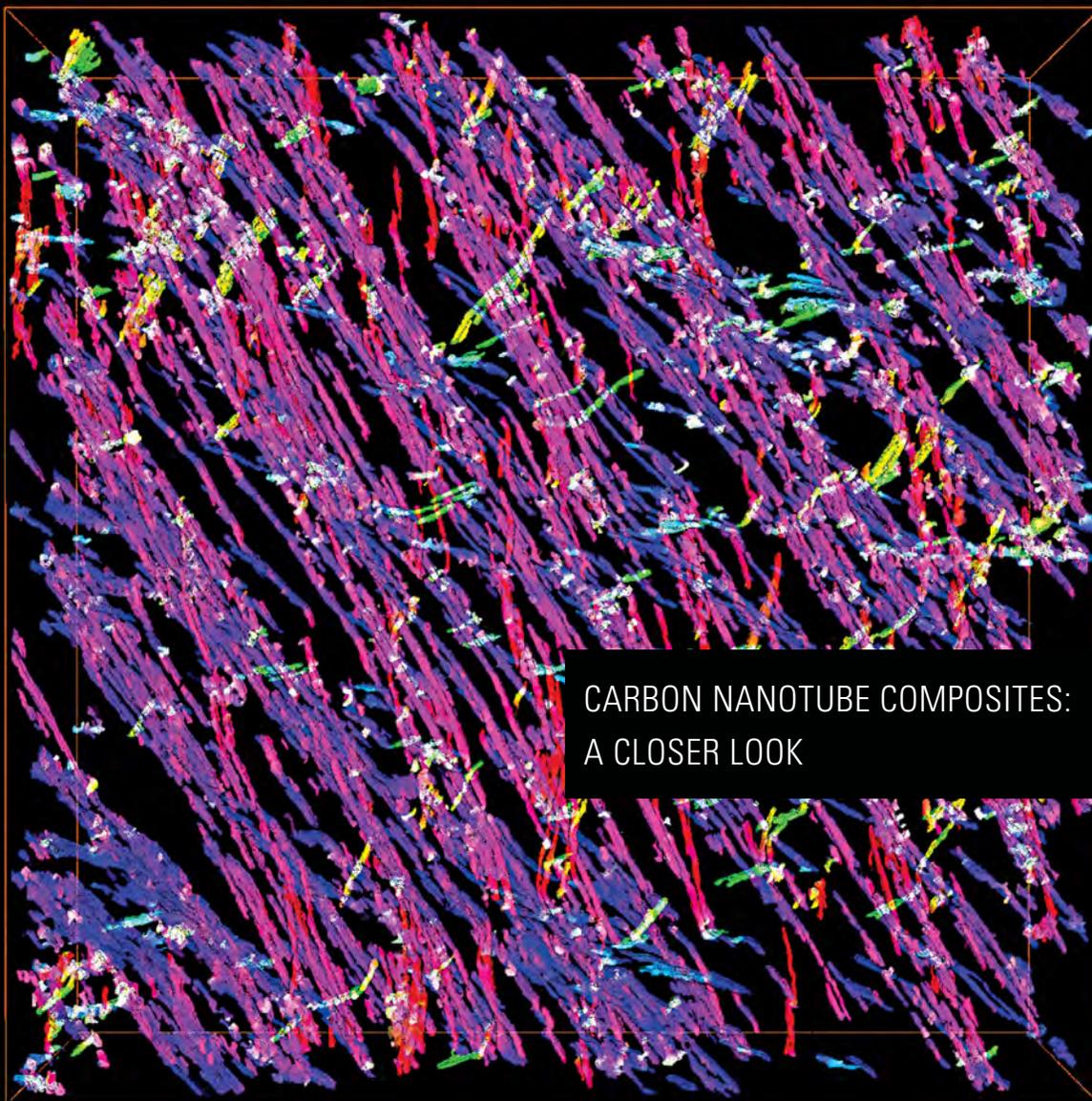


THE CNST NEWS

SPRING 2016



CARBON NANOTUBE COMPOSITES:
A CLOSER LOOK

INSIDE

NANODEVICE SHIFTS LIGHT'S COLOR

A DIMPLED WAY TO STUDY CELL PROTEINS

NEW TOOL CREATES ULTRA-SMOOTH FILMS

NIST
National Institute of
Standards and Technology
U.S. Department of Commerce

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FROM THE DIRECTOR



The words you're reading were written on the computer in my office at the CNST. It's a pretty standard computer, probably similar to the one you have in your workplace or at home. But these machines, as efficient as they may seem, have a problem that plagues even the most sophisticated supercomputing devices: They process information in one location and store that information in another.

As explained in the February 2015 *Scientific American*, because the two locations are physically separate, data is constantly being shuttled back and forth between them via an electronic circuit. This continual data transfer wastes time and energy. The problem is only getting worse with the computational and power demands of computer vision, robotics and processing systems that rely on pattern recognition of large data sets.

Fortunately, scientists at NIST and other research institutions exploring ways to build new types of computers can borrow ideas from a system that already does an amazing job of performing complex computations while consuming only a few watts of power. That system is our brain.

