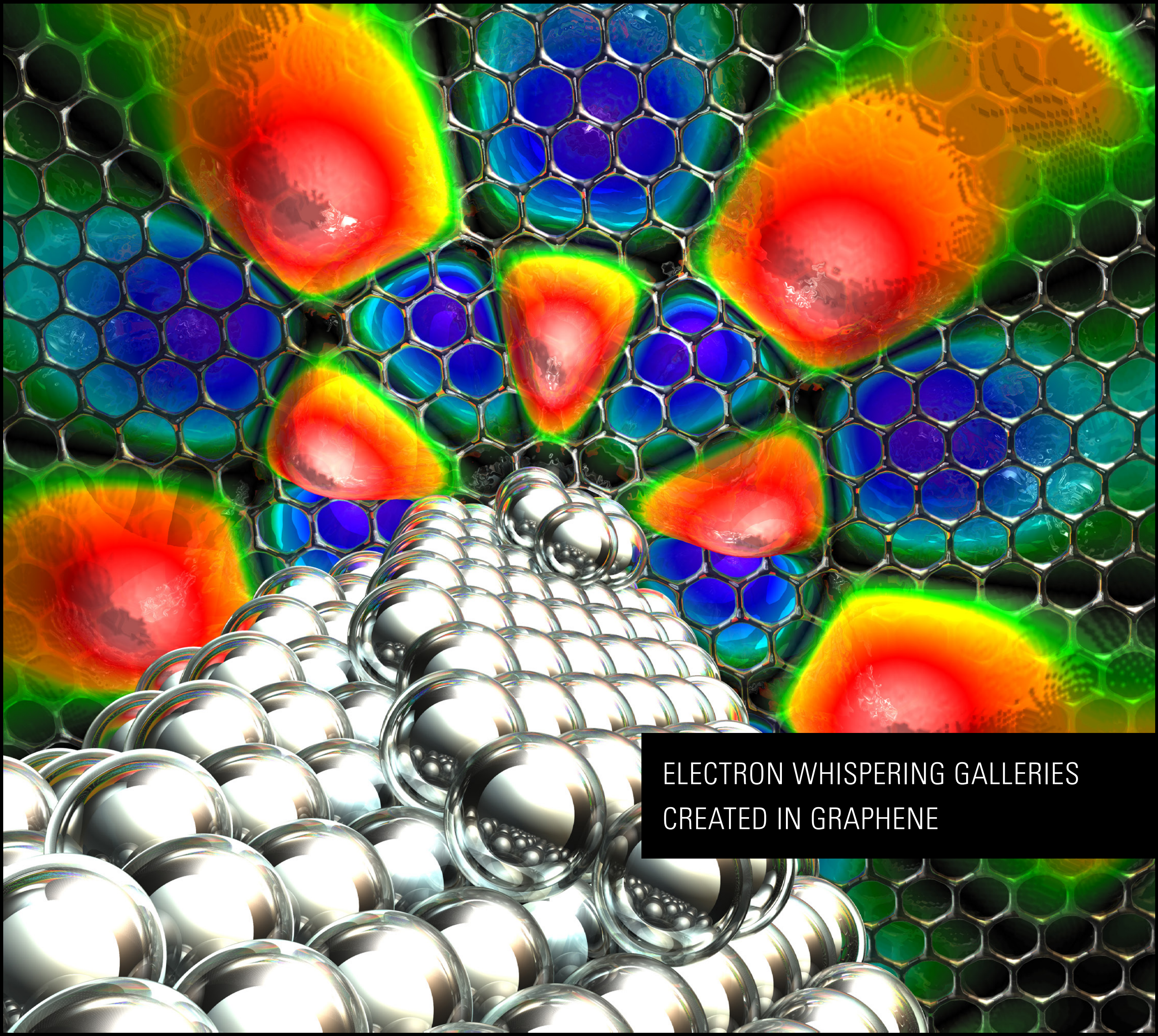
THE CNST NEWS

SPRING/SUMMER 2015



ELECTRON WHISPERING GALLERIES CREATED IN GRAPHENE

INSIDE

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FROM THE DIRECTOR

If you've been following the *CNST News* for any period of time, you probably understand that the Center for Nanoscale Science and Technology is a user facility with a unique design. It has two parts, the NanoFab and the NanoLab, with the NanoFab offering easy access to a full set of commercial state-of-the-art fabrication and measurement technology and the NanoLab offering potential solutions to problems that reach beyond current, commercial measurement or fabrication solutions. So, it is natural to think of the NanoFab as the "go to" destination for a nanotech measurement requirement. However, a rather broad spectrum of nanotechnology measurement solutions exist within the NanoLab and are available for use through collaboration. This issue illustrates three of those opportunities.

The research described on page three makes use of a unique instrument, an Environmental Scanning Transmission Electron Microscope (ESTEM) with Raman spectroscopy incorporated into the heart of the microscope by the CNST. It allows one to focus (literally) on the atomic scale to determine stoichiometry and structure while using spectroscopy to monitor both the chemistry and the temperature — all at the temperatures and pressures typical of the catalytic reactions we want to better understand.

On page four, a probe is described that uses electrons in a very different way. Here the CNST's low temperature scanning tunneling microscope is used to form a circular potential barrier on a graphene surface. This barrier constrains the electrons to propagate around its edge in a so-called "whispering gallery mode", emulating the phenomena that allows sound to propagate long distances within the dome of St. Paul's Cathedral in London and adding a new tool to our kit for controlling and focusing electrons on surfaces.

Finally, the article on page six explains how a variety of tools, including scanning and Auger electron microscopy and photoelectron spectroscopy, are used to explore what's happening beneath the surface in solid-state batteries. The changing terrain those ions see as they move nanoscale distances accounts for the degradation of the battery with use. By facilitating access to nanoscale techniques and tools, such as those described on page six, we hope, working with our interested users, to better understand how the changing structure affects performance and ultimately play a role in extending battery lifetimes.

If you have a challenging nanofabrication or nanoscale measurement problem, you may want to see whether ongoing research in CNST's NanoLab could help. To see if we are already working on your problem or might have the necessary expertise to help solve it, check the CNST webpages or look in the NanoLab section of the CNST brochure.

Robert Celotta

DOUBLE VISION: NIST TECHNIQUE OFFERS WAY TO SEE THE NANOSCALE ‘FOREST’ AND ‘TREE’ SIMULTANEOUSLY

A close up view of an individual tree won’t tell you much about what’s going on in the forest. The same goes for studying collections of nanoparticles. What is happening on one nanoparticle may not be indicative of what’s going on with the group as a whole. In fact, just as shining a light on a single plant to observe it will lead to an overestimate of the average growth rate, the electron beam that you shine on nanoparticles to see them may actually affect the reaction processes, giving a skewed reading.

To correct for this experimental myopia, researchers at the National Institute of Standards and Technology (NIST) have developed a relatively simple setup that makes it possible for scientists to image individual nanoscale features and collect microscale (nano x1,000) chemical information simultaneously. Their approach combines two powerful analysis tools, environmental scanning transmission electron microscopy (ESTEM), a variation on traditional electron microscopes that enables researchers to view a specimen in a reactive gas environment—i.e. not in a vacuum—and Raman spectroscopy, which uses light interactions to identify molecular structures from their characteristic vibrations. Their description of the development of the new imaging setup appeared in the journal *Ultramicroscopy*.

