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Materials Research
Institute

FOCUS

on MATERIALS

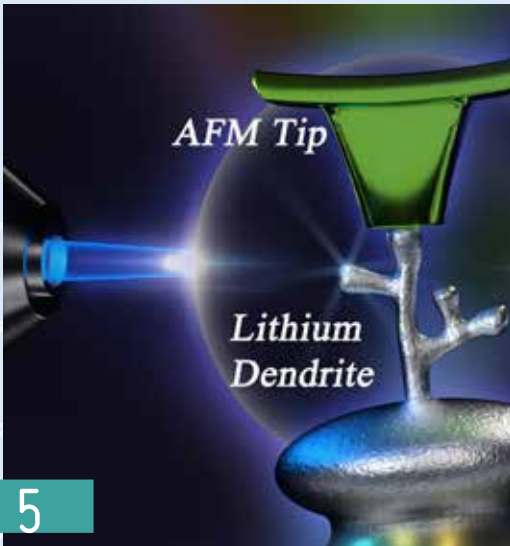
MATERIALS RESEARCH INSTITUTE BULLETIN

SPRING 2020



5G & Beyond

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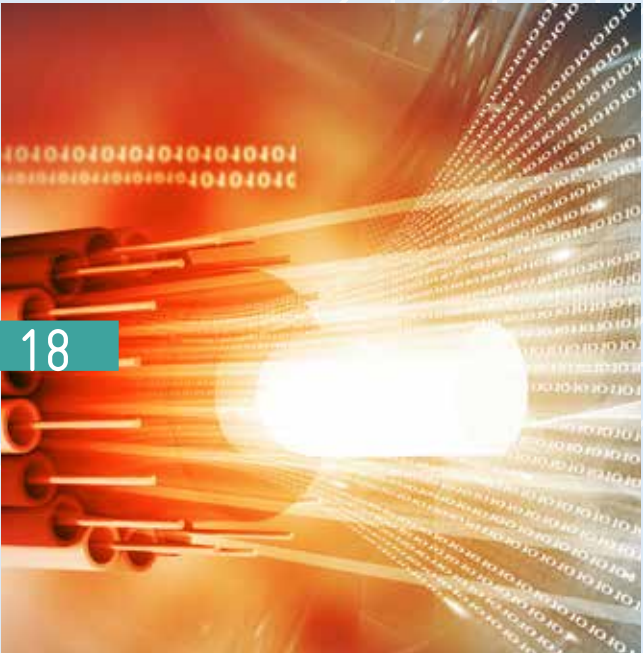
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From the Director

In the spring of 2020 our lives changed, and the interconnection of society, business, education, and conferences has been dramatically accelerated into a new way of doing things. The experience of this will not be completely reversible, and these modes of interactions will become more the rule in the future. Telenetworking will drive the need for extending the bandwidth for communications and therefore the need for 5G and beyond.

This Focus on Materials was designed to coincide with the immediate and imminent deployment of 5G over 2020 and 2021. This may be limited, in the near term, by the worldwide disruptions in the supply chain and production. This is a short-term issue, and this vision of greater interconnectivity with much faster download speeds will enable new opportunities. So, the worldwide quarantines, social distancing, remote working and education could be a catalyst for 5G and beyond.



China, as they worked to suppress the spread of COVID-19, used their 5G networks to aid health monitoring. An application of 5G that was already being discussed was in the form of telemedicine. After this breakout, and the dangers that the medical profession were and are being exposed to, it will mean that hospitals and medical centers will protect themselves with higher levels of technology.

Whatever the long-term future applications, a broader, more interconnected way of working will be introduced. The social acceptance of all these technologies is now going to be accelerated, so 5G companies and the electronic manufacturers that support them will be very active in research, development, and production to address many of the technical

challenges that are there for 5G and beyond.

The supply chain challenges that companies face have been exposed, and the global network of suppliers may be under pressures to re-shore, but this will take time to adjust, and it will also take time for the work force to be developed to enable these changes. Universities and their research and education in these critical areas will play an important role.

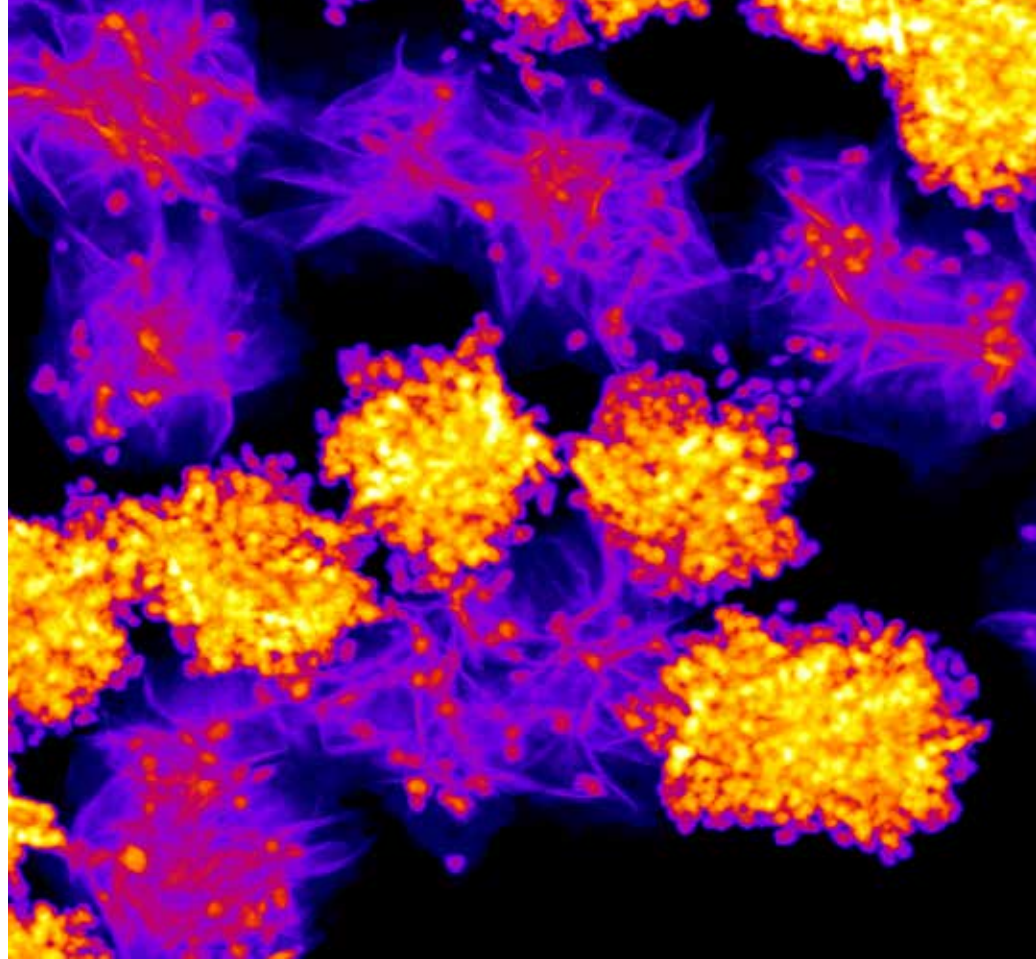
Keep safe and be prepared for new opportunities.

Sincerely,

Director, Materials Research Institute

research SNAPSHOTS

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



*Electron microscope image showing preferential deposition of gold nanoparticles onto transition metal ditellurides relative to the disulfide counterparts
Credit: Yifan Sun / Penn State*

When Bonding Noble Metals to 2D Materials, Interfaces Matter

RESEARCHERS AT PENN State and Purdue University have developed new materials for improved single-atom catalysis and future electronics.

The materials, based on two-dimensional transition metal dichalcogenides (TMDs) that include disulfides, diselenides and tellurides, have a variety of interesting properties that scientists would like to exploit, especially for next-generation electronics and catalysis.

