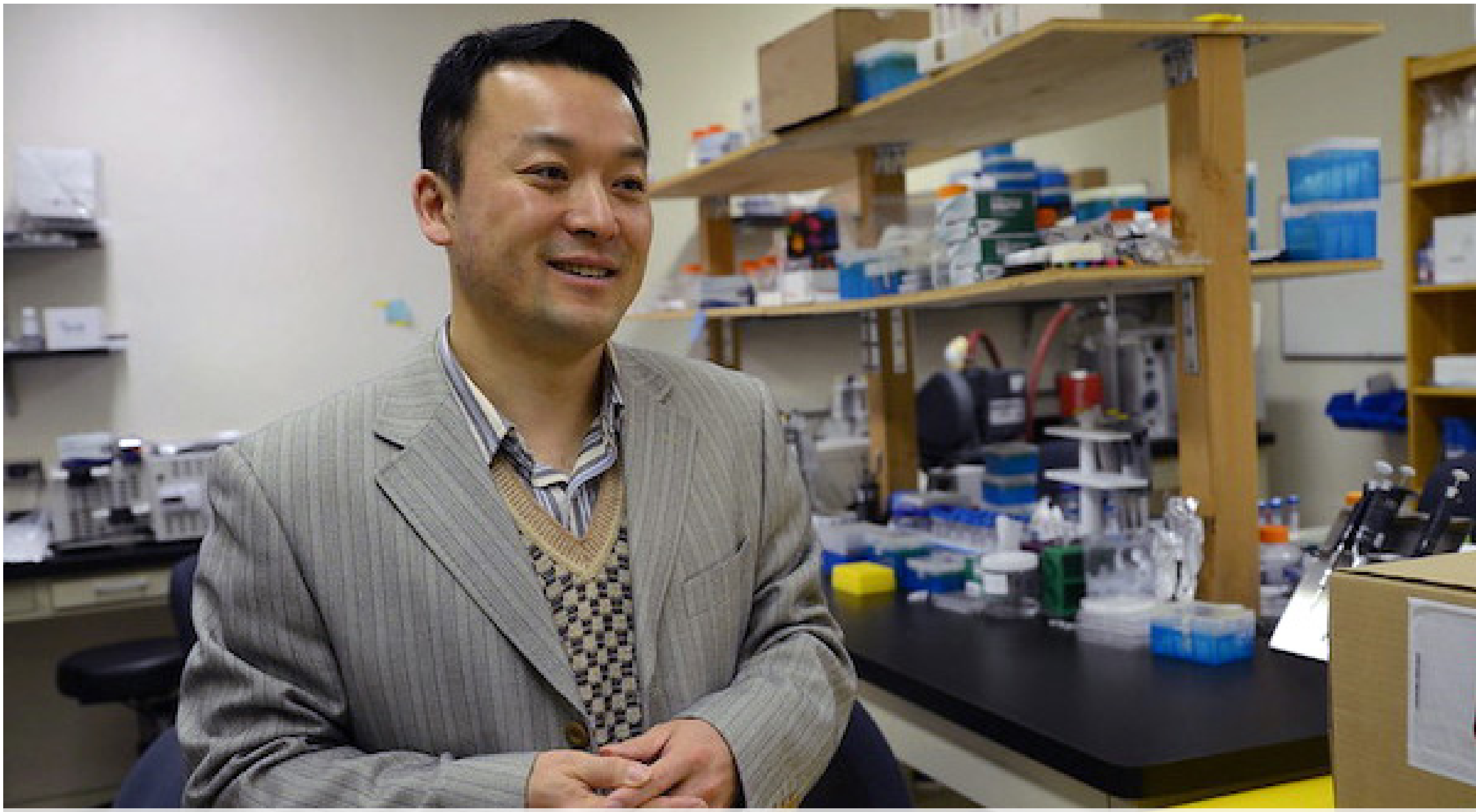
Wang's method involves detection of COVID-19 RNA — the virus' genetic material — with a portable handheld fluorometer, which uses magnetic beads of iron oxide to extract the RNA.

"The current tests take a long time, require a complicated process, and may not be accurate," Wang said. "When there are millions of people who need to be diagnosed, you want it to be ready for a very fast examination that gives a clear signal quickly."