Having such a combined close-up and wide-angle view of nanoparticle behavior, allows researchers to understand both what the nanoparticles are doing and how they are doing it. It also ensures that researchers have enough information to make sure they are not being fooled by any unusual effects that could be caused by the electron beam. Such comprehensive and reliable data would be useful to scientists working in a broad range of research areas from nanotechnology to pharmaceuticals and biotechnology.

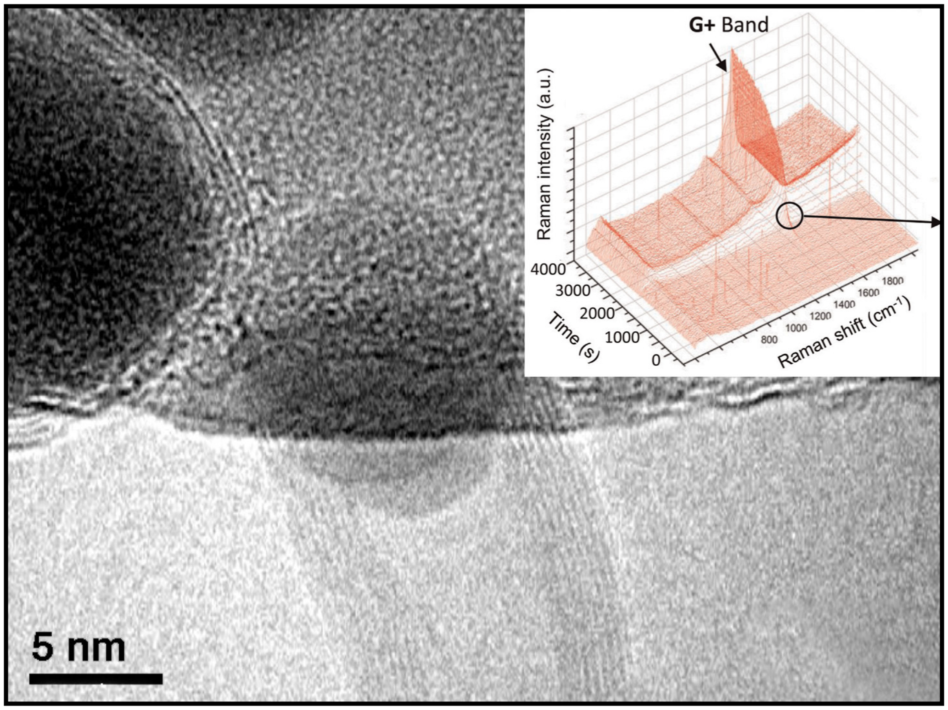


Image of a multi-wall CNT growing from a nanoscale catalyst particle. **Inset:** Plot of the Raman spectrum as a function of time during carbon nanotube growth at 625°C in a low pressure (10^{-3} Pa) atmosphere of acetylene (C_2H_2). After an initial nucleation period, the signal from the G+ band, characteristic of the graphene that makes up the walls of the carbon nanotubes, appears and rises rapidly, before increasing at a constant rate. This indicates that, once they have formed, the nanotubes grow at a constant rate.

The team’s technique consists of inserting a tiny, diamond-machined, parabolic mirror attached to a hollow rod below the sample they wish to study. The parabolic mirror serves two purposes. It focuses the light from a source, such as a laser, outside the ESTEM, that passes through the hollow rod, onto the sample to excite it and collects the sample’s response to that excitation, i.e. the Raman spectra, for analysis. The Raman signal comes from an area about a million times bigger than the area that can be seen at the atomic scale with the electron beam. That way, the close-up data from the images can be compared with the “wide-angle” view of the chemistry to make sure it all matches up correctly.

As a bonus, according to NIST researcher Renu Sharma, measuring the shifts in Raman signal energy also enables them to measure the local temperature of a sample region – which is normally very hard to do – letting them make accurate measurements of the chemical kinetics.

“Most importantly, the ESTEM-Raman combination will provide us with the unique opportunity to study gas and temperature effects on technologically important nanostructures,” says Sharma. “For example, the morphology or make-up of nanoscale structures may change as function of temperature, environment and time, thus degrading their efficiency or performance. Being able to see exactly what’s going on may enable the production of better, longer-lasting nanostructures.”

Finally, while the technique was initially developed to enable Raman spectroscopy of the sample, the parabolic mirror can also collect light generated when the electron beam interacts with the sample. This light contains masses of useful information on things like the energy levels in nanoscale semiconductor structures and the surface plasmons on metal nanoparticles. All of this data can be used to help understand the essential link between structure and properties on the nanoscale.

While the system was developed for use with an ESTEM, the vibrational and optical spectroscopy elements the group developed can be adapted for any transmission electron microscope column.

Vibrational and optical spectroscopies integrated with environmental transmission electron microscopy, M. Picher, S. Mazzucco, S. Blankenship, and R. Sharma, *Ultramicroscopy* **150**, 10–15 (2015).

FIRST WHISPERING GALLERY FOR GRAPHENE ELECTRONS

A CNST-led international research group has developed a technique for creating nanoscale whispering galleries for electrons in graphene. The development opens the way to building devices that focus and amplify electrons just as lenses focus light and resonators (like the body of a guitar) amplify sound.

In some structures, such as the dome in St. Paul's Cathedral in London, a person standing near a curved wall can hear the faintest sound made along any other part of that wall. This phenomenon, called a whispering gallery, occurs because sound waves reflect along a curved surface and re-inforce themselves for certain frequencies to create the whispering gallery modes. Using this same principle, scientists have built whispering galleries for light waves as well, and whispering galleries are found in applications ranging from sensing, spectroscopy and communications to the generation of laser frequency combs.