The team deposited the noble metals gold and silver on the two-dimensional TMD substrates and studied how the metals formed and grew on the TMD surfaces. In every case but one, the metals formed zero-dimensional nanoparticles, as theory predicted. But in the case of silver deposited on ditellurides, the silver formed a single atom layer coating the entire substrate.

“We tried the experiments again and again, but did not see any evidence of silver nanoparticle formation on the transition metal ditellurides, yet we knew the silver was there,” said Yifan Sun, former Penn State doctoral student and lead author on a paper published in the journal Nature Chemistry.

The team found that the interfaces between the TMDs and the noble metals were important in determining the growth and final structure of the metals.

“THAT WAS REALLY interesting to us and provides new insights into how to probe the interfaces between 2D and 3D nanostructures,” Sun added.

The team believes this knowledge will be useful in an important field of chemistry called single-atom catalysis. The problem that single-atom catalysis currently faces is that as the density of the catalytic atoms increases they tend to form aggregates that cluster into nanoparticles, which lowers the catalytic activity. As more than 85 percent of chemicals are produced by catalysis, a single-atom process that didn’t aggregate could have huge benefits.

“The process allows us to think in the future of how you could design single-atom catalysts that had minimal amounts of these expensive noble metals and have enhanced properties because of that,” said Ray Schaak, Dupont Professor of Chemistry, and corresponding author on the Nature Chemistry paper.

Another place where people would like to use this type of material is in electronics. They often need to make a contact with a metallic wire and this kind of growth on TMDs gives that anchoring point. ■

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A New Ultra-Safe High Energy Li-Ion Battery for Electric Vehicles

A LITHIUM-ION BATTERY THAT is safe, has high power and can last for 1 million miles has been developed by a team in Penn State's Battery and Energy Storage Technology (BEST) Center.

Electric vehicle batteries typically require a tradeoff between safety and energy density. If the battery has high energy and power density, which is required for uphill driving or merging on the freeway, then there is a chance the battery can catch fire or explode in the wrong conditions. But materials that have low energy/power density, and therefore high safety, tend to have poor performance. There is no material that satisfies both. For that reason, battery engineers opt for performance over safety.

"In this work we decided we were going to take a totally different approach," said Chao-Yang Wang, Professor of Mechanical, Chemical and Materials Science and Engineering, and William E. Diefenderfer Chair in Mechanical Engineering, Penn State. "We divided our strategy into two steps. First we wanted to build a highly stable battery with highly stable materials."

Their second step was to introduce instant heating. About four years ago, Wang developed a self-heating battery to overcome the problem of poor performance in cold climates. The battery uses an electric current to heat up in seconds compared to the hours an external heater required. By heating the battery from room temperature to around 60 degrees Celsius (140 degrees F) the battery gets an instant boost in reactivity because the law of kinetics is that reactivity increases exponentially with temperature.

"With these two steps I can get high safety when the battery is not being used and high power when it is," he said.

The self-heating battery, called the All Climate battery, has been adopted by several car companies, including BMW, and was chosen to power a fleet of 10,000 vehicles that will be used to ferry people between venues at the next Winter Olympics in Beijing.

Because their batteries are built using stable materials, they have a long cycle life. Even at 60 degrees C, their cycle number is over 4000, which translates to over a million miles. ■

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Close-up image of a mm-size Blue-phase liquid crystal during its formation stage. Credit: Khoo Lab / Penn State

Fabrication of New Photonic Liquid Crystals Could Lead to Next-generation Displays and Advanced Photonic Applications

A NEW TECHNIQUE TO change the structure of liquid crystals could lead to the development of fast-responding liquid crystals suitable for next-generation displays (e.g. 3-D, augmented and virtual reality) and advanced photonic applications (e.g. mirrorless lasers, bio-sensors and fast/slow light generations), according to an international team of researchers from Penn State, the Wright Patterson Air Force Research Laboratory and the National Sun Yat-Sen University, Taiwan.

"The liquid crystals we are working with are called blue-phase liquid crystals," said Iam Choon Khoo, the William E. Leonhard Professor of Electrical Engineering, who is the corresponding author for this article. "The most important thing about this research is the fundamental understanding of what happens when you apply an electric field, which has led to the development of Repetitively-Applied Field technique; we believe that this method is almost a universal template that can be used for reconfiguring many similar types of liquid crystals and soft-matters."

Blue-phase liquid crystals typically self-assemble into a cubic photonic-crystal structure; the researchers believed that by creating other structures they could develop properties not present in the current form. After nearly two years of experimentation, they realized that by applying an intermittent electrical field and allowing the system to relax between applications and to dissipate accumulated heat, they could slowly coax the crystals into stable and field-free orthorhombic and tetragonal structures.

The resulting liquid crystals show a photonic band gap that can be tailor-made to be anywhere within the visible spectrum and possess fast responses necessary for a variety of next generation displays and advanced photonic applications. The addition of a polymer to the crystal could stabilize them in a wide temperature range from freezing to nearly boiling point compared to their typical pristine counterparts that are stable in only a 5-degree range. The polymer scaffold also speeds up the switching response. ■

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A Virtual New Method to Detect Defects In 2D Materials for Future Electronics, Sensors

TWO-DIMENSIONAL MATERIALS ARE atomically thin, the most well-known being graphene, a single-atom-thick layer of carbon atoms. The semiconductor industry is interested in using 2D materials for future electronic devices to further shrink these devices and to lower energy consumption. However, a quick and accurate method of detecting defects in 2D materials is needed in order to determine if the material is suitable for manufacturing. Now a team of researchers from Penn State, Northeastern University, Rice University and Universidade Federal de Minas Gerais in Brazil have developed a technique to quickly and sensitively characterize defects in 2D materials.

“People have struggled to make these 2D materials without defects. That’s the ultimate goal,” said Mauricio Terrones, Distinguished Professor of Physics, Chemistry and Materials Science and Engineering, Penn State. “We want to have a 2D material on a four-inch wafer with at least an acceptable number of defects, but you want to evaluate it in a quick way.”

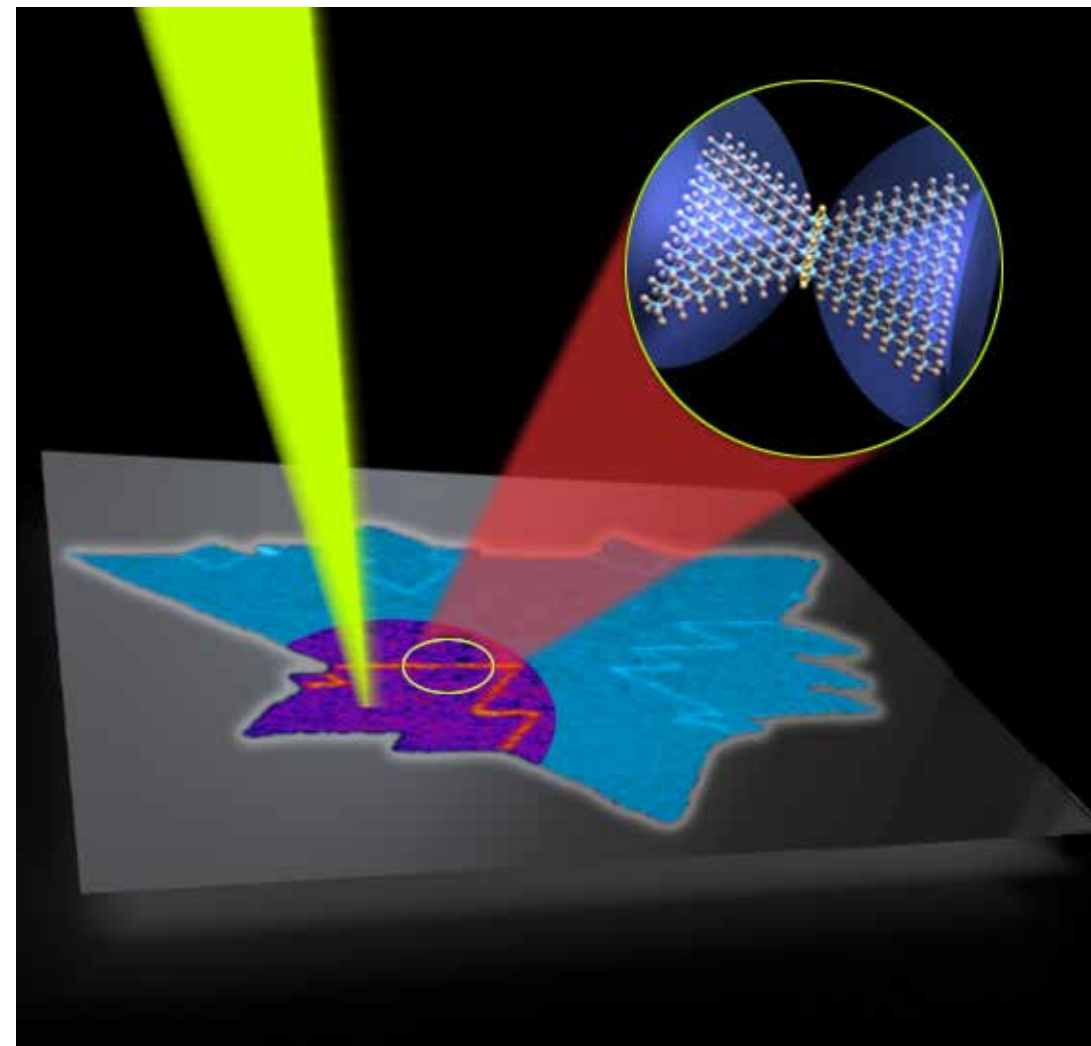
Their solution is to use laser light combined with a phenomenon called second harmonic generation, in which the frequency of the light shone on the material reflects at double the original frequency. Add to this a technique called dark