This three-pound organ manages to store and process data in the same location. The CNST has now invested in a new program that will use components such as memristors, spin-torque oscillators and single-flux quanta (devices that have the potential to both store and process data) to create an electronic version of the brain and its neural connections. This area of endeavor is usually referred to as neuromorphic computing.

New devices, along with algorithms and architectures of these new systems, are an active area of research, spurred by the latest findings from neuroscience. As the nation's premier measurement laboratory, NIST is ideally positioned to provide critical support to the growing neuromorphic computing effort in the U.S.

NIST in general, and the CNST in particular, can help at several levels. Work is needed to develop the devices that will serve as the synapses, dendrites, axons and other neural components of this brain-like computer. Memristors and other devices will have to be more energy efficient if they are to be part of such a system. The CNST, working with its facility users, will play an important role in developing the measurement methods necessary to both elucidate the physical processes that govern these systems and in evaluating the devices to make sure they are performing as desired.

At the small-system level, the CNST's strength in state-of-the-art fabrication will be invaluable in the design and construction of prototype circuits and in developing new ways to electrically characterize these miniature replicas of memory/processing components in the brain.

Let the revolution begin!

Robert Celotta

NEW NANODEVICE SHIFTS THE COLOR OF LIGHT AT THE SINGLE-PHOTON LEVEL

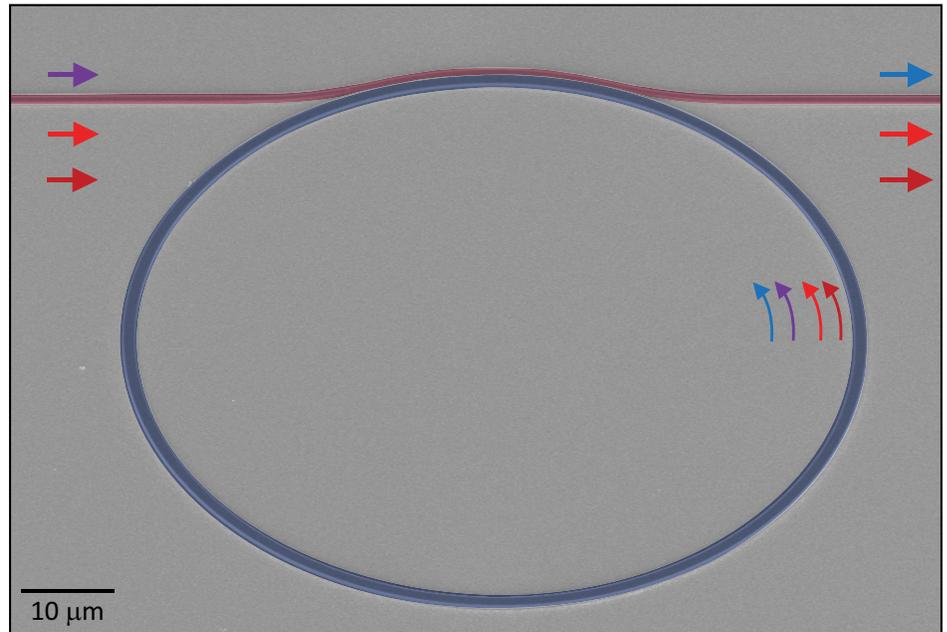
Converting a single photon from one color, or frequency, to another is an essential tool in quantum communication, which harnesses the subtle correlations between the subatomic properties of photons (particles of light) to securely store and transmit information. Scientists at the CNST have now developed a miniaturized version of a frequency converter, using technology similar to that used to make computer chips.

The tiny device, which promises to help improve the security and increase the distance over which next-generation quantum communication systems operate, can be tailored for a wide variety of uses, enables easy integration with other information-processing elements and can be mass produced.

The new nanoscale optical frequency converter accomplishes these feats with unprecedented performance. The device efficiently converts photons from one frequency to the other while consuming only a small amount of power and adding a very low level of noise, namely background light not associated with the incoming signal.

Frequency converters are essential for addressing two problems. The frequencies at which quantum systems optimally generate and store information are typically much higher than the frequencies required to transmit that information over kilometer-scale distances in optical fibers. Converting the photons between these frequencies requires a shift of hundreds of terahertz (one terahertz is a trillion wave cycles per second).

A much smaller, but still critical, frequency mismatch arises when two quantum systems that are intended to be identical have small variations in shape and composition. These variations cause the systems to generate photons that differ slightly in frequency instead of being exact replicas, which the quantum communication network may require.



False-color scanning electron micrograph of the nanophotonic frequency converter, consisting of a ring-shaped resonator (blue) into which light is injected using a waveguide (red). The incoming light signal (purple arrow) is converted to a new frequency (blue arrow) through the application of two pump lasers (light and dark red arrows).