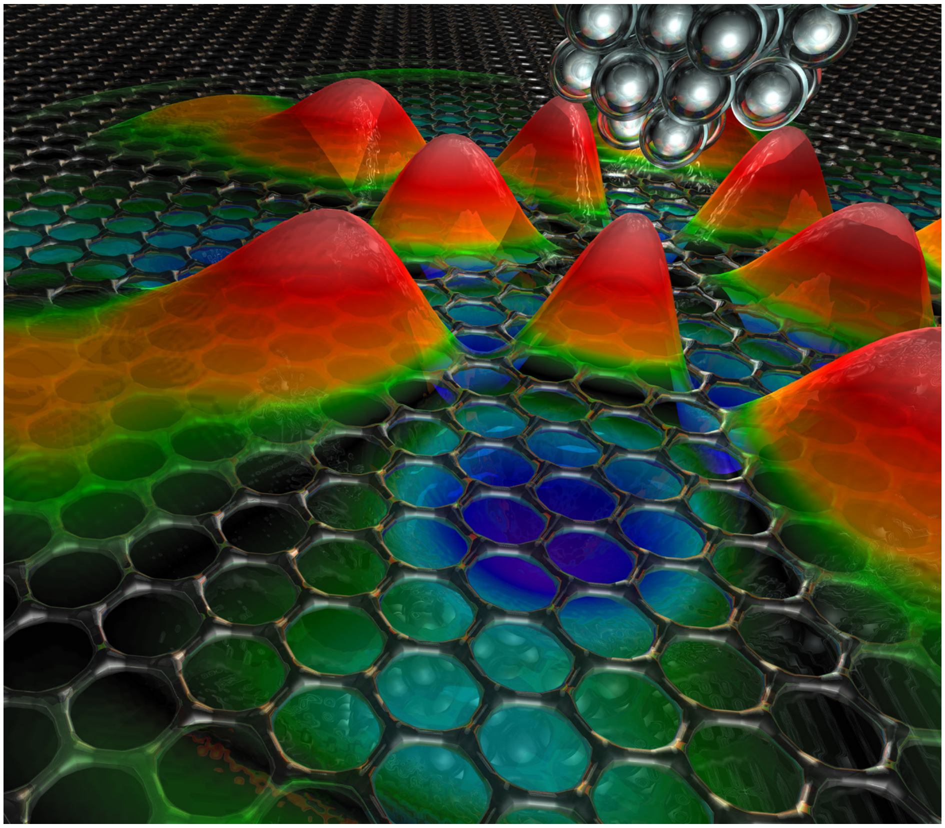
"The cool thing is that we made a nanometer scale electronic analogue of a classical wave effect," said NIST Fellow Joe Stroscio, who led the research team. "These whispering galleries are unlike anything you see in any other electron based system, and that's really exciting."

Ever since graphene, a single layer of carbon atoms arranged in a honeycomb lattice, was first created in 2004, the material has impressed researchers with its strength, ability to conduct electricity and heat and many interesting optical, magnetic and chemical properties.

However, early studies of the behavior of electrons in graphene were hampered by defects in the material. As the manufacture of clean and near-perfect graphene becomes more routine, scientists are beginning to uncover its full potential.

When moving electrons encounter a potential barrier in conventional semiconductors, it takes an increase in energy for the electron to continue flowing. As a result, they are often reflected, just as one would expect from a ball-like particle.

However, because electrons can sometimes behave like a wave, there is a calculable chance that they will ignore the barrier altogether, a phenomenon called tunneling. Due to the light-like properties of graphene electrons, they can pass through unimpeded—no matter how high the barrier—if they hit the barrier head on. This tendency to tunnel makes it hard to steer electrons in graphene.



Using the voltage from a scanning tunneling microscope tip (top) to push graphene electrons out of a nanoscale area, the researchers created a whispering gallery (centered on the dark blue area on the graphene surface), which is like a circular wall of mirrors to the electron.

Enter the graphene electron whispering gallery.

To create a whispering gallery in graphene, the team first enriched the graphene with electrons from a conductive plate mounted below it. With the graphene now crackling with electrons, the research team used the voltage from a scanning tunneling microscope (STM) to push some of them out of a nanoscale-sized area. This created the whispering gallery, which is like a circular wall of mirrors to the electron.

"An electron that hits the step head-on can tunnel straight through it," said CNST researcher Nikolai Zhitenev. "But if electrons hit it at an angle, their waves can be reflected and travel along the sides of the curved walls of the barrier until they began to interfere with one another, creating a nanoscale electronic whispering gallery mode."

The team can control the size and strength, i.e., the leakiness, of the electronic whispering gallery by varying the STM tip's voltage. The probe not only creates whispering gallery modes, but can detect them as well.

CNST/UMD Postdoctoral Researcher Yue Zhao fabricated the high mobility device and performed the measurements with her colleagues Fabian Natterer and Jon Wyrick. A team of theoretical physicists from the Massachusetts Institute of Technology developed the theory describing whispering gallery modes in graphene.

Graphene-based quantum electronic resonators and lenses have as yet untold potential, but if conventional optics is any guide, the ramifications could be huge.

Creating and probing electron whispering-gallery modes in graphene, Y. Zhao, J. Wyrick, F. D. Natterer, J. F. Rodriguez-Nieva, C. Lewandowski, K. Watanabe, T. Taniguchi, L. S. Levitov, N. B. Zhitenev, and J. A. Stroscio, *Science* **348**, 672–675 (2015).

GOOD VIBRATIONS: MEASURING PHONONS IN GRAPHENE

CNST scientists, leading a worldwide group of researchers, have developed a method for measuring crystal vibrations in graphene. Understanding these vibrations is a critical step toward controlling future technologies based on graphene, a one-atom thick form of carbon.

Carbon atoms in graphene sheets are arranged in a regularly repeating honeycomb-like lattice—a two-dimensional crystal. Like other crystals, when enough heat or other energy is applied, the forces that bond the atoms together cause the atoms to vibrate and spread the energy throughout the material, akin to how the vibration of a violin's string resonates throughout the body of the violin when played.

And just like every violin has its own unique character, each material vibrates at unique frequencies. The collective vibrations, which have frequencies in the terahertz-range (a billion billion oscillations per second), are called phonons.

Understanding how phonons interact gives clues as to how to put in, take out or move energy around inside a material. In particular, finding effective ways to remove heat energy is vital to the continued miniaturization of electronics.

One way to measure these tiny vibrations is to bounce electrons off the material and measure how much energy the electrons have transferred to the vibrating atoms. But it's difficult. The technique, called inelastic electron tunneling spectroscopy, elicits only a small blip that can be hard to pick out over more raucous disturbances.

"Researchers are frequently faced with finding ways to measure smaller and smaller signals," says CNST/SNSF Postdoctoral Researcher Fabian Natterer, "To suppress the chaos and get a grip on the small signals, we use the very distinct properties of the signal itself."

Unlike a violin that sounds at the lightest touch, according to Natterer, phonons have a characteristic threshold energy. That means they won't vibrate unless they get just the right amount of energy, such as that supplied by the electrons in a scanning tunneling microscope (STM).

To filter the phonons' signal from other distractions, the researchers used their STM to systematically alter the number of electrons moving through their graphene device. As the number of electrons were varied, the unwanted signals also varied in energy, but the phonons remained fixed at their characteristic frequency. Averaging the signals over the different electron concentrations diluted the annoying disturbances, but reinforced the phonon signals.