field imaging, in which extraneous light is filtered out so that defects shine through. This is the first instance in which dark field imaging has been utilized, and it provides three times the brightness as the standard bright field imaging method, making it possible to see types of defects previously invisible.

“The localization and identification of defects with the commonly used bright field second harmonic generation is limited because of interference effects between different grains of 2D materials. In this work we have shown that by the use of dark field SHG we remove the interference effects and reveal the grain boundaries and edges of semi-conducting 2D materials. Such a novel technique has good spatial resolution and can image large area samples that could be used to monitor the quality of the material produced in industrial scales,” said Leandro Malard, a senior author on a recent paper in Nano Letters and a professor at the Brazilian university.

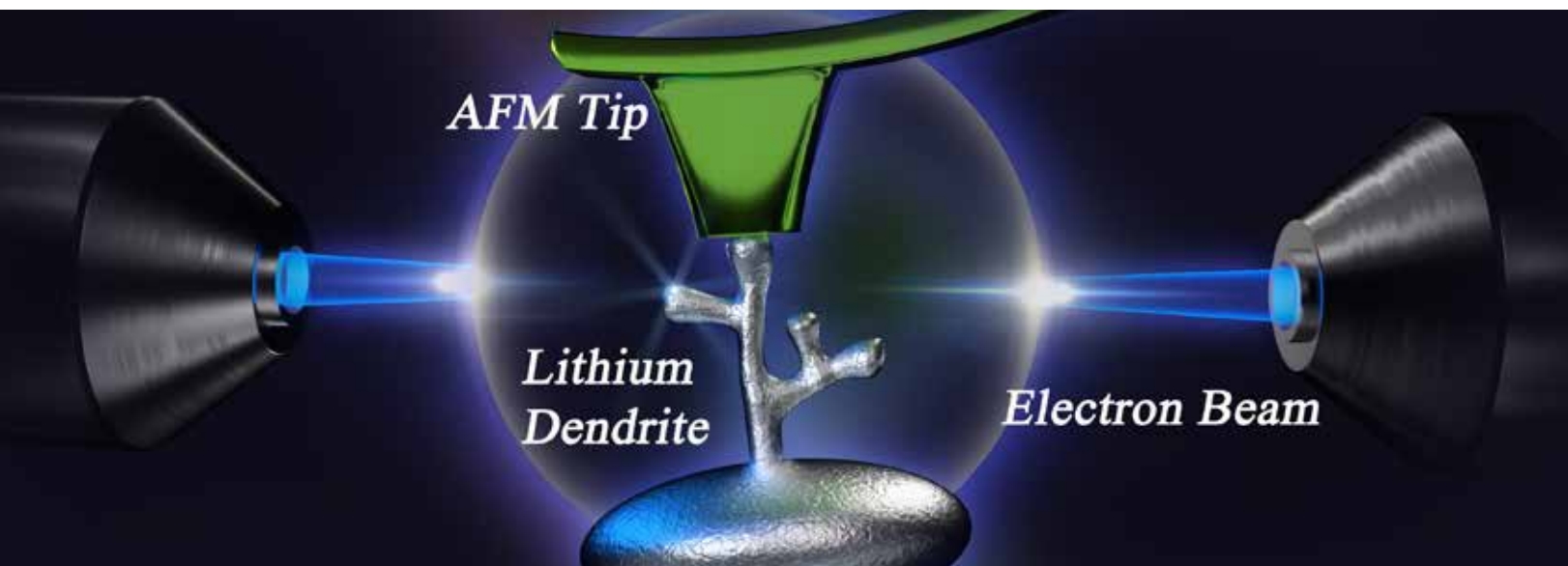
Another coauthor compared the technique to finding a particular letter O on a page full of zeroes. “In the dark field, all the zeroes are made invisible so that only the defective O stands out,” said Yuanxi Wang, assistant research professor, Penn State. ■

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A laser beam (yellow) reflects off a 2D material (orange), highlighting a grain boundary defect in the atomic lattice. Credit: MRI / Penn State.

Lithium Whisker Growth and Stress Generation in an In Situ Atomic Force Microscope—Environmental Transmission Electron Microscope Set-Up



A lithium dendrite is imaged and stress tested under an atomic force microscope tip. Credit: Zhang Lab / Penn State

LITHIUM ION BATTERIES often grow needle-like structures between electrodes that can short out the batteries and sometimes cause fires. Now, an international team of researchers has found a way to grow and observe these structures to understand ways to stop or prevent their appearance.

“It is difficult to detect the nucleation of such a whisker and observe its growth because it is tiny,” said Sulin Zhang, professor of mechanical engineering, Penn State. “The extremely high reactivity of lithium also makes it very difficult to experimentally examine its existence and measure its properties.”

Lithium whiskers and dendrites are needle-like structures only a few hundred nanometers in thickness that can grow from the lithium electrode through either liquid or solid electrolytes toward the positive electrode, shorting out the battery and sometimes causing fire.

The collaborative team from China, Georgia Tech, and Penn State successfully grew lithium whiskers inside an environmental transmission electron microscope (ETEM) using a carbon dioxide atmosphere. The reaction of carbon dioxide with lithium forms an oxide layer that helps stabilize the whiskers. They report their results in Nature Nanotechnology.

Innovatively, the team used an atomic force microscope (AFM) tip as a counter electrode and the integrated ETEM-AFM technique allows simultaneous imaging of the whisker growth and measurement of the growth stress. If the growth stress is too high, it would penetrate and fracture the solid electrolyte and allow the whiskers to continue growing and eventually short-circuit the cell.

“Now that we know the limit of the growth stress, we can engineer the solid electrolytes accordingly to prevent it,” Zhang said. Lithium metal based all-solid-state batteries are desirable because of greater safety and higher energy

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research
SNAPSHOTS

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

New Class of Materials Shows Strange Electron Properties

A METHOD TO OBSERVE a new class of topological materials, called Weyl semimetals, was developed by researchers at Penn State, MIT, Tohoku University, Japan, and the Indonesian Institute of Sciences. The material's unusual electronic properties could be useful in future electronics and in quantum physics.