The new photon frequency converter, an example of nanophotonic engineering, addresses both issues, CNST researchers Qing Li, Marcelo Davanço and Kartik Srinivasan write in an article posted online in the April 18 *Nature Photonics*. The key component of the chip-integrated device is a tiny ring-shaped resonator, about 80 micrometers in diameter (slightly less than the width of a human hair) and a few tenths of a micrometer in thickness. The shape and dimensions of the ring, which is made of silicon nitride, are chosen to enhance the inherent properties of the material in converting light from one frequency to another. The ring resonator is driven by two pump lasers, each operating at a separate frequency. In a scheme known as four-wave-mixing Bragg scattering, a photon entering the ring is shifted in frequency by an amount equal to the difference in frequencies of the two pump lasers.

Like cycling around a racetrack, incoming light circulates around the resonator hundreds of times before exiting, greatly enhancing the device's ability to shift the photon's frequency at low power and with low background noise. Rather than using a few watts of power, as typical in previous experiments, the system consumes only about a hundredth of that amount. Importantly, the added amount of noise is low enough for future experiments using single-photon sources.

While other technologies have been applied to frequency conversion, "nanophotonics has the benefit of potentially enabling the devices to be much smaller, easier to customize, lower in power and compatible with batch fabrication technology," says Srinivasan. "Our work is a first demonstration of a nanophotonic technology suitable for this demanding task of quantum frequency conversion."

GEOMETRY RULES: BY FABRICATING TINY DEPRESSIONS, CNST SHEDS LIGHT ON HOW PROTEINS RECOGNIZE CELL SHAPES AND STRUCTURES

The CNST's NanoFab is now in the business of sculpting dimples.

Working with biomedical researchers from the National Institutes of Health, NanoFab engineers are creating nanoscale depressions, or dimples, in silicon wafers in a pioneering effort to understand how proteins bind to specific sites within cells. New insights into how proteins are directed to particular cellular structures could lead to new treatments for some types of cancers and other human diseases.

Researchers have gathered evidence for two decades that some proteins inside cells have an affinity for curved surfaces—in a few cases convex, or rounded structures, in many others, concave, or bowl-shaped. The preference among some proteins to migrate and bind to structures that have a particular geometry is now under intense study by several research groups, including a team led by NIH scientist Kumaran Ramamurthi.

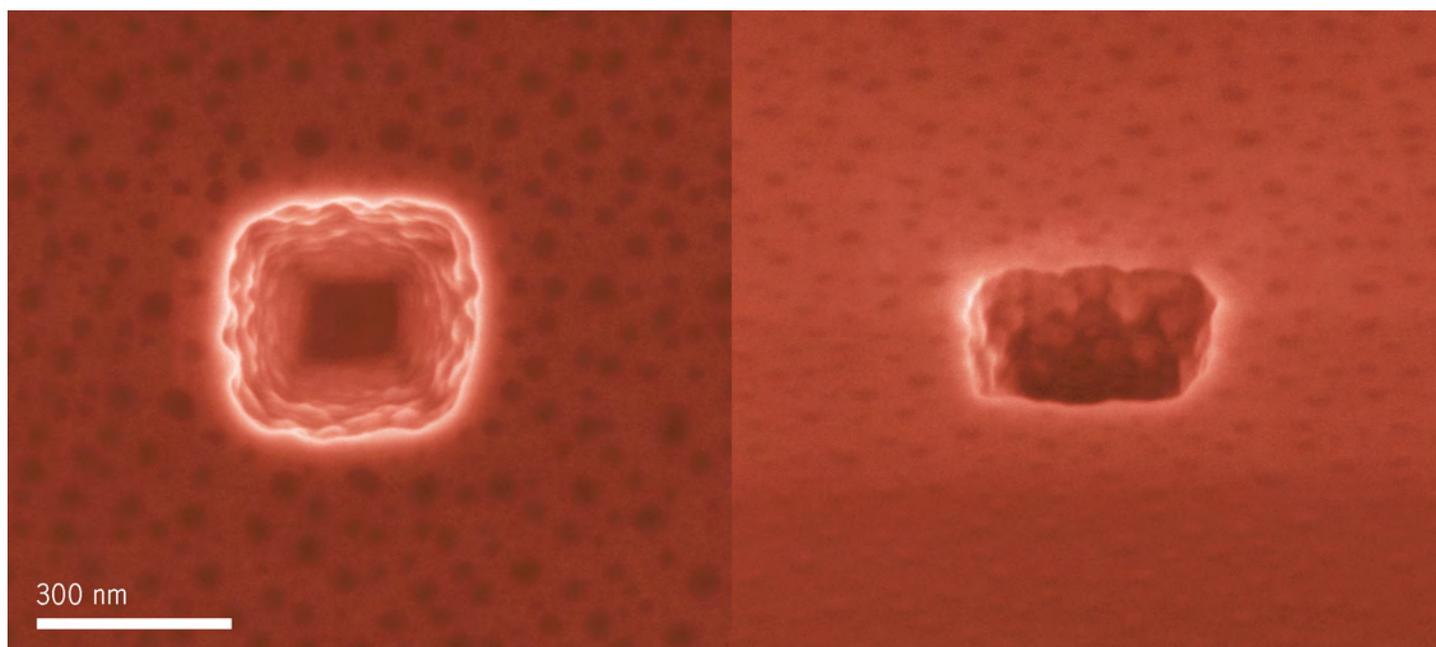
Ramamurthi's team has already developed a method to measure how strongly proteins bind to convex biomembranes. But how proteins bind to bowl-shaped surfaces remained largely unknown because no such concave nanoscale structures had ever been fabricated.