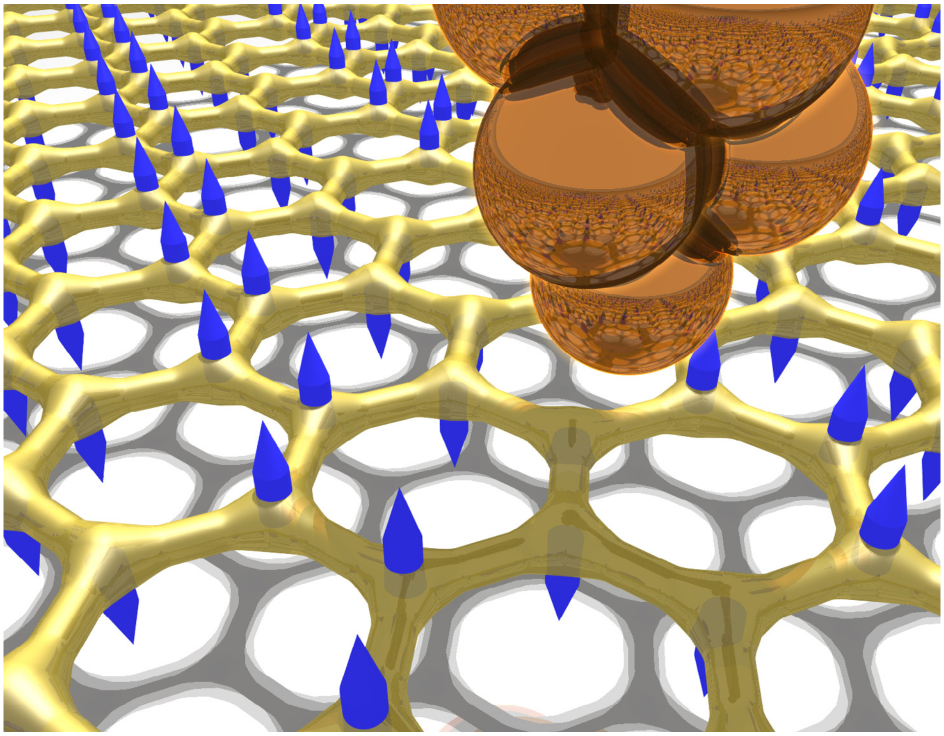
The team was able to map all the graphene phonons this way, and their findings agreed well with their Georgia Tech collaborators' theoretical predictions.

According to NIST Fellow Joe Stroscio, learning to pick out the phonons' signal enabled them to observe a peculiar and surprising behavior.

"The phonon signal intensity fell off sharply when we switched the graphene charge carrier from holes to electrons—positive to negative charges," says Stroscio. "A clue to what's initially enhancing the phonons' signals and then causing them to fall off are whispering gallery modes, which become filled with electrons and stop the phonons from vibrating when we switch from hole to electron doping."

The team notes that this effect is similar to resonance-induced effects seen in small molecules. They speculate that if the same effect were happening here, it could mean that the system—graphene and STM—is mimicking a giant molecule, but say that they still don't have a firm theoretical foundation for what's happening.

The high purity graphene device was fabricated by CNST/UMD Postdoctoral Researcher in the CNST NanoFab.



Credit: Wyrick/NIST

Tunneling electrons from a scanning tunneling microscope tip excite phonons in a graphene lattice. Blue arrows indicate the direction of moving carbon atoms for one of the low-energy phonon modes.

Strong asymmetric charge carrier dependence in inelastic electron tunneling spectroscopy of graphene phonons, F. D. Natterer, Y. Zhao, J. Wyrick, Y.-H. Chan, W.-Y. Ruan, M.-Y. Chou, K. Watanabe, T. Taniguchi, N. B. Zhitenev, and J. A. Stroscio, *Physical Review Letters* **114**, 245502 (2015).

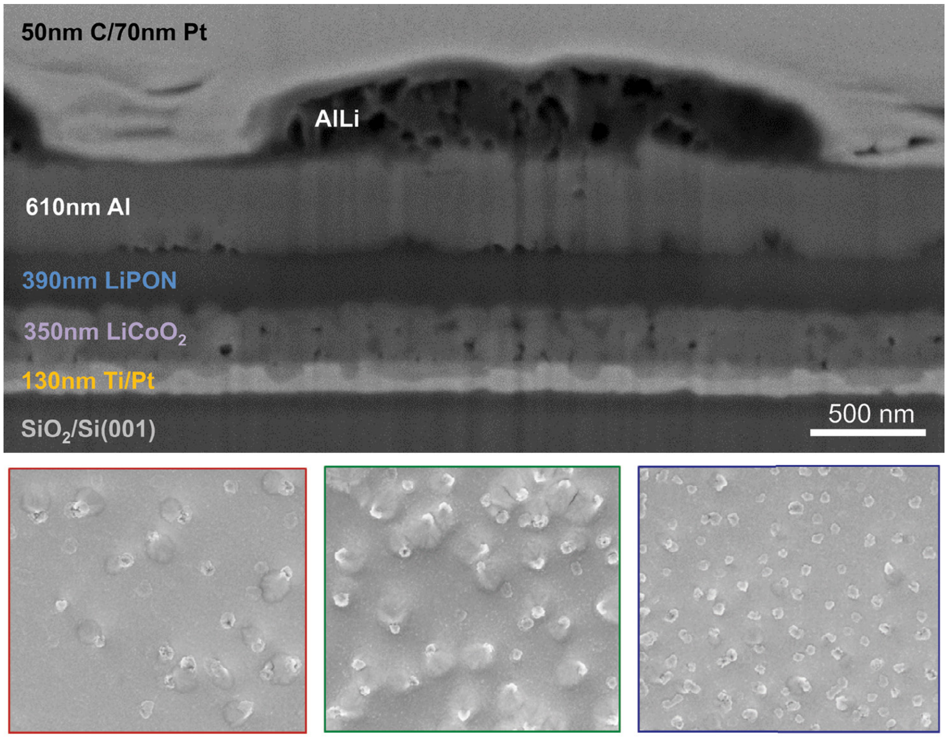
OXIDATION ON ALUMINUM ANODES DEGRADES PERFORMANCE OF SOLID STATE BATTERIES

Researchers working at the CNST, the University of Maryland, and Sandia National Laboratories, have for the first time imaged the inner workings of experimental solid-state batteries as they charged and discharged while making detailed measurements of their electrochemical health. Their work has helped explain why the batteries rapidly lose performance and suggests a way for improving them.

While most batteries on the market today have liquid electrolytes, solid-state batteries have, as the name implies, a solid one. Not needing a liquid makes these batteries amenable to high throughput manufacturing techniques and opens the door to making them smaller, safer, thinner, and even flexible. In fact, the entire battery assembly can be little more than a few micrometers thick.

In commercially available lithium-ion batteries used in cell phones, for example, the anode (the side of the battery where electrons flow out to a circuit) is usually made of carbon. But in these new solid-state batteries, scientists have been experimenting with other materials, including aluminum because it's so light, an important consideration for mobile devices. These batteries' performance degrades rapidly after a small number of charge and discharge cycles. In fact, they lose 90 percent of their capacity after 10 cycles. What no one knew was why.

According to University of Maryland researcher Marina Leite, most of the work on imaging large areas of solid-state batteries has only shown snapshots of the device before and after charging it. "In effect, they are post mortems of a battery in which you try to infer what happened as the battery was charging or discharging," says Leite. "In our case, we could follow as the morphology changed on the anode's surface and track how it impacted the performance of the battery, quantifying the capacity loss while charging and discharging the battery and mimicking what happens when a battery is in use."



Top: A cross-section scanning electron microscope image of a representative Al anode all-solid-state thin-film battery before cycling. **Bottom:** Top down scanning electron microscope images showing the how the aluminum anode surface evolves during the first cycling step. By increasing the charging current, the density of clusters also increases (red shows the effect of 10 nanoamps after 50 minutes, green is 20 nanoamps at 17 minutes, and blue is 30 nanoamps at 3 minutes), indicating that the aluminum–lithium alloy formation is a kinetically driven process.