The most common current method of COVID-19 testing, polymerase chain reaction (PCR), adds enzymes to jump-start a chemical process to enable detection of RNA in nasal swab samples. Sometimes during this process the enzymes can lose their bioactivity and cause false negative results. Another issue with the tests is that a highly trained individual is needed to read the data to determine the results.

With Wang's proposed test, special equipment would not be required, something Wang said would give the test a unique portability.

"Since we plan to do tests at room temperature with simple technology, you wouldn't have to get test results in a laboratory. You can do it in the field," Wang said. "You can quickly test people on a cruise ship, you can do tests in a parking lot and just about anywhere, so there are a lot of advantages to this method."



Professor Yang Wang, professor of biomedical engineering in his lab at Penn State Universtiy Park Campus. Photo: Walt Mills / Penn State

The other seed grant Wang received is for a potential treatment method focused on suppressing cytokine storms induced by COVID-19 in the lungs of patients. A cytokine storm, or cytokine release syndrome, is a severe immune reaction where the immune system releases too many cytokines into the blood too quickly. Cytokines are messenger proteins, requesting more or less immune activity depending on the situation. Releasing too many into the blood causes the immune system to overreact and attack healthy tissues, leading to organ damage and even death.

Wang is working with a co-primary investigator, Troy Sutton, Penn State assistant professor of veterinary and biomedical sciences, on this grant. They aim to suppress cytokine storms via living cells and a new cell delivery mechanism.

"Once COVID-19 patients enter intensive care units, pretty much you can only do one thing to keep them alive, and that's provide oxygen via ventilators," Wang said. "For full recovery, we have to rely on the patient's immune system. But the immune system is in chaos due to COVID-19, so we have to rely on something that will allow the immune system to go back to normal."

In the next three months, Wang and Sutton will collect preliminary data to demonstrate that their new system is able to calm the immune system in cell samples. After that, they will conduct animal studies to see if they can reduce immune activity and even reduce the amount of viral activity. Sutton's expertise is in working in high containment with highly infectious respiratory pathogens, making him an ideal research partner for Wang.

"We hope to have the first step done within six months," Wang said.

For Wang, helping humanity, such as fighting a pandemic, is why he became a biomedical engineer.

"Now is the time for us to help our fellow humans, to help our nation, and to help our world," Wang said. ■

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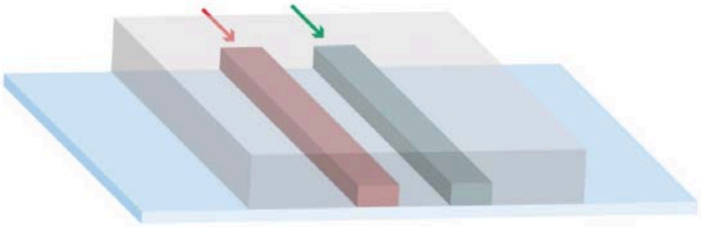

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Cremer group developing detect corona

By Maria Landschoot

THE CREMER GROUP — led by Penn State professor of chemistry Paul Cremer — has a long history of biosensor research. Over a decade ago, the group developed a platform that could perform real-time, continuous detection. The lab originally envisioned their research as a counter-terrorism tool; for example, the lab's sensors might be used to detect biothreats in the New York City subway system. However, when the COVID-19 crisis emerged, the group immediately realized that their research could help.

"With the advent of the coronavirus pandemic, we quickly turned our attention to building a platform for airborne monitoring of SARS-CoV-2," Cremer explains. "Viral detection is new for us, but the principles of making selective interfacial measurements are the same."

Cremer's lab has developed sensors that allow them to look at changes in interfacial potential to detect the binding of ions, small molecules, peptides, and proteins at interfaces. Receptor species are immobilized on a surface, and the fluids to be measured — for example, an aqueous solution — flows over it, allowing scientists to identify analyte agents in the fluid.

The Cremer group has now received a grant from the Penn State Huck Institutes of the Life Sciences Coronavirus Research Seed Fund to develop an inexpensive sensor that can continuously monitor for SARS-CoV-2, the virus that causes COVID-19.

Cremer noted that this technology has the potential to save lives. "A management meeting of 175 employees at Biogen Inc. took place between Feb. 26 and 27, 2020, in Boston," he explains. "As of March 11, 70 of the attendees had tested positive for coronavirus, which represented the majority of known cases in Massachusetts at that time. Unfortunately, many of those people might have unknowingly taken the virus home with them and infected their families."