"Weyl semimetals are interesting because their electron transport shows some unusual behavior," says Shengxi Huang, assistant professor of electrical engineering, Penn State. "For example, they can show negative magnetoresistance, which means when you apply a magnetic field, the resistance drops. With many conventional materials, it increases."

In Weyl semimetals, the electronic band structure is different from normal. The electrons have chirality, meaning "handedness." The chirality is connected to the electrons' spin and traveling direction. Electrons with left chirality travel in the opposite direction of its spin, while electrons with right chirality travel in the same direction of its spin.

"Normally, a material would have some kind of conservation, for example, charge neutrality conservation — meaning if you had a certain number of negative charges you would have the same number of positive charges," according to Kunyan Zhang, Huang's graduate student and lead author on a paper in the journal Physical Review B. "Similarly, you would also normally have the same number of righthanded electrons as lefthanded ones. But this is not the case in this material and that seems to boost new electron transport properties."

The team decided to use light to study the peculiar behavior of the electrons because it is simple to use and easier than building sophisticated devices. The light interacts with the electrons and also with the lattice, causing the atoms to vibrate, creating phonons. The phonons and electrons interact and the Raman signals — the difference between the laser and scattered light — can show the unusual behavior of the electrons.

The main result of the researchers' work is to show that the material's symmetry is broken. In principle, this crystalline material should have four-fold symmetry, which means that when the crystal is rotated 90 degrees the property is exactly the same. However, in this study, if the Weyl semimetal is rotated 90 degrees, there is a deviation from symmetry.

In addition, this material should show three peaks in the Raman spectrum, but in one 633-nanometer — red — light excitation one peak is missing. That is peculiar, according to the researchers. The explanation lies in the band structure of Weyl semimetal. When electrons interact with light, they absorb enough energy to jump to a higher state. In Weyl semimetals, there are many higher states very close to each other. The interaction between the electrons jumping to two adjacent bands can break symmetry.

In this type of material, the electrons can flow without any back scattering under certain conditions, making it a good platform for future electronics. There is also a connection to quantum computing, since a material that does not scatter has the potential to be used in quantum qubits. ■

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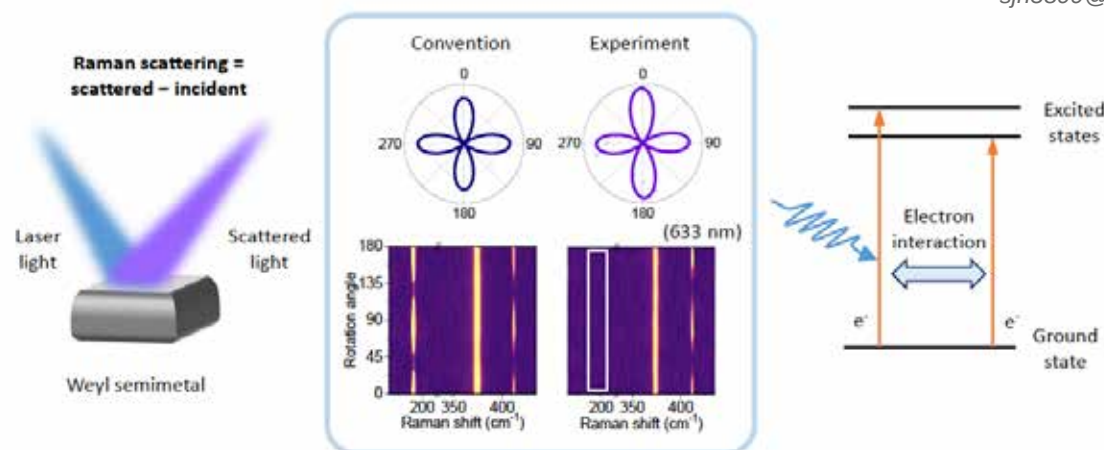
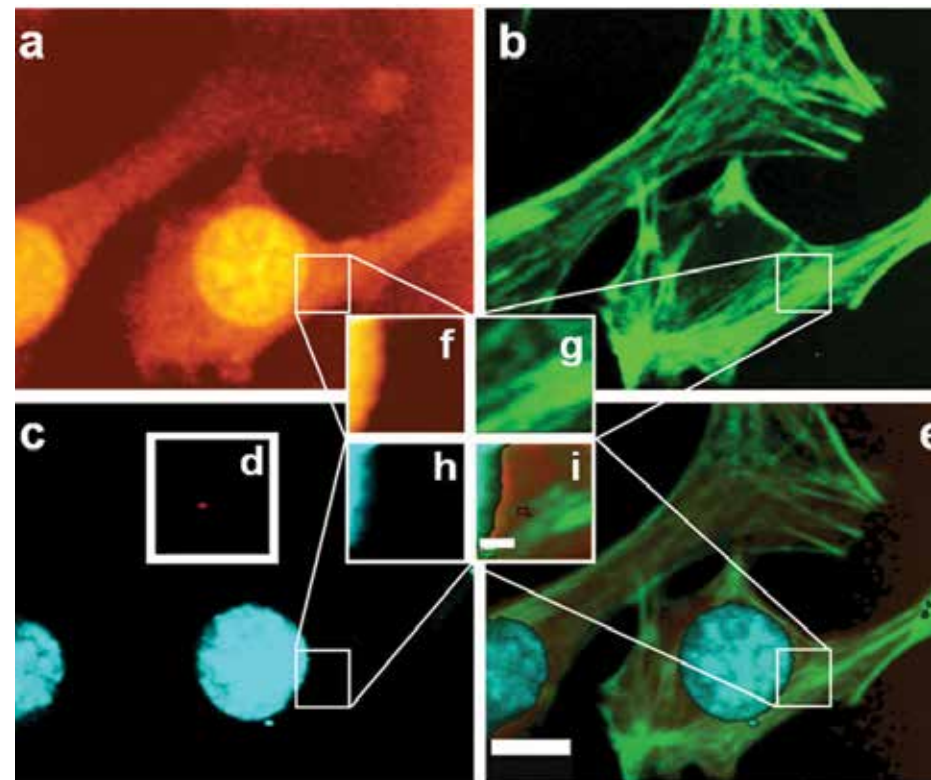


Illustration of Raman scattering (left) and electrons jumping to two close higher bands (right). Credit: Shengxi Huang / Penn State



Raman imaging of individual nanotubes inside neural stem cells: different colors show different parts of the cell (proteins in yellow, cytoskeleton in green and nucleus in blue). The central insets show magnified view of cell organelles inside a white 6x6 micron square, overlaid with a nanotube image from separate inset (d). Credit: Rotkin Lab / Penn State

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Banning Carbon Nanotubes Would Be Scientifically Unjustified and Damaging to Innovation

IN A CORRESPONDENCE published today in the journal Nature Nanotechnology, scientists from Penn State and 31 other universities and medical centers take issue with an article published in the same journal calling for the banning or restriction of carbon nanotubes in Europe.

In their rebuttal, the nanotube researchers say that restriction of the entire class of nanomaterial on the basis of safety is casting much too wide a net, that safety concerns of early biomedical experiments have been overcome recently — with better methods of functionalization of nanotube-derived materials, and restrictions would limit scientific and medical progress unnecessarily.

According to Slava V. Rotkin, one of the Penn State cosigners along with Mauricio Terrones, "These materials have been used for intracell imaging, for example. Nanotubes are bright but very small. What people were doing in earlier studies was pushing a bunch of nanotubes into a cell in order to see them well. But that was too many — they clumped together and quickly killed the cell."

Around fifteen years ago, Ming Zheng (NIST) and Anand Jagota (Lehigh University) found a way to wrap the nanotubes in artificial DNA. Artificial DNA allows researchers the ability to process nanotubes without clumping and separate them by electronic properties. These functionalized nanotubes were biocompatible and useful for biomedical applications. These could be applied, for instance, to treat kidney disease and investigate Parkinson's disease. Rotkin and his co-workers Sabrina Jedlicka (Lehigh University) and Tetyana Ignatova (UNCG) applied individual DNA-wrapped tubes for mechanical stimulation of neural stem cells. In these papers (DOI: 10.1039/C7TB00766C and 10.1002/adbi.201800321), cells that uptake nanotubes were tracked for more than 3 weeks and survived well the experiment (see Fig.)