The imaging technique can be used with any solid state battery. It combines a number of different tools including photoelectron spectroscopy, scanning electron microscopy and Auger electron microscopy (which analyzes electrons emitted by excited atoms to determine the elemental composition of a surface) under high vacuum. The setup enables the team to precisely control the lithium reaction rate, the battery state-of-charge and state-of-discharge, record the electrochemical potential, and to correlate these parameters with specific changes in the electrode's structure and chemical composition.

Their experiments revealed that the batteries' performance degrades due to oxidation of the surface of the aluminum anode. The aluminum oxide, which appear as cottage cheese-like lumps, captures lithium ions and prevents them from returning to the cathode during recharging. Fewer lithium ions in the cathode means the returning electrons have fewer places to return to, progressively reducing the batteries' energy capacity.

"The formation of an alloy at the surface of the anode strongly suggests that in order to successfully use aluminum as an electrode its surface needs to be protected by adding a different material that will not alloy," says CNST Project Leader Andrei Kolmakov.

Leite further notes that new research will focus on the anode's surface-driven reactions and the critical role they play in the ultimate performance of these types of batteries, instead of the electrolyte/anode interface as is common with other battery architectures.

Insights into capacity loss mechanisms of all-solid-state Li-ion batteries with Al anodes, M. S. Leite, D. Ruzmetov, Z. Li, L. A. Bendersky, N. C. Bartelt, A. Kolmakov, and A. A. Talin, *Journal of Materials Chemistry* A 2, 20552–20559 (2014).

MIND THE GAP: NANOSCALE SPEED BUMP COULD REGULATE PLASMONS FOR HIGH-SPEED DATA FLOW

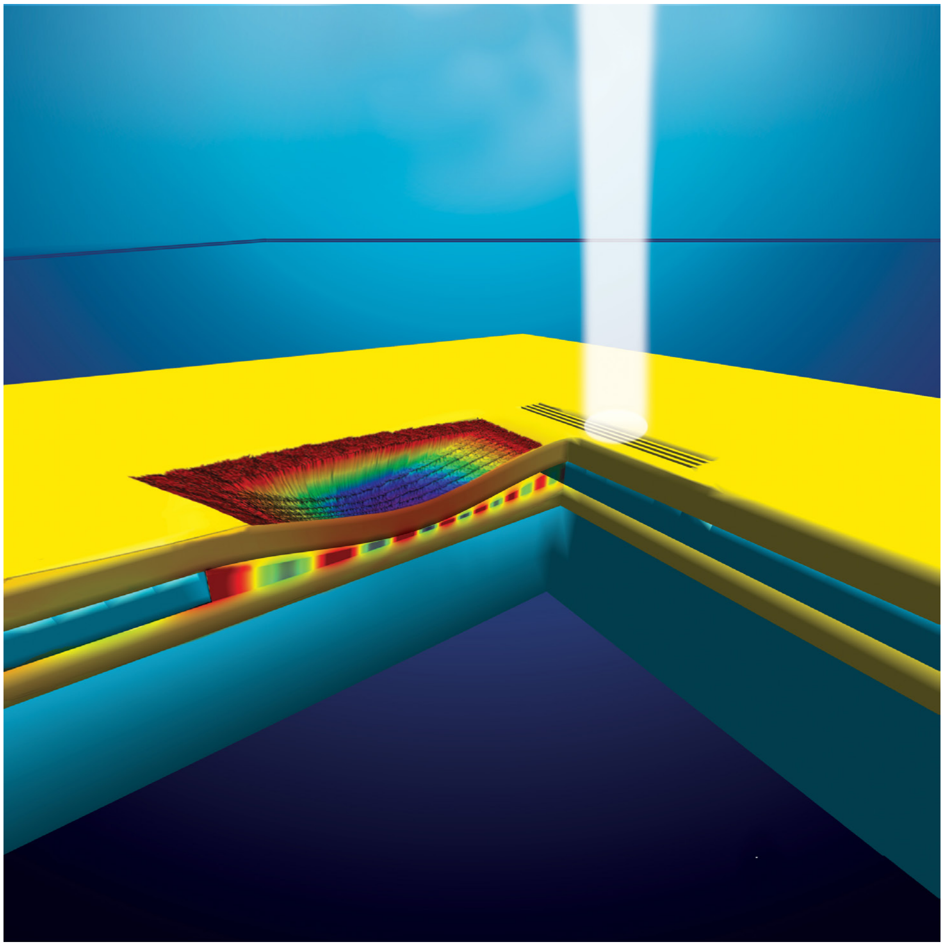
The name sounds like something Marvin the Martian might have built, but the "nanomechanical plasmonic phase modulator" is not a doomsday device. Developed by a team of government and university researchers, including scientists from the CNST, the innovation harnesses tiny electron waves called *plasmons*. It's a step towards enabling computers to process information hundreds of times faster than today's machines.

Computers currently shuttle information around using electricity traveling down nanoscale metal wires. Although inexpensive and easy to miniaturize, metal wires are limited in terms of speed due to the resistance in the metal itself. Fiber optics use light to move information about 10,000 times faster, but these and other nonmetallic waveguides are constrained by pesky physical laws that require critical dimensions to be at least half the wavelength of the light in size; still small, but many times larger than the dimensions of current commercial nanoscale electronics.

Plasmonics combines the small size and manufacturability of electronics with the high speeds of optics. When light waves interact with electrons on a metal's surface, strong fields with dimensions far smaller than the wavelength of the original light can be created—plasmons. Unlike light, these plasmons are free to travel down nanoscale wires or gaps in metals.

The team, which included researchers from Rutgers, the University of Colorado at Colorado Springs, and Argonne National Laboratory, fabricated their device using commercial nanofabrication equipment at the CNST NanoFab. Small enough to serve in existing and future computer architectures, this technology may also enable electrically tunable and switchable thin optical components.

The plasmonic phase modulator is effectively an inverted, nanoscale speed bump. Eleven gold strands are stretched side by side like footbridges across a 23-micrometer gap just 270 nanometers above the gold surface below them. Incoming plasmons, created by laser light at one end of the array, travel though this air gap between the bridges and the bottom gold layer.



The plasmonic phase modulator is an inverted, nanoscale speed bump. Gold strands are stretched side by side across a gap just 270 nanometers above the gold surface below them. Incoming plasmons travel though this air gap between the bridges and the bottom gold layer. Lowering the "bump" with a control voltage that squeezes the gap and makes the device function like a plasmon phase modulator.

When a control voltage is applied, electrostatic attraction bends the gold strands downwards into a U shape. At a maximum voltage—close to the voltages used in today's computer chips—the gap narrows, slowing the plasmons. As the plasmons slow, their wavelength becomes shorter, allowing more than an extra half of a plasmonic wave to fit under the bridge. Because it's exactly out of phase with the original wave, this additional half wavelength can be used to selectively cancel the wave, making the bridge an optical switch.