Using state-of-the-art instruments at the NanoFab, CNST engineers Marc Cangemi, Lei Chen and Joshua Schumacher developed a series of processing and characterization techniques to fabricate a device with thousands of nanoscale concave structures, or dimples.

Their biggest challenge was to form deep and smooth dimples that can be reproduced in a repeatable pattern. To create the tiny depressions, the CNST team used plasma etching, a process in which a silicon wafer is placed inside a chamber filled with an electrified gas. The electric field applied to the gas tightly controls the chemical reaction

between the gas molecules and molecules on the wafer's surface. The chemical reaction dissolves material from the wafer's surface to form the desired shape and depth.

The goal is to fabricate four devices, each with a highly uniform pattern of smooth dimples. The dimple diameter varies from 200 to 2,000 nanometers. That feat, a work in progress, had never before been attempted, says Chen. So far, the team has for the first time succeeded in making smooth, bowl-shaped depressions—about 400 nanometers in diameter—that have a square cross section when viewed from above the wafer. High-resolution images taken with the NanoFab's focused ion beam revealed the details of the structure, says Schumacher. The dimples, which can be reproduced from wafer to wafer and meet the requirements for the protein assay analysis, are soon to be tested by the NIH researchers.



Left: Top-down view of a dimple. **Right:** Oblique view of a dimple.

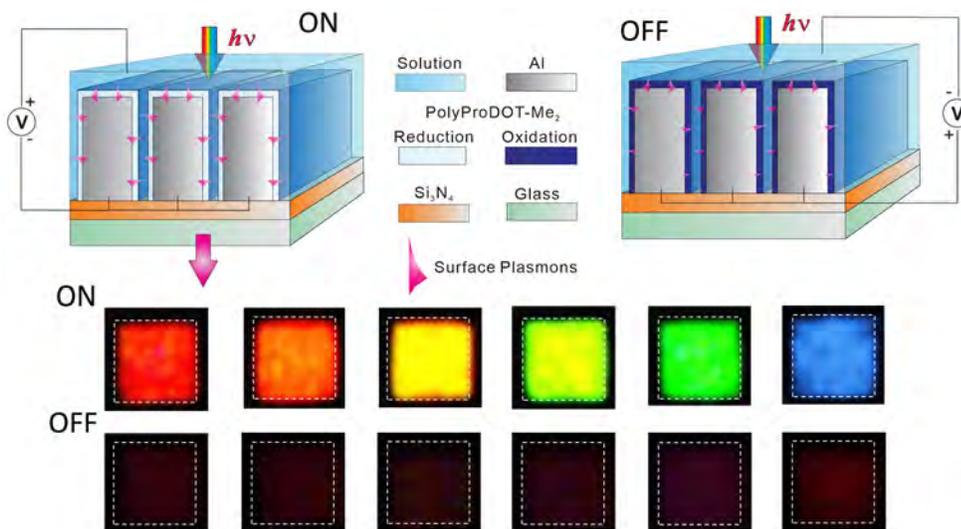
SHINY AND (ELECTRO)CHROME: NEW TWIST ON OLD TECH COULD BRING LIVING COLOR AT LOW POWER

By marrying state-of-the-art nanometer-scale gratings with a space-age era thin-film polymer, researchers working at the CNST have developed a new technology for building power-sipping full-color video displays, switches and routers for optical signals, as well as smart windows and coatings.

Electrochromic polymers make up a special class of materials that can switch from clear to colored and back again when their electrical charge changes. Their wide adoption, however, has been hindered because this transformation depends on how quickly electrons can get into and out of the material, which can take several seconds depending on the thickness of the film. Why not just make the films thinner so they'll change color faster? Good idea, but unfortunately, reducing the film's thickness robs the colors of their contrast, giving you a semitransparent black tint when what you wanted was an impenetrable, opaque black.

If the choice between being slow or weakly colored weren't bad enough, an electrochromic display using an additive color scheme—in which red, green and blue are mixed to achieve full color—would need up to six transparent electrically conducting layers to work, adding substantially to the cost of manufacturing.

Using some clever engineering, the researchers overcame this impasse by layering a thin film of electrochromic polymer over an aluminum nanograting. In their setup, the light first encounters the nanograting which, depending on the spacing of the slits, filters out all but one color of light. The electrochromic coating serves to modulate that light by allowing all or some (or none) of it to pass. A display based on this scheme would have an array of nanogratings acting as single-color pixels whose colors would, by adding or subtracting them, produce all



Light enters from above and encounters a nanometer-scale grating made of aluminum coated with a special “electrochromic” material. Light passes through the nanograting as surface plasmons, oscillations that travel at the interface of a metal and a dielectric (insulating) material. The spacing of the slits serves to filter out all but one color of light, and an additional layer of silicon nitride further spectrally purifies the escaping light.

the colors of the rainbow, with the individual pixels having adjustable levels of brightness or contrast.