Carbon nanotubes could also be used to track viral outbreaks, improve the strength of building materials, for gene delivery, image-guided surgery and non-invasive disease monitoring.

"The opinion we are arguing with is from a group of risk and toxicology specialists, not necessarily reflecting all existing expertise of materials science, physics, chemistry and biology of nanotubes," Rotkin says. "People, having a full grasp of the complexity of the topic, expressed their strong disagreement with conclusion that all nanotubes are bad, carcinogenic, deadly. What we emphasize is you have to know how to functionalize it for biomedical applications and how to use it in appropriate quantity. What we are trying to say is people should not put a ban on the propagation of knowledge without performing deep scientific analysis and providing very good reasons." ■

UNCONVENTIONAL BUILDING TECHNOLOGIES FOR AFRICA

THE 10TH INTERNATIONAL Conference of the African Materials Society was held in Arusha, Tanzania, in December 2019. In a pre-conference workshop, coordinated by Penn State faculty, MRI director Clive Randall and associate professor Esther Obonyo, presenters discussed a variety of topics crucial to developments in Africa, including unconventional building materials, waste disposal, recycling concrete for high-end applications in developing countries, using cardboard as a building material, and Penn State’s cold sintering process for low-energy manufacturing of building materials.

The workshop, titled Drawing Down Building Material Matter at the Human Scale, was based on Penn State’s Humanitarian Materials Engineering at a Human Scale project, an initiative of the Materials Research Institute. The workshop was well attended by students eager to learn about humanitarian engineering from a global group of speakers at the workshop, according to Esther Obonyo, also a presenter.

“This is something Clive and I wanted to do because we thought it would be a nice opportunity to get input from a diverse group of people,” said Obonyo. The crucial question they discussed was Why, if the science is available, is it not being translated into practice at scale, particularly in developing countries in Africa?

“One of the reasons is that unconventional technologies have typically been used in low income and poor communities and that introduces a special stigma,” she said. For that reason, it was especially useful to hear from a

Swiss researcher who has developed a technology to use recycled concrete for building materials in developed countries.

“I SAY WE ARE MISSING THE TARGETED POPULATION. BECAUSE WE ENGAGE WITH THEM AS CUSTOMERS RATHER THAN CO-DEVELOPERS OF THE POSSIBLE SOLUTIONS, WE ARE NOT ABLE TO ADEQUATELY CAPTURE THE NUANCES OF CONTEXT FROM THE PERSPECTIVE OF THE END USERS,” OBONYO SAID.

A Penn State presenter who doing his Ph.D. research on uses for cardboard highlighted the dual benefits through focusing on the two areas: the problem of affordable materials that can be accessible to people informal settlements and the waste disposal of cardboard. He showed in his research that cardboard can be used structurally and architecturally to design components for structures in developed countries.

A researcher from Tanzania’s National Building Research Agency (NHBRA) in Tanzania talked about his agency’s success in seeding and catalyzing the emergence of an ecosystem for alternative building materials and technologies. Their activities in selected regions within Tanzania have focused on enhancing the local manufacturing capacity, skills training for workers, producing equipment, and providing technical support for new business ventures.



“We have several examples showcasing the successful translation of science into usable products or methodologies such as material design properties. The knowledge exists and there is a market. There are examples of government agencies with platforms for enabling these types of translations. Yet our best efforts as a community of people working in this rarely scale beyond pilots and case study implementations. What are we missing?” she asked.

The African Material Research Society’s bi-annual convention seeks to address this problem. Although the researchers come from all over the world, the convention’s program is driven by the African scientists and other stakeholders from

the government, private sector and community sector organizations. The workshop is directed at harness the research of globally engaged scientists and engineers to address Africa’s most pressing issues, which include water purification, solar and other renewable energy, building materials, and manufacturing. The conference brings together people who are interested in advancing the use of material science to answer humanitarian engineering needs.

Other Penn State faculty who presented at the conference were D.K. Osseo-Asare. Kwadwo Osseo-Asare, Ismaila Dabo, Kofi Adu, and Clive Randall. ■

5G & Beyond

AN OVERVIEW

The fifth generation (5G) is upon us, but how is Penn State equipped to advance the technology? Focus on Materials talked to six Penn State faculty with expertise in 5G to gain a perspective on Penn State's role in the future of 5G and beyond.

The rollout of 5G devices is in its infancy. With the exception of a few square blocks in a few American cities, no one in the U.S. is currently using 5G technology. Current 4G technology, the generation that delivers data to your smart phone, took three to five years from its inception to reach a large number of users, which means wide-spread adoption will likely come in the early 2020s for the new technology. As with high-speed internet, rural areas will likely be left behind for years.

THE PROMISE OF 5G

In a 5G network, many multiples of data transfer speeds beyond 4G are expected. In addition, something called latency, or the time required to respond from a base station to your device, will be a small fraction of a second. This will enable benefits such as self-driving cars being able to operate in safer ways and increase the feasibility of robotic telesurgery.

Because of the small size of the wavelength, millimeters as compared to current centimeter wavelengths, the size of base stations will shrink as will the size of antennas, since antenna size is comparable to wavelength size. With the ability to fit hundreds of antennas into a small transmitter, comes the possibility of operating hundreds of devices simultaneously to facilitate the internet of things. The IOT envisions a future factory with hundreds of machines operated from a single control booth (maybe not such a benefit for workers).

WHY PENN STATE?

Clive Randall is the director of Penn State's Materials Research Institute and a professor of materials science and engineering. His take on Penn State's capabilities stems from his long-standing research on dielectric materials – a key component in 5G devices -- as well as intimate knowledge of the current research portfolios of the key scientists and engineers involved in 5G-related research.

"Penn State has a long history of working in dielectrics and antenna design," he said. "The current 5G technology is at the bottom end of the megahertz range, which doesn't have such technical challenges. But the interesting part comes at 40 gigahertz and beyond where a lot of challenges in materials choice and antenna design and dealing with dielectric loss mechanisms will lie." ►►►



Dielectric loss can lead to serious overheating problems and runaway heating issues even in the hundreds of antennas required. Thermal management will require that thermal expansion of the materials is contained, which requires temperature stable materials. The precision control of that is going to get much more complicated, Randall contends. “So it’s going to mean composites, it’s going to mean active cooling, it’s going to mean a whole set of different design criteria that we presently have not had to face.”

RANDALL GOES ON to name a number of faculty experts, some long standing, others recently hired into this space. Those experts are included in this issue. The university has also made an investment in the characterization facilities required to make advances in the field. In terms of measurement capabilities, these facilities are capable of testing from very low frequencies up to 100 gigahertz. There is also work being done to expand the temperature ranges and electric field conditions at which materials can be characterized.

Fast Facts About 5G

- ✓ **5G is 20 times faster than 4G**
- ✓ **5G has millisecond latency**
- ✓ **Download speeds of 20gb per second**
- ✓ **Requires 5 times more cell sites than 4G**
- ✓ **China has deployed 10 times more wireless sites than the U.S.**
- ✓ **The U.S. is about 5 years behind China in rolling out 5G**
- ✓ **5G applications include self-driving vehicles, smart cities, smart factories, remote surgery.**

One promising avenue to mitigate heat problems without affecting dielectric properties lies in a new technology developed at Penn State by Randall’s team called cold sintering. This process allows ceramics or metals to be sintered at low enough temperatures that they can be infused with small amounts of polymers and other inclusions that would improve their thermal properties.

At present, much of the dielectric measurement work is supported by the Center for Dielectric and Piezoelectrics (CDP), a joint Industry/University Cooperative Research jointly operated by Penn State and North Carolina State, and supported by member companies and the National Science Foundation.

Members of the CDP are interested in basic research applicable to a number of areas related to 5G, such as packaging, blue tooth antennas, and microwave filters for bandwidth control.