At 23 micrometers, the prototype is relatively large, but according to CNST researcher Vladimir Aksyuk, their calculations show that the device could be shortened by a factor of 10, scaling the device's footprint down by a factor of 100. According to these calculations, the modulation range can be maintained without increase in the optical loss, as the length and the size of the gap are reduced.

"With these prototypes, we showed that *nanomechanical* phase tuning is efficient," says Aksyuk. "This effect can be generalized to other tunable plasmonic devices that need to be made smaller. And as they get smaller, you can put more of them on the same chip, bringing them closer to practical realization."

Compact nanomechanical plasmonic phase modulators, B. S. Dennis, M. I. Haftel, D. A. Czaplewski, D. Lopez, G. Blumberg, and V. A. Aksyuk, *Nature Photonics* **9**, 267–273 (2015).

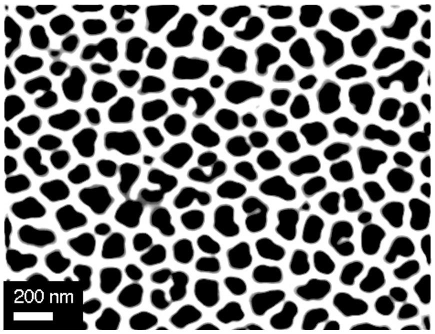
NEW ATOMIC LAYER DEPOSITION TECHNIQUE COATS HIGH-ASPECT-RATIO NANOPOROUS MEMBRANES WITH PLATINUM

Engineers in the CNST NanoFab have used atomic layer deposition (ALD) to make a conformal coating of platinum inside a high-aspect-ratio (60 µm high with a 0.2 µm diameter) nanoporous anodic alumina membrane (AAO). High-surface membranes of this type have been in great demand for applications ranging from catalysis to fuel cells to biosensors.

By demonstrating that ALD can be used to coat platinum, the researchers' results provide a pathway to introducing self-assembled monolayers of thiol molecules which can adhere to the platinum. A range of proteins can then be immobilized by the thiol layer. The high aspect ratio increases the exposed surface area, resulting in functionalized membranes with protein concentrationsapproximately two orders of magnitude greater than on a planar substrate. This increased surface area opens up the possibility of numerous novel applications in biosensing.

With more typical physical and chemical vapor deposition techniques, thin films are deposited on top of the substrate, where they typically cover the tops of nanopores rather than coating inside them. ALD forms a thin film on the surface by a self-limiting chemical reaction at the interface between the coating material and the substrate, allowing the material to infiltrate inside the structures instead of aggregating on the top. ALD has been demonstrated as an effective technique for the conformal coating of metal oxides inside high aspect ratio AAO structures, but until now only limited penetration depth has been achieved inside high-aspect nanostructures when ALD is used with metals.

The engineers tuned the process deposition temperature and precursor exposure time in order to enhance both the infiltration depth and the conformal coating of the platinum inside the AAO membranes. They then used cross-sectional scanning electron microscopy, energy dispersive x-ray spectroscopy, and small angle neutron scattering to analyze the platinum coverage and layer thickness inside the AAO nanopores.



Top view scanning electron micrograph of a nanoporous anodic alumina membrane.

According to the engineers, their conformal coating technique is potentially very useful for making high-aspect-ratio surfaces and other structures with high surface to volume ratios for use in conjunction with functional materials with a broad range of biological and catalytic applications.

Enhancing the platinum atomic layer deposition infiltration depth inside anodic alumina nanoporous membrane, A. Vaish, S. Krueger, M. Dimitriou, C. Majkrzak, D. J. Vanderah, L. Chen, and K. Gawrisch, *Journal of Vacuum Science & Technology A* **33**, 01A148 (2015).

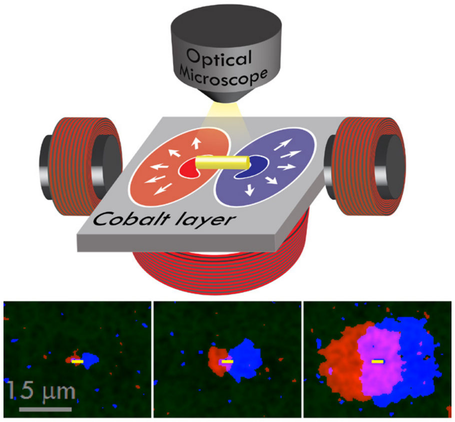
MAGNETO-OPTICAL TECHNIQUE MEASURES FIELDS FROM INDIVIDUAL MAGNETIC NANOPARTICLES

In two recent studies, CNST scientists showed that the thin layers of magnetic cobalt they had developed to study the fundamental physics of magnetic noise, also function as extremely sensitive magnetic sensors. The researchers demonstrated these new sensors by measuring the magnetic properties of nickel particles only a few billionths of a meter wide.

Using thin cobalt layers as sensors has significant advantages over other sensing methods. The material has an intrinsic amplification property, which transforms the extremely small magnetic signature of a nanoparticle into a much larger optical signal for easy and rapid measurement. The optical nature of the method furthermore allows measurement of many particle simultaneously under a microscope objective, yielding a multiplicative speedup over other techniques.

The researchers believe their work is an example of how fundamental research in measurement science often has applications in practical technologies. The tiny magnetic particles they studied are widely used for nanoscale diagnostics, therapeutics, and robotics but, until now, could not be rapidly characterized on an individual particle basis. The sensing layers can function without cryogens or vacuum, making the technique accessible to the hundreds of laboratories around the world involved in magnetic research.

According to CNST/UMD Postdoctoral Researcher Andy Balk, scientists will be able to use this technique to finely tune the magnetic properties of small magnetic particles and devices, which could lead to advances in medical therapeutics, diagnostics, and nanorobotics.



Top: A thin cobalt layer (gray) detects the magnetic state of the nickel nanoparticle sample (yellow). Tiny magnetic fields from the nanoparticle sample (small red and blue shapes) are amplified (white arrows) by an electromagnet (red coil underneath the cobalt layer) into much larger signals (large red and blue ovals). The scientists monitored how these amplified signals changed in response to magnetic field from a set of electromagnets mounted on either side of the cobalt layer (red coils, right and left). A microscope objective for measurement is shown schematically above the cobalt layer. **Bottom:** Experimental data showing amplification of the otherwise invisible signal from the sample nanorod.

Critical behavior of zero-field magnetic fluctuations in perpendicularly magnetized thin films, A. L. Balk, M.D. Stiles, and J. Unguris, *Physical Review B* **90**, 184404 (2014).

Magnetometry of single ferromagnetic nanoparticles using magneto-optical indicator films with spatial amplification, A. L. Balk, C. Hangarter, S. M. Stavis, and J. Unguris, *Applied Physics Letters* **106**, 112402 (2015).