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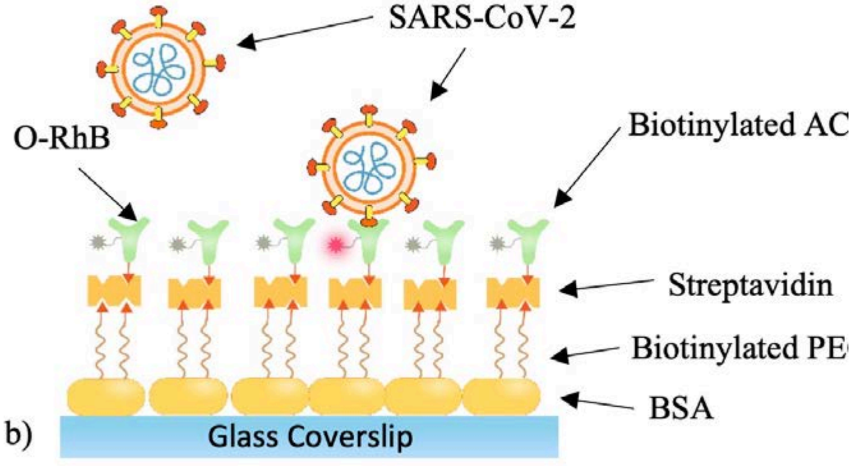


sensors to virus in enclosed spaces

The Cremer lab's sensors could have alerted company executives that SARS-CoV-2 was present in the room, allowing them to protect their employees.

Although most gatherings like the Biogen meeting have been canceled for the foreseeable future, these sensors will be particularly useful once COVID-19 containment measures begin to be phased out and economic and social activities resume. For example, the technology could be used to monitor enclosed spaces like the cabin of an airplane, a crowded conference center room, or an indoor sporting event. These sensors potentially could help governmental bodies and private companies in their efforts to maintain public safety, while also allowing the public to go about their day-to-day lives with confidence.

Cremer hopes that his sensor technology will be helpful in preventing a resurgence of COVID-19 in the future.■

ABOVE IMAGE:
Penn State Professor of Chemistry Paul Cremer is developing a biosensor platform that could be used to perform real-time, continuous detection of SARS-CoV-2. When the virus binds to the sensor, a compound fluoresces, indicating that the virus is present in the room. Credit: Penn State

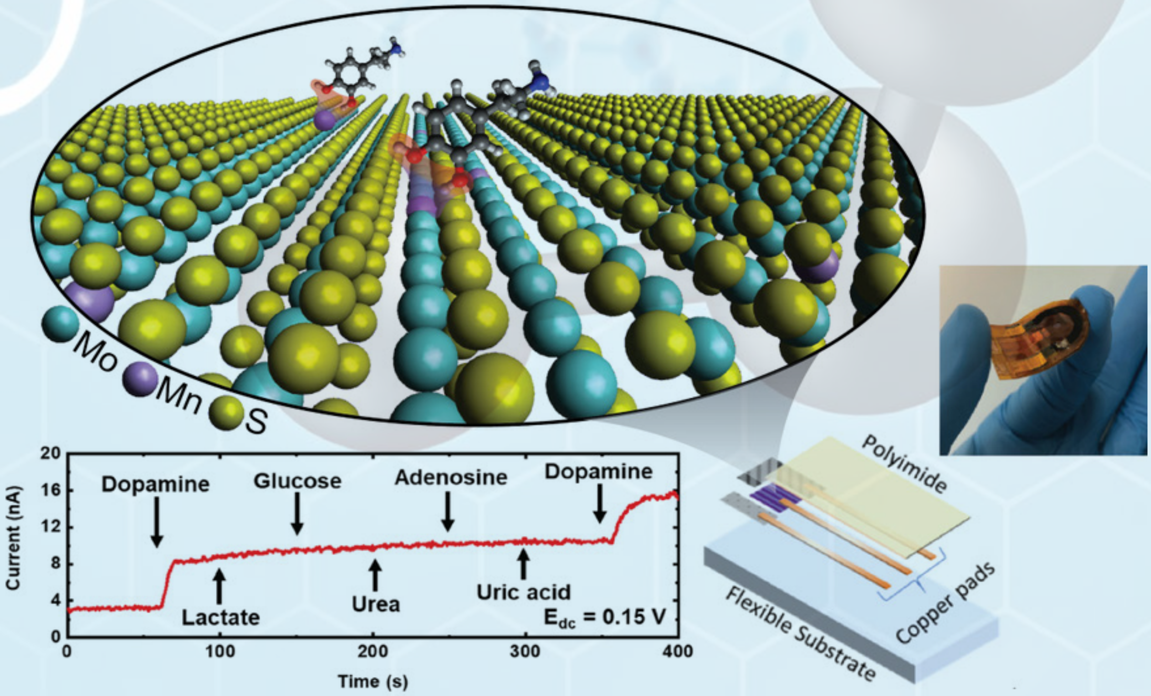
ABOUT THE CORONAVIRUS RESEARCH SEED FUND