“WE EVEN FORESEE NEW COMPANIES JOINING CDP WHO ARE INTERESTED IN THE DIELECTRIC PROPERTIES OF THE BUILDING ENVIRONMENT, AND THAT’S SOMEWHERE THAT RAM NARAYANAN’S EXPERTISE COMES IN,” RANDALL SAID. A PROBLEM WITH THE 5G FREQUENCY IS THAT IT CAN BE SCATTERED BY OBJECTS SUCH AS FOLIAGE AND BUILDINGS AND EVEN THE FURNITURE INSIDE A ROOM.

“We will be interested in doing free space measurements as well as substrate and resonance measurements that help us to bridge the new bandwidth issues that will need to be addressed for 5G and beyond,” he concluded. ■

With 5G, Expect the Unexpected

MIKE LANAGAN IS a professor of engineering science and mechanics and one of the organizers of the 5G push at Penn State. He says, “5G is just so new. It’s just now pushing from 2 gigahertz up to 30 gigahertz, so if you look at the electromagnetic spectrum, it’s not that great a jump in the physics. There are so many people at Penn State doing electromagnetics that those faculty can easily move over to 5G.”

When 3G moved over to 4G, nobody really knew what to expect, Lanagan says. Then, as the bandwidth expanded with 4G, suddenly applications like Uber and Lyft were possible because you could now locate people and vehicles instantly. Most people were happy with 3G, but the change enabled something transformational. The same is likely to be true with 5G, with things like self-driving cars and more advanced virtual reality, but companies are keeping their ideas to themselves.

The PA Partnership for 5G estimates that 5G will be 40 times faster than the current fastest network, called 4G LTE, with four times greater capacity. It will create three million new jobs and add 500 billion to GDP. The two-hour movie that takes 90 minutes to download on your 4G device will take four seconds to download on your 5G device.

A lot of the advances will be on the software side, coming up with new apps, an area that most scientists and engineers at Penn State are not involved with. But on the hardware side, companies working with Penn State and the Materials Research Institute are seeing opportunities in 5G. Companies working with materials and devices are excited by new technologies and new materials, recalling the boost the widespread development of cell phones helped to engender a new glass technology.

“THE COMPANIES THAT GET TO MARKET FIRST WILL HAVE THAT MARKET WRAPPED UP,” SAYS LANAGAN. “BETTER MATERIALS MAY COME ALONG, THERE MIGHT BE 10 OTHER THINGS THAT ARE VIABLE, BUT THEY MADE THE FIRST INROADS AND THEY ARE SET FOR DECADES.”

As frequency increases the size of the antennas goes down. A good rule of thumb is that the antenna size is the same as the wavelength size. So, for instance, an AM radio wavelength is hundreds of meters in size and therefore requires huge radio towers. But going from 4G to 5G isn’t a big leap in size reduction. But there will be many more antennas required that can interact with each other in a detrimental way. New designs will be required and fortunately Penn State has one of the most advanced antenna labs in the world, led by Doug Werner.

BUT THERE COULD also be interesting possibilities for new materials. The materials required are driven by devices, says Lanagan. And companies will determine which materials are required. That’s why the companies that are members of the Center for Dielectrics and Piezoelectrics will be driving the direction of much of Penn State’s materials research in the 5G space.

The CDP includes companies that do electronic materials, including antenna structure, transmission lines, and all of the varied connectors. There are companies interested in the dielectric side, represented by the CDP, and another set of companies interested in the semiconductor device side.

SAFETY

Because of the attenuation of shorter wavelengths, base stations will be required on most buildings and telephone poles. With more transmission comes more and more radiation. All waves emit radiation, like the ultraviolet waves in sunlight that can cause a bad sunburn or eventually lead to skin cancer. Are we going to cook ourselves when we move into the microwave band or develop skin cancer?

This is a controversial issue, with scientific organizations coming down on both sides of the matter. Millimeter wavelength, the standard for 5G, is nonionizing, and so unlikely to cause cancer. Further, the waves barely penetrate the skin. Some scientists claim, however, that cell phone use is already leading to a rise in infertility and head and neck tumors. Others who have studied the scientific literature and surveyed the data see no evidence of harm. It is likely that 5G will be no more harmful than current 4G, but how safe is 4G?

“It’s straightforward. If you have ionizing radiation, that’s cancer,” Lanagan says. “5G is below the level of ionizing radiation. But still, I’d like to check with other scientists who have studied this.” ■

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Tunable Electronics for 5G

IN THE PRIYA lab, his team designs various magnetic ceramics – materials that have high resonance frequencies. They design the magnetic composition, then utilize either bulk (tape-casting), thick film (aerosol deposition), or thin film (sputtering) to develop the component structures.

“These components could be as simple as filters or resonators,” said Shashank Priya, Associate Vice President for Research and professor of materials science and engineering. His lab has also been developing energy harvesting devices, wireless power transfer components, and tunable electronics using these magnetic materials.

“The next thing we are trying to do is tune the ferromagnetic resonance frequency or permeability by using piezoelectric materials.”

On applying the electric field, piezoelectric materials generate strain which can be transferred to magnetic materials for changing their properties. They call this tunable electronics, and they have been testing devices in the megahertz range to develop model components and evaluate their hypotheses for high-power, high-frequency components. Using thin-films they plan to develop similar components in the high-frequency domain.

BEYOND 5G

There are many ways people are trying to utilize 5G, he said. His team works a lot with wireless sensor nodes. For example - in a building on campus there could be many types of sensors, for instance, humidity sensors, light sensors, sensors to measure temperature, or occupancy sensors. These are now mostly connected to the grid or battery operated, but they could be automated so that sensors can be deployed in larger quantities and have a more robust power source. This will allow machine learning algorithms to get access to enough data, ►►►



Wirelessly powered machines can be quickly configured based on factory needs. Wireless power is ideal for robotics with high-power demands.

Autonomous equipment works continuously without downtime for charging or refueling.

Integrated sensors enable communication and data transfer between devices for efficient operations.

RFID enabled packages allow for precise, real-time inventory control.

which will improve the learning capability of the control systems. Over a certain period, the control system will be able to automate most of the function for the user, such as temperature control, lighting, humidity level, etc.

5G could enhance this automation significantly by both improving the rate of data transfer from sensors to controls and providing low power for sensors. This wireless power and data transfer can expediate what is being called the Industry 4.0 Revolution. A lot of those machines that would be manual before, say in a factory setting, will now be smart or digitized, incorporating many sensors at different stages of the process. These sensors will transfer all their data to a cloud-based server, which will process the data and control the operating conditions of those machines.

“Before it was all human beings turning this knob and that knob. Now it is all being done automatically. People can visualize everything on their laptop screen,” he said. The operator is in the control room overseeing everything and only interfering when a problem arises.

Powering the large network of sensors has been a problem. If a battery fails, that can be the cause of a breakdown in the process, and there could be 1,000 or more batteries required in a factory on a periodic basis. The hope is that while the data is being transferred on allocated specific frequency bands there could also be a small amount of power transmitted at the same frequency to keep the sensor power. If 5G is able to do that, it will change the game. Other applications, like structural health monitoring, could also be possible with 5G.

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HOW DOES PENN STATE FIT INTO THE 5G SPACE?

Penn State is probably the guru of smart materials manufacturing,” Priya said. “We have people who are amazing in computational modeling all the way up from the atomic level. And because we have a very good supercomputing center through the Institute for Computational and Data Science, it means we can simulate materials with many atoms. Then we have people who do meso to macroscale modeling.” For example – “The atomic scale modelers can hand off to the people doing phase field,” he continued. Once the modeling results are available, “then we have experts doing synthesis.

“Before it was all human beings turning this knob and that knob. Now it is all being done automatically. People can visualize everything on their laptop screen,” he said. The operator is in the control room overseeing everything and only interfering when a problem arises.”

We have the Nanofabrication Laboratory and the Materials Characterization Lab and tons of manufacturing machines of different types.”