VLADIMIR AKSYUK ELECTED FELLOW OF THE AMERICAN PHYSICAL SOCIETY

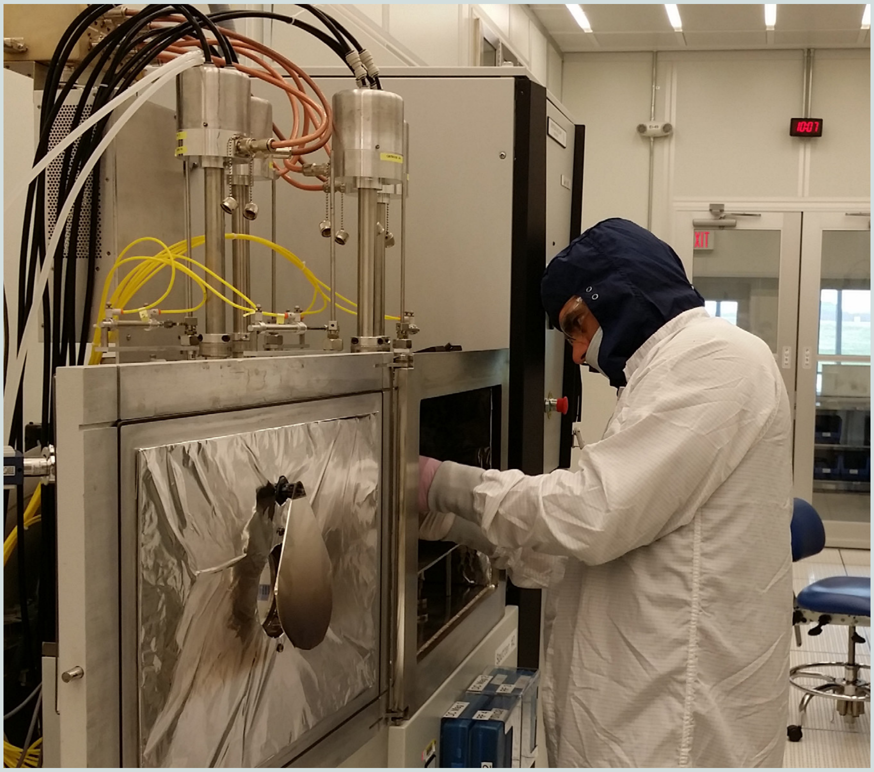
CNST researcher Vladimir Aksyuk has been elected a Fellow of the American Physical Society (APS). His fellowship citation notes his "contributions to the development of integrated photonic and mechanical microsystems, for pioneering work in using such systems to enable both telecommunications and novel nanoscale, high-throughput, measurement methods, and for contributions to the understanding of the Casimir force." Fellows comprise no more than one half of one percent of the APS membership. This status is awarded to recognize outstanding contributions to physics. His name and fellowship citation were published in the March 2015 issue of *APS News*.

Aksyuk is a Project Leader in the Nanofabrication Research Group. He received a B.S. in Physics from Moscow Institute of Physics and Technology and a Ph.D. in Physics from Rutgers University. Following research as a Member of Technical Staff and then Technical Manager at Bell Labs, he joined the research staff at NIST. Vladimir's research focuses on the design and fabrication of novel optical microelectromechanical systems (MEMS). He holds more than 30 patents, and has published over 40 papers. In 2000 he received the Bell Labs President's Gold Award, in 2005 was named among MIT Technology Review magazine's TR35, and in 2008 received a Distinguished Alumni award for Early Career Accomplishments from Rutgers Graduate School. He is currently developing multiple schemes to use optical MEMS and nanoelectromechanical systems (NEMS) to address problems in nanomanufacturing.

He was presented with his fellowship certificate at the meeting of the Forum on Industrial and Applied Physics on March 3, 2015 at the APS March Meeting in San Antonio, TX.

Vladimir Aksyuk has been elected a Fellow of the American Physical Society .

LEARNING CLEANROOM SKILLS THROUGH HANDS-ON EXPERIENCE



Paul Barrett, an Undergraduate Researcher in the NanoFab Operations Group, adjusting the Denton Discovery 550 sputtering system. Paul recently completed a 12-week internship working in the CNST NanoFab as part of a program with the Northeast Advanced Technological Education Center. The internship at the CNST provides an opportunity to gain hands-on training and experience working in a nanotechnology facility. The experience gained from this internship helps qualify students to compete for highly skilled jobs working as an engineering technician in semiconductor manufacturing. These jobs can pay as much as $50,000 to $60,000 per year. At the CNST, Paul supported the NanoFab staff, assisting in regular equipment repair and maintenance.

ROBERT CELOTTA, DANIEL PIERCE, AND JOHN UNGURIS SHARE 2015 KEITHLEY AWARD FOR ADVANCES IN MEASUREMENT SCIENCE

CNST researchers Robert Celotta, Daniel Pierce, and John Unguris were honored with the 2015 Joseph F. Keithley Award for Advances in Measurement Science. The three researchers were cited for "the invention and development of electron spin sources and detectors, and their application to measurement science."

Robert Celotta, Daniel Pierce, and John Unguris were honored with the 2015 Joseph F. Keithley Award for Advances in Measurement Science.

The Keithley Award recognizes physicists who have been instrumental in the development of measurement techniques or equipment that have impact on the physics community by providing better measurements. It is made annually to one or a few individuals working in the same area and is endowed by Keithley Instruments, Inc. and the Instrument and Measurement Science Topical Group. The award was created to honor Joseph F. Keithley for his outstanding contributions and numerous accomplishments in the area of sensitive and precision instrument development and measurement techniques. Recipients receive a prize of $5,000 and a certificate citing their contributions.

Robert Celotta is the current and founding Director of NIST's Center for Nanoscale Science and Technology. During his career at NIST, he was a long-time Leader of the Electron Physics Group. His primary research activities have included nanomagnetics, magnetic imaging, the use of scanning tunneling microscopy for nanostructure characterization and assembly, the optical control of free atoms, and the generation, detection, and application of free electron polarization to measurement.

Daniel T. Pierce is a NIST Fellow Emeritus. As a Postdoctoral Researcher at ETH-Zurich working on early spin-polarized photoemission studies, Dan and his collaborators, H.C. Siegmann and F. Meier, discovered spin-polarized photoemission from gallium arsenide. This discovery formed the basis for the spin polarized electron gun developed by Pierce and coworkers when he joined the NIST in 1975. The polarized electron gun was applied to studies of surface magnetism and aided the invention (with Celotta and Unguris) of a low-energy, fist-sized spin-polarization analyzer ideal for scanning electron microscopy with polarization analysis, a high-resolution magnetic imaging technique.

CNST Electron Physics Group Project Leader John Unguris joined NIST as a National Research Council postdoctoral research associate investigating the application of electron spin measurements to various surface-sensitive spectroscopies. This work led to the development (in collaboration with Pierce and Celotta) of an electron microscopy technique for directly imaging magnetic nanostructures, scanning electron microscopy with polarization analysis (SEMPA). He has since used SEMPA to measure the magnetic properties of a wide variety of structures, including ultrathin patterned magnetic films, oscillatory exchange-coupled magnetic multilayers, and multiferroic heterostructures.

Celotta, Pierce, and Unguris were presented with the award on March 2, 2015 during a special session at the American Physical Society March Meeting in San Antonio, TX.