But how does combining a thin film of electrochromic polymer with a nanograting make up for the just-described deficiencies of using said thin film? According to co-lead author Amit Agrawal of the CNST, it's all about the architecture.

“Because the electrochromic film that coats the sidewalls of the nanograting is so thin, it's very easy for electrons to make their way through and change its opacity,” Agrawal says. “The slits are much narrower (about 60 nanometers) than the wavelengths of light they are transmitting (from about 400 to 700 nanometers). This forces the incoming light to cling to the interface between the metal and the electrochromic layer on its way down the slits. And because the grating is so much deeper (about 250 nanometers) than it is wide,

and the walls of the slits are coated with electrochromic polymer all the way down, it can reduce the light's intensity to the same degree as if the light were passing through a much thicker layer of electrochromic film, enabling a great amount of control.”

CNST Scientist Henri Lezec, an author of the paper, says the setup they have now uses a liquid electrolyte, a chemical that facilitates the proper flow of electrons, which is not ideal for manufacturability and reliability, but that it could easily be replaced with a more physically stable and compact solid-state electrolyte.

Alec Talin, a co-author based at Sandia National Laboratories, says that the next step in extending this principle would be toward reflective, sunlight-readable displays that do not require an energy-consuming backlight.

BUILDING BETTER MATERIALS: CNST EXPLORES THE POTENTIAL OF CARBON NANOTUBE COMPOSITES

Using carbon nanotubes (CNTs)—rolled-up sheets of graphene—to strengthen a material or enhance its electrical or thermal conductivity has had scientists excited for a long time. But getting just the right arrangement of CNTs turns out to be critical for the task. By varying the density and distribution of CNTs suspended in an epoxy resin, researchers can engineer a composite material to have a wide array of electrical, thermal and mechanical properties.

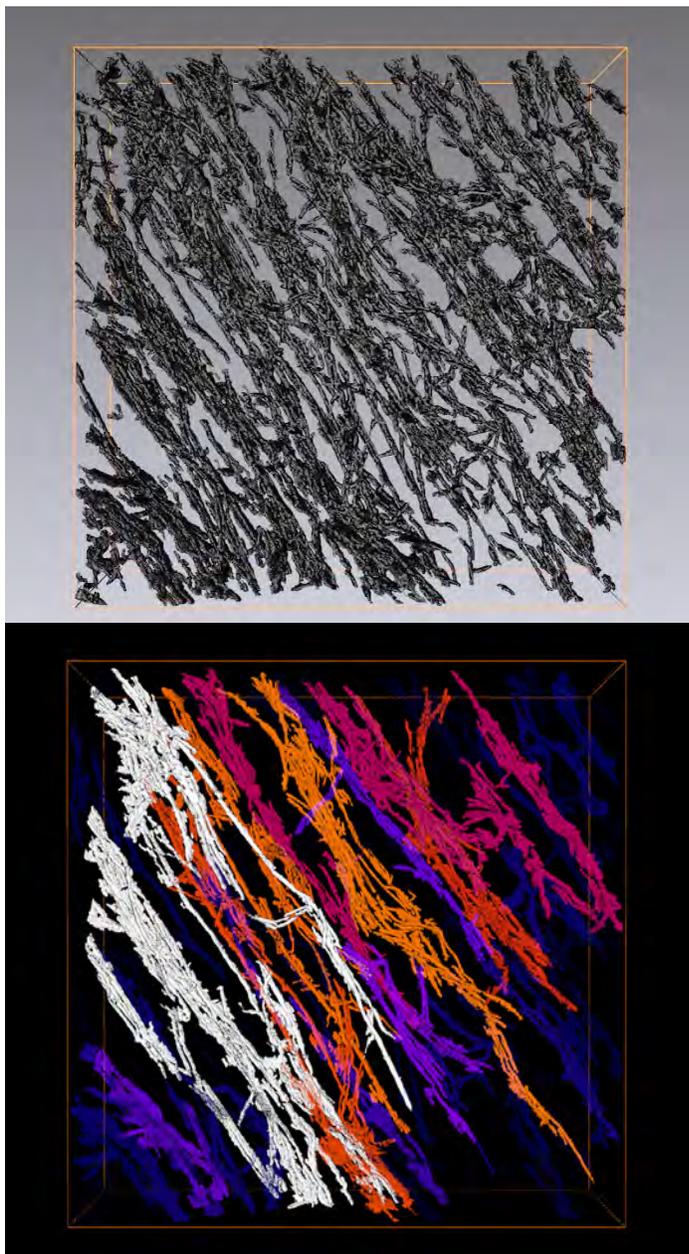
“You can make composites that are electrically conductive, you can make them opaque to microwaves; and you can control these properties independently of the strength of the material,” notes Alex Liddle, leader of the CNST’s Nanofabrication Research Group. “There’s a maturation in the thinking about what you can do with CNT composites.”

Recent studies at the CNST’s NanoLab, part of a NIST-wide exploration of CNT composites, are suggesting new ways to fully realize the promise of the composites for selecting the properties of materials.