On March 3, the Penn State Huck Institutes of the Life Sciences launched a rapid-response internal call-for-proposals across the university to address the emerging outbreak, with support from the Materials Research Institute, Social Sciences Institute, Institutes for Energy and the Environment, and the Institute for Computational and Data Science.

Over the course of five weeks, units across Penn State stepped up to assist. To date, more than 120 faculty members in 45 research teams from across eight colleges at Penn State have been granted $2.25 million in seed-funding to initiate their vitally important work.

The projects span six core areas: Diagnostics and Detection, Therapeutics and Vaccines, Transmission-blocking Interventions, Social Sciences, Cohort Studies, and Predictive Modeling.

Highly Sensitive Dopamine Detector Uses 2D Materials



Schematic of a highly selective dopamine detector using two-dimensional material. IMAGE: Derrick Butler / Penn State

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By Walt Mills

A SUPERSENSITIVE DOPAMINE DETECTOR can help in the early diagnosis of several disorders that result in too much or too little dopamine, according to a group led by Penn State and including Rensselaer Polytechnic Institute and universities in China and Japan.

Dopamine is an important neurotransmitter that can be used to diagnose disorders such as Parkinson's disease, Alzheimer's disease, and schizophrenia.

"If you can develop a very sensitive, yet simple-to-use and portable, detector that can identify a wide range of dopamine concentration, for instance in sweat, that could help in non-invasive monitoring of an individual's health," said Aida Ebrahimi, assistant professor of electrical engineering, Penn State.

Their work shows that by adding a small amount of manganese to a two-dimensional layered material called molybdenum disulfide, they can improve the sensitivity by many orders of magnitude compared to other reported results, while also achieving high specificity. Importantly, their detector is low-cost and flexible, and can detect dopamine in background media including buffer, serum, and sweat, and in real-time.

"Regarding our method, electrochemical deposition is a new way of depositing these chemicals that is very simple and scalable," said Mauricio Terrones, Verne M. Willaman Professor of Physics, Materials Science, and Chemistry. "The Air Force is interested in these neurotransmitters that are markers of stress. I envision this as a wearable sensor."

Humberto Terrones and his group, at RPI, performed the computational investigation that allowed them to explain how addition of manganese results in an improved response to dopamine. The experimental work was performed within the Center for Atomically Thin Multifunctional Coatings (ATOMIC) at Penn State.

> "Combining the experimental results with computational studies proved to be very insightful, and I think we all learned much more throughout this project because of that," said Derrick Butler, a doctoral student at Penn State. "Developing these materials and applying them in a way that could improve the health and well-being of others makes the work especially enjoyable and rewarding."

Doctoral candidate Yu Lei, added, "One challenge is to develop a scalable method to bridge fundamental studies and practical applications. Our method is based on electrodeposition, which has been widely used in industry, thus providing a scalable route to functionalize molybdenum disulfide (MoS2) in a scalable way. Also, I believe this multidisciplinary team is the key to find the right way to functionalize MoS2 for ultrasensitive dopamine detection."

In further work, the group hopes to find other material combinations to detect a variety of other biomarkers with the specificity of their current sensor. Creating such a "toolkit" combining experimental investigations with computational methods will lead to new materials with multifunctional capabilities. This might be useful beyond human health, for example, for detecting noxious gases, water contamination, or biodefense agents.

"In future, we can envision a combined sensor/actuator that can detect the dopamine and provide therapy at the same time. The sensors can be integrated with miniaturized chips for integration of sensing, actuating, control, and data processing," Ebrahimi said. ■

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PennState

In the Next Issue:

Meet the New Guard

Spotlights on New Materials Faculty

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