All of this, the modeling, device manufacturing, and testing can all be done in one place. Normally this type of infrastructure would be spread out across many groups or universities. But Penn State has invested in all of this infrastructure and hired many talented people who can implement these new ideas in a very rapid manner.

“For us, this 5G or other topics, as long as they are focused on developing materials or developing materials-driven devices, Penn State is probably one of the best places to come and work.” ■

Werner Group Contributions to 5G

MY RESEARCH GROUP (PSU CEARL: cearl.ee.psu.edu) has been developing advanced technology for 5G and beyond applications that is based on a new type of multifunctional phased array antenna system that exploits orbital angular momentum (OAM) modes in vortex beams to dramatically increase the information capacity (i.e., the amount of information that can be processed and transmitted over a communications channel) compared to conventional systems. This requires developing a completely new and transformative type of phased array antenna technology which heavily relies on an ability to manipulate and control electromagnetic waves in an arbitrary fashion using engineered quasi-two-dimensional materials, also known as metasurfaces.

My research group is also working on developing wearable antenna technology for body area networks that supports future 5G and MIMO systems.

Doug Werner is the John L. and Genevieve H. McCain Chair Professor in Electrical Engineering and the director of the Computational and Antennas Research Lab. ■

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Credit: Adobe Stock

Mitigating Wave Scattering

IT IS TIME for us to start ramping up our footprint in the 5G world, because everyone else is doing 5G, according to electrical engineering’s Ram Narayanan.

“5G is a new scheme for fast and very reliable communications. It connects humans with machines, the internet of things, provides streaming video and audio,” he said.

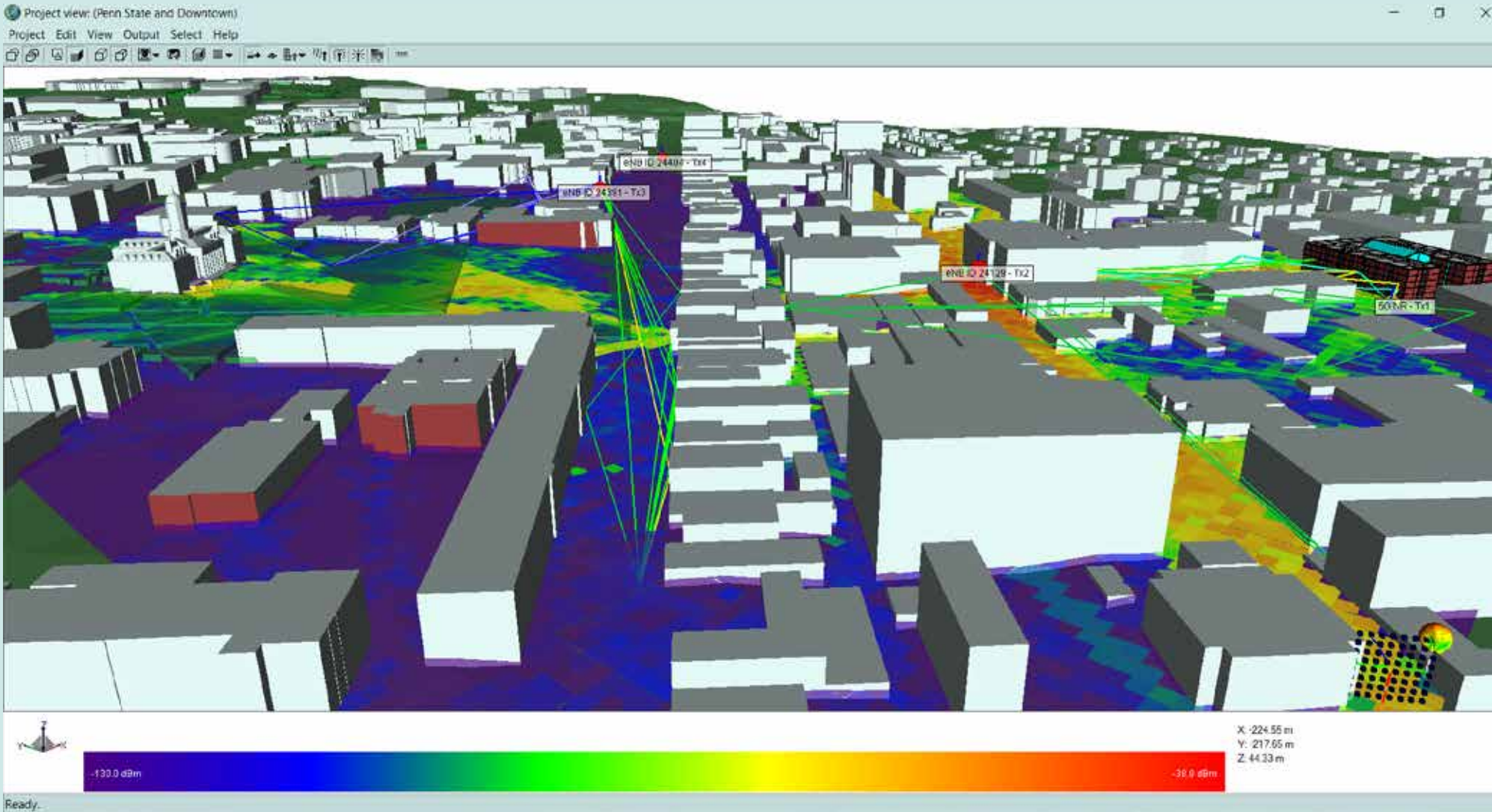
As we move into higher frequencies, first 10 gigahertz, then 30 gigahertz, the problem of short range and interference with obstacles, such as trees and even oxygen molecules in the atmosphere appear. Unlike radio waves, which can travel long distance and can pass through walls and other obstacles, 5G signals are short range and require a much higher number of base stations. These are the problems Narayanan is trying to overcome.

Penn State has been studying various aspects of 5G and has considerable expertise in areas that could easily translate into 5G, but so far there has been no coordinated efforts. There are people in electrical engineering who are looking at new designs for antennas (as carrier waves shrink, the size of

A 5G mmWave coverage concept using existing AT&T towers in State College. The lines represent radio-frequency ray paths predicted using Remcom's Wireless InSite propagation simulation. Image Courtesy of Remcom®.

antennas shrink). Computer engineering is looking at modulation - 5G requires new signal schemes to be transmitted. It requires people like Narayanan who are working on propagation, for instance, what happens when the signal goes into a building with multiple reflections?

“We require people working in electromagnetics and in signal processing. We require materials people, because some of these designs require exotic materials. All of these have to come together. In this, the College of Engineering can play an important role, because I do not believe we are tapping our full potential. This is the time we need to have a cohesive approach so we can go after bigger funding,” he said.

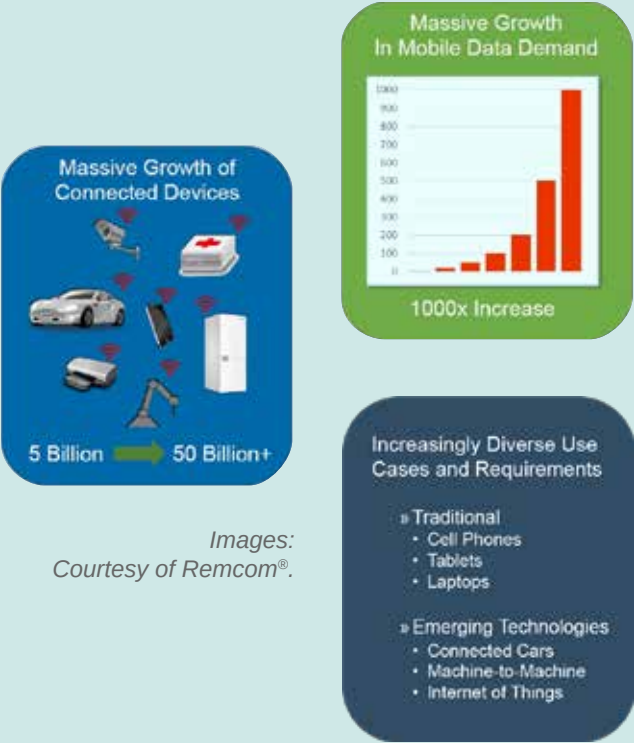


NARAYANAN'S RESEARCH

Narayanan is working on microwave engineering, which includes radio wave propagation through the atmosphere. He is looking at what happens when radio waves get scattered by obstacles in nature. He studies how different frequencies can be used for different applications, for instance using lower frequencies to look for land mines. And most important for 5G, propagating electromagnetic energy inside buildings.