In one of the new studies, researchers from the NanoLab, the Massachusetts Institute of Technology and the University of Maryland have developed image acquisition and processing techniques to map the 3-D structure of carbon nanotubes inside a composite material. Exactly how the nanotubes are distributed and arranged within the material plays an important role in determining its overall properties. The new data will help researchers studying composites to build and test realistic computer models of materials to find out what arrangements of CNTs will yield the desired array of thermal, electrical, and mechanical features.

Their research was featured as an editors’ choice in *ACS Nano*.

While researchers already had reliable methods to measure a nanocomposite’s bulk properties, scientists didn’t know exactly why various formulations of the composite had different properties, says Liddle. “Figuring out why these materials have the properties they do requires a detailed, quantitative understanding of their complex 3-D structure,”



Top: Using electron tomography, CNST researchers obtained this 3-D reconstruction of the shape and network structure of aligned carbon nanotubes in epoxy resin. **Bottom:** Colors in this 3-D reconstruction denote bundle size, with white the largest and blue the smallest.

says Liddle. “We need to know not only the concentration of nanotubes but also their shape and position, and relate that to the properties of the material.”

Seeing the arrangement of carbon nanotubes in a composite material is tough, though, because they’re suspended in an epoxy resin, which is also made of mostly carbon atoms.

Even with sophisticated probes the contrast is too low for software image processors to discern the carbon nanotubes easily.

Bharath Natarajan, a CNST-University of Maryland postdoc, designed an image-processing algorithm that can distinguish CNTs from an epoxy resin as well as his trained eye can.

According to Liddle, a CNT expresses its full potential for conferring strength and electrical and thermal conductivity when it is stretched out and straight.

However, when CNTs are suspended in an epoxy resin, which makes a tough, strong material, “they spread out, bundle and twist into different shapes,” Liddle says. “Our analysis revealed that the benefits of CNTs increases in a non-linear fashion as their concentration increases,” he notes. “As the concentration rises, the CNTs come into contact with each other, which increases the composite’s electrical and thermal conductivity, and the physical contact causes them to conform to one another, which straightens them, increasing the material’s strength.”

While it’s not particularly surprising that increasing the concentration of CNTs would enhance various properties, researchers now know how this happens and why. Earlier models of nanocomposite materials’ performance never quite matched how they performed in practice.

The exploration of CNT composites for engineering material properties has only just begun, says Liddle. “There are all sorts of ways other researchers might slice and dice the data to model and eventually manufacture optimal materials for thermal management, mechanical reinforcement, energy storage or a particular combination of those properties,” he says.

Now that researchers have demonstrated how the structure of CNT composites can alter basic properties, there’s a new focus on how to process a material to get that structure.

Moving toward that goal, manufacturers will need process and quality-control tests to ensure that products have desired characteristics and lack flaws. Current test procedures often require off-line, time-consuming, and destructive tests. NIST physicists have now developed a speedy, non-contact and nondestructive way to

test a wide array of materials under real-world conditions.

Working at the CNST, physicists Nathan Orloff and Jan Obrzut of NIST’s Material Measurement Laboratory, along with CNST-UMD postdoc Christian Long, measured properties of films by passing them through a specially designed microwave cavity. Electromagnetic waves build up inside the cavity at a specific “resonance” frequency determined by the box’s size and shape, similar to how a guitar string vibrates at a specific pitch depending on its length and tension. When an object is placed inside the cavity, the resonance frequency changes in a way that depends on the object’s size, electrical resistance and dielectric constant, a measure of an object’s ability to store energy in an electric field. The frequency change is reminiscent of how shortening or tightening a guitar string makes it resonate at a higher pitch, says Orloff.

The researchers also built an electrical circuit to measure these changes in real time. They first tested their device by running a strip of plastic (polyimide) tape through the cavity, using a roll-to-roll setup resembling high-volume roll-to-roll manufacturing devices used to mass-produce nanomaterials. As the tape’s thickness increased and decreased—the researchers made the changes in tape thickness spell “NIST” in Morse code—the cavity’s resonant frequency changed in tandem. So did another parameter called the “quality factor,” which is the ratio of the energy stored in the cavity to the energy lost per frequency cycle. Because polyimide’s electrical properties are well known, a manufacturer could use the cavity measurements to monitor whether tape is coming off the production line at a consistent thickness—and even feed back information from the measurements to control the thickness.

Alternatively, a manufacturer could use the new method to monitor the electrical

properties of a less well-characterized material of known dimensions. Orloff and Long demonstrated this by passing 12- and 15-centimeter-long films of carbon nanotubes deposited on sheets of plastic through the cavity and measuring the films’ electrical resistance. The entire process took “less than a second,” says Orloff. He added that with industry-standard equipment, the measurements could be taken at speeds beyond 10 meters per second, more than enough for many present-day manufacturing operations.

The new method has several advantages for a thin-film manufacturer, says Orloff. One, “You can measure the entire thing, not just a small sample,” he said. Such real-time measurements could be used to tune the manufacturing process without shutting it down, or to discard a faulty batch of product before it gets out the factory door. “This method could significantly boost prospects of not making a faulty batch in the first place,” Long notes.