RECENT PUBLICATIONS BY CNST STAFF RESEARCHERS

Below is a list of recent publications by CNST staff researchers. Visit the CNST Publications Portal (nist.gov/cnst/pubs/index.cfm) to view full text versions of these papers and a complete list of publications from research supported by the CNST, including work performed in the NanoFab and by CNST grant recipients.

Compact nanomechanical plasmonic phase modulators, B. S. Dennis, M. I. Haftel, D. A. Czaplewski, D. Lopez, G. Blumberg, and V. A. Aksyuk, *Nature Photonics* **9**, 267–273 (2015).

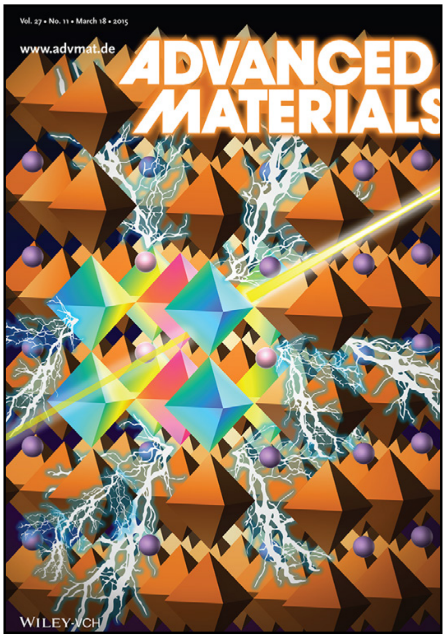
Electrical conductivity and grain boundary composition of Gd-doped and Gd/Pr co-doped ceria, W. J. Bowman, J. Zhu, R. Sharma, and P. A. Crozier, *Solid State Ionics* **272**, 9–17 (2015).

Absorption spectroscopy and imaging from the visible through mid-infrared with 20 nm resolution, A. M. Katzenmeyer, G. Holland, K. Kjoller, and A. Centrone, *Analytical Chemistry* **87**, 3154–3159 (2015).

Magnetometry of single ferromagnetic nanoparticles using magneto-optical indicator films with spatial amplification, A. L. Balk, C. Hangarter, S. M. Stavis, and J. Unguris, *Applied Physics Letters* **106**, 112402 (2015).

Photodetectors: high-gain and low-driving-voltage photodetectors based on organolead triiodide perovskites (Adv. Mater. 11/2015), R. Dong, Y. Fang, J. Chae, J. Dai, Z. Xiao, Q. Dong, Y. Yuan, A. Centrone, X. C. Zeng, and J. Huang, *Advanced Materials* **27**, 1967 (2015).

Vibrational and optical spectroscopies integrated with environmental transmission electron microscopy, M. Picher, S. Mazzucco, S. Blankenship, and R. Sharma, *Ultramicroscopy* **150**, 10–15 (2015).



Nonlinear ferromagnetic resonance shift in submicron Permalloy ellipses, F. Guo, L. M. Belova, and R. D. McMichael, *Physical Review B* **91**, 064426 (2015).

Near-field asymmetries in plasmonic resonators, V. Aksyuk, B. Lahiri, G. Holland, and A. Centrone, *Nanoscale* **7**, 3634–3644 (2015).

***In situ* SEM study of lithium intercalation in individual V_2O_5 nanowires**, E. Strelcov, J. Cothren, D. Leonard, A. Y. Borisevich, and A. Kolmakov, *Nanoscale* **7**, 3022–3027 (2015).

New insights into subsurface imaging of carbon nanotubes in polymer composites via scanning electron microscopy, M. Zhao, B. Ming, J.-W. Kim, L. J. Gibbons, X. Gu, T. Nguyen, C. Park, P. T. Lillehei, J. S. Villarrubia, A. E. Vladár, and J. A. Liddle, *Nanotechnology* **26**, 085703 (2015).

Probing electric field control of magnetism using ferromagnetic resonance, Z. Zhou, M. Trassin, Y. Gao, Y. Gao, D. Qiu, K. Ashraf, T. Nan, X. Yang, S. R. Bowden, D. T. Pierce, M. D. Stiles, J. Unguris, M. Liu, B. M. Howe, G. J. Brown, S. Salahuddin, R. Ramesh, and N. X. Sun, *Nature Communications* **6**, (2015).

Magnetic structure and anisotropy of [Co/Pd]$_5$/NiFe multilayers, L. Tryputen, F. Guo, F. Liu, T. N. A. Nguyen, M. S. Mohseni, S. Chung, Y. Fang, J. Åkerman, R. D. McMichael, and C. A. Ross, *Physical Review B* **91**, 014407 (2015).

Spin Hall effect and irreversible thermodynamics: center-to-edge transverse current-induced voltage, W. M. Saslow, *Physical Review B* **91**, 014401 (2015).

Enhancing the platinum atomic layer deposition infiltration depth inside anodic alumina nanoporous membrane, A. Vaish, S. Krueger, M. Dimitriou, C. Majkrzak, D. J. Vanderah, L. Chen, and K. Gawrisch, *Journal of Vacuum Science & Technology A* **33**, 01A148 (2015).

New ion source for high precision FIB nanomachining and circuit edit, A. V. Steele, B. Knuffman, and J. J. McClelland, *in Proceedings of the 40th International Symposium for Testing and Failure Analysis*, (Houston, TX, 2014), p. 293–297.

CNST Center for Nanoscale Science & Technology

CENTER FOR NANOSCALE SCIENCE AND TECHNOLOGY

The CNST is a national user facility purposely designed to accelerate innovation in nanotechnology-based commerce. Its mission is to operate a national, shared resource for nanoscale fabrication and measurement and develop innovative nanoscale measurement and fabrication capabilities to support researchers from industry, academia, NIST, and other government agencies in advancing nanoscale technology from discovery to production. The Center, located in the Advanced Measurement Laboratory Complex on NIST's Gaithersburg, MD campus, disseminates new nanoscale measurement methods by incorporating them into facility operations, collaborating and partnering with others, and providing international leadership in nanotechnology.

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SUPPORTING THE DEVELOPMENT OF NANOTECHNOLOGY FROM DISCOVERY TO PRODUCTION

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CNST TO HOST WORKSHOP ON ADVANCING NANOPARTICLE MANUFACTURING

On October 7th and 8th, the CNST will host a two-day workshop, *Advancing Nanoparticle Manufacturing*, in Building 215, Room C103 - 106.

Following decades of research and development, commercial products enabled by nanoparticles are poised to have broad impact in diverse sectors of the global economy, ranging from electronics to healthcare to energy. However, applications of nanoparticles remain limited by challenges at all stages of the manufacturing process, from production and purification, to characterization and integration of nanoparticles into products.

The workshop will gather experts from across industry, government, and academia to discuss these technical challenges, as well as application forecasts and market insights, determining the path forward in nanoparticle manufacturing. In particular, *Advancing Nanoparticle Manufacturing* will focus on the manufacturing of nanoscale particles, rods, and tubes in the liquid phase.

ADVANCING NANOPARTICLE MANUFACTURING

This NIST Workshop is being held under the auspices of the NIST Nanomanufacturing Initiative. To learn more, including information about speakers, registration, and accommodations, please visit http://www.nist.gov/cnst/anm.cfm.