“If you look around inside a building, there are so many ways the waves can be deflected. And when they are deflected, they come back at different phases. We are working to mitigate those types of issues,” he concluded. ■

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Advanced Antenna Technologies

ADVANCED ANTENNA TECHNOLOGIES serve as the physical gateway into the high-speed wireless world offered by 5G communication and sensing systems. My research focuses on adaptive antenna technologies and beamforming systems for this exact purpose, and we're on a mission to engineer transformative antenna technologies that enable society to utilize every dimension of the amazing capabilities that these and future (beyond 5G) networks can provide. Everything is on the table for this, including additive manufacturing, multi-functional materials, physical reconfiguration, structural integration, and other innovative concepts. This allows us to leverage our creativity and passion to explore the role of new technologies to derive biologically-inspired and other concepts for synthetic systems and materials. Through these efforts we are removing the constraints of modern fabrication technologies for circuit boards and other devices and re-thinking how we can derive the desired antenna functionality from complex three-dimensional structures. Engineering these new antenna technologies will be critical for both near- and far-term needs of 5G as we move beyond its deployment in smartphones and laptops and look to extend the connectivity and capabilities of these systems into smart infrastructure, robotics, medical, virtual reality, assistive technologies, autonomous vehicles, sensing, wearable devices, and other application spaces. ■

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*Photos: Additively-manufactured conformal beamforming component (printed in clear resin with raft and supports still attached) and antenna (metalized in opaque resin) for 5G (V-Band) networks.
Credit: Huff Lab/Penn State*

Energy and Frequency

BRIAN FOLEY CAME to Penn State with a background in industry. The company he worked for prior to grad school, Virginia Diodes, is a small company in Charlottesville that makes testing and measurement equipment at the high end of the 5G range, but even higher at 6G.

"So what I have been saying to the 5G community here is let's shorten the learning curve and get the equipment in to start to work in that space," he said.

Foley's expertise in 5G is on two fronts: nanoscale energy transport, primarily dealing with heating problems, and the high frequency measurement skills he picked up in industry. The advanced materials like semiconductors and oxides that many people at Penn State are working on will be used in 5G, and with high frequencies, heating concerns will be a major issue.

"Nanoscale thermal transport is one thing, but then there is making the frequencies, shooting them at something, and making the measurements," said Foley, who is an assistant professor in the Department of Mechanical Engineering.

He describes his research as looking at structure-property relationships of materials, everything from certain functionalities to certain properties – dielectric, thermal, and optical properties. And how these properties depend on the structure of the material or the material design. His group does fundamental research on materials, then put them together in some kind of functional device.

"I THINK PENN STATE'S ROLE IS THINKING ABOUT HOW WE ARE GOING TO MAKE MATERIALS THAT CAN HELP 5G BE RELIABLE AND FUNCTIONAL, GIVEN THE PROBLEMS THAT COME WITH 5G TECHNOLOGIES," HE SAID.

Penn Staters might make components for base stations, he continued. But there are no U.S. players making hardware for 5G. The companies making cell towers for 4G are not taking the risk. When 5G is finally rolled out, primarily in major cities, Foley does not foresee the same kind of service, reliability, or range that people are used to.

HD video will be available quickly, but if people are within line of sight of a base station. If you are not within line of sight, 5G will have fundamental reception problems.

Penn State can think about making advanced materials to make new structures to help the waves get to our phones, such as in-building transmitters and new building technologies, since millimeter waves have a hard time penetrating walls.

"Since Penn State has such a history of making everything from nanomaterials to large composites, we want to talk about scale, about roll-to-roll processing. I think Penn State is in a good spot. ■

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Perspective on 5G

5 G IS A technology of major strategic and impending importance, which will be supporting many advanced aspects of the economy, such as manufacturing, in the mid-term future. Large national governments, particularly such as China, are investing in, developing, and influencing the deployment of this technology. In particular in the US, the major telecommunications companies such as Verizon are also well aware of the projected impacts of 5G; in addition to their involvement as implementors of the technology, they also have strong political biases and motivations, any of which, in my opinion, run contrary to the strategic economic interests of the US as a country. ■

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Building the Components of a 5G Phone

RONGMING CHU BUILDS semiconductor devices and the components that will make millimeter wave 5G possible.

“My group's work in 5G is basically going up in the frequency band. That is not an easy thing to do,” says Chu, who is the Roell Early Career Associate Professor of electrical engineering. “For example, one of my students is working on something called a varactor. A varactor is a tuning device for communications.”

In a cell phone there are multiple frequency bands. To control the frequencies, people are developing an impedance-matching network, or filter, corresponding to that band. They use a switch to switch between different frequency bands.

At least that's how it is done today. But for each frequency band a separate component is required. Moving into 5G the number of frequency bands increases, which is not desirable from a cost perspective and a size perspective. The varactor Chu and his student are working on works in a different way. Instead of using multiple filters to control the frequency bands, they are developing a single tunable filter to control all bands. ►►►

The challenge with that is parasitical resistance. There are three different kinds of varactor. One is a ferroelectric varactor. Ferroelectric is a material where when you apply an electric field the dielectric constant of the material will change. That is a kind of tuning device for this purpose. With a ferroelectric material you have the limitation of the Q factor. Basically, that is the definition of how much power loss you have when you apply an electromagnetic field on the material. The Q factor is fairly low and the tuning speed is not high enough. Another problem with ferroelectric material is the emperature sensitivity. When it's hot it can behave differently.

Another route is MEPS – microelectronic mechanical systems. There are two electrodes and the space between the electrodes can be adjusted. So far, this device has the best Q factor. There is very little loss. One of the problems is mechanical reliability. Another is tuning speed.

The approach Chu’s group is taking uses three innovations. First, they are using a new semiconductor – gallium nitride. Gallium nitride is a material that can handle high speed and high power. Second, instead of using a traditional varactor, they use a varactor in which, by applying a bias, they change the width of the semiconductor, which corresponds to the capacitance of the device. In order to house the component, a substrate of a few hundred microns is required. But that is resistive. It’s the source of power loss in the varactor. Instead of that, they modify the electrons. The third innovation is that instead of heavy doping of the semiconductor, they use something called a 3D gas.

“My student will spend his entire Ph.D. research making a good varactor.” ■

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The Millimeter Wave

MEHDI KIANI'S EXPERTISE is not necessarily in the 5G space, but some of his research could be applied to 5G he believes.

Unlike the omnidirectional cell signal in current receivers and transmitters, in 5G the signal takes the form of a tight beam. It's called beam forming, and it is what allows 5G to get high bandwidth.

“One area we are working in has synergy with 5G. It’s called ultrasound neuromodulation, says Kiani, who is the Dorothy Quiggle Career Development Assistant Professor in electrical engineering. “We are trying to modify brain activity. We use beam forming so we can focus the ultrasound to different regions of the brain. 5G is a similar concept, only with electromagnetic waves.”

His group's core expertise in electronics could be useful in developing circuits for transmitters or receivers, he believes.

The power of 5G comes when the frequency goes up from 30 gigahertz to 300 gigahertz, also called millimeter wave. Designing circuits in that regime is very challenging. He does not know of anyone at Penn State who is doing that.

“I believe Penn State is strongest on the materials and devices side, since Penn State is historically strong in materials. Other experts can complement that group,” he says. ■

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