And because the method is nondestructive, Orloff adds, “If a batch passes the test, manufacturers can sell it.”

Films of carbon nanotubes and graphene are just starting to be manufactured in bulk for potential applications such as composite airplane materials, smartphone screens and wearable electronic devices.

Orloff, Long and Obrzut submitted a patent application for this technique in December 2015.

In related work, the CNST recently collaborated with a small tech firm, PaneraTech of Chantilly, Virginia, to develop microwave devices that rapidly characterize and provide immediate feedback on the properties of thin films composed of CNTs and other materials. The devices promise to improve the yield and lower the cost of manufacturing the films and were developed under the auspices of the Small Business Innovation Research Program.

Noncontact conductivity and dielectric measurement for high throughput roll-to-roll nanomanufacturing, N.D. Orloff, C.J. Long, J. Obrzut, L. Maillaud, F. Mirri, T.P. Kole, R.D. McMichael, M. Pasquali, S.J. Stranick & J.A. Liddle. *Scientific Reports* 5, Article Number 17019, November 23, 2015. DOI: 10.1038/srep17019

The evolution of carbon nanotube network structure in unidirectional nanocomposites resolved by quantitative electron tomography, B. Natarajan, N. Lachman, T. Lam, D. Jacobs, C. Long, M. Zhao, B. L. Wardle, R. Sharma and J. A. Liddle. *ACS Nano*. DOI: 10.1021/acsnano.5b01044. Published online June 1, 2015.

NEW MICROWAVE IMAGING APPROACH OPENS A NANOSCALE VIEW ON PROCESSES IN LIQUIDS

Nanotechnology researchers have developed a new window to view what are now mostly clandestine operations occurring in soggy, inhospitable realms of the nanoworld—technologically and medically important processes that occur at boundaries between liquids and solids, such as in batteries or along cell membranes.

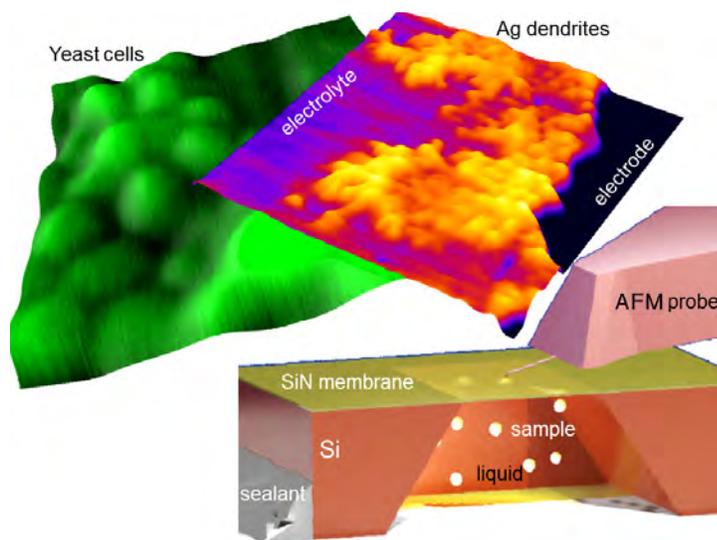
The new microwave imaging approach, developed by researchers at the CNST and the Department of Energy's Oak Ridge National Laboratory (ORNL), trumps X-ray and electron-based methods that can damage delicate samples and muddy results. And it spares expensive equipment from being exposed to liquids, while eliminating the need to harden probes against corrosive, toxic, or other harmful environments.

Writing in the journal *ACS Nano*, the CNST-ORNL collaborators describe their new approach to imaging reactive and biological samples at nanoscale levels under realistic conditions.

The key element is a window, an ultrathin membrane that separates the needle-like probe of an atomic force microscope from the underlying sample, held in tiny containers that maintain a consistent liquid or gas environment. The addition transforms near-field microwave imaging into a versatile tool, extending its use beyond semiconductor technology, where it is used to study solid structures, to a new realm of liquids and gases.

"The ultrathin, microwave-transparent membrane allows the sample to be examined in much the same way that Earth's radar was used to reveal images of the surface of Venus through its opaque atmosphere," explained CNST physicist Andrei Kolmakov.

"We generate microwaves at the apex—or very end—of the probe tip," Kolmakov said. "The microwaves penetrate through the membrane a few hundred nanometers deep into the liquid up to the object of interest.



Scientists have devised a near-field microwave imaging approach to capture images of nanoscale processes under natural conditions. In this graphic, the tip of an atomic force microscope (AFM) scans an ultrathin membrane, it emits microwaves into the sample below. Images show yeast cells and silver dendrites that formed on an electrode during electroplating.

As the tip scans the sample from across the membrane, we record the reflected microwaves to generate the image."

Microwaves are much larger than the nanoscale objects they are used to "seeing." But when emitted from only a minuscule distance away, near-field microwaves reflected from a sample yield a surprisingly detailed image.

In their proof-of-concept experiments, the CNST-ORNL collaborators used their hybrid microscope to get a nanoscale view of the early stages of a silver electroplating process. Microwave images captured the electrochemical formation of branching metal clusters, or dendrites, on electrodes. Features nearly as small as 100 nanometers (billionths of a meter) could be discerned.

As important, the low-energy microwaves were too feeble to sever chemical bonds, heat, or interfere in other ways with the process they were being used to capture in images. In contrast, a scanning electron microscope that was used to record the same electroplating process at comparable levels of resolution yielded images showing

delamination and other destructive effects of the electron beam.

The team reports similar success in using its microwave set-up to record images of yeast cells dispersed in water or glycerol. Levels of spatial resolution were comparable to those achieved with a scanning electron microscope, but again, were free of the damage caused by the electron beam.

In their experiments, the team used membranes—made either of silicon dioxide or silicon nitride—that ranged in thickness from 8 nanometers to 50 nanometers. They found, however, that the thinner the membrane the better the resolution—down to tens of nanometers—and the greater the probing depth—up to hundreds of nanometers. "These numbers can be improved further with tuning and development of better electronics," Kolmakov said.

In addition to studying processes in reactive, toxic, or radioactive environments, the researchers suggest that their microwave-imaging approach might be integrated into "lab-on-a-chip" fluidic devices, where it can be used to sample liquids and gases.

NEW PLUNGE FREEZER FOR NANOFAB

Researchers often want to examine nanoparticles and biological specimens in their native state. One way to do this is by suspending the specimens in solution and analyzing them using cryo-transmission electron microscopy (TEM). Since wet specimens cannot be placed in the high vacuum of a TEM, the suspended specimen must first be frozen. The cooling must be done quickly to avoid forming ice crystals, which can obscure the detailed structure of the material under study.

To achieve the rapid cooling, the NanoFab has acquired an automatic plunge freezer, the Leica EM GP. The instrument prepares samples for cryo-TEM using the bare grid method. In that process, a liquid sample is placed on an electron microscope grid and excess material is automatically blotted until

only a thin film remains. The sample is then plunged into a cryogen and can then be directly transferred to a cryo-TEM specimen holder for analysis in the TEM. The automated blotting and plunging are key features of the instrument to ensure sample reproducibility. The plunge freezer allows preservation of the internal, 3-D structure of the nanomaterial, rather than have the structure collapse, which can occur when the specimen is dried out.

Applications for the plunge freezer include preparing cryo-TEM specimens of nanoparticles, DNA, liposomes, proteins, viruses and other biological particles in their native solution environment.



A new automated plunge freezer helps researchers examine nanoparticles and biological specimens in their native state.

SCIENCE WANNABEES VISIT THE CNST

They asked cogent questions, peered at computer chips and insect eyes through an electron microscope and were awed by the coolness of using a beam of lithium atoms chilled to just a few millionths of a degree above absolute zero to probe the detailed workings of lithium batteries. Some 65 students from Paul the VI High School in Fairfax, Virginia, accompanied by their science teacher, the vice-principle and four parents, visited the CNST on March 11.

In addition to touring several laboratories, the students learned about the magnetic behavior of thin films, the importance of time standards and possible routes to a career in science and engineering. They also chatted one-on-one with CNST researchers over a pizza lunch.



SPUTTERING TOOL OFFERS NOVEL WAY TO DEPOSIT SMOOTH, ULTRA-THIN FILMS

The CNST's NanoFab has acquired a state-of-the-art Sputtering Cluster System (SCS). The tool creates ultra-thin, smooth, dense and uniform films across 200-millimeter wafers at room temperature. The automated system operates around the clock without need for supervising personnel.

The system has two deposition chambers connected to a wafer-transfer robot that moves wafers from cassette to cassette. Each chamber houses six sputtering targets, a residual gas analyzer sensor head and a quartz crystal thickness monitor, along with an ion gun for sputter-cleaning wafers prior to deposition.

One of the tool's chambers is dedicated to Ion Beam Deposition for high density, pinhole-free and ultra-smooth films. The other chamber is dedicated to Biased Target Deposition (BTD), in which ion beam sputtering is directed at an electrically-biased target. This technology allows changing the adatom energy during film growth and provides the least amount of interface mixing, while still depositing dense and ultra-smooth films.

The system is currently configured to deposit Cr, Au, Fe, Ni, NiFe, Ti, Pt, Ta, Al, Co, SiO₂, ITO, TiO₂ and Ta₂O₅.

Advanced capabilities of the tool have been demonstrated as shown below. Atomically flat interfaces can be achieved using the BTD technique. By lowering the target bias voltage in the beam target deposition chamber, the energy of the atoms forming

the first few monolayers can be reduced, ensuring that these layers do not mix with the underlying layer. Increasing the target bias voltage in subsequent layers minimizes surface roughness. Magnetic tunnel junctions and memristors are among the devices that require such controls.

The left image in the graphic below shows a transmission electron microscopy image of a chrome/platinum bilayer film on silicon. Each layer of the film has a thickness of 5 nanometers. The first nanometer of the platinum film was deposited at a target bias of 300 V, while the remaining 4 nm was deposited at 800 V. The image confirms that the BTD technique offers a way to fabricate continuous and pinhole-free nanometer films with well-defined interfaces between different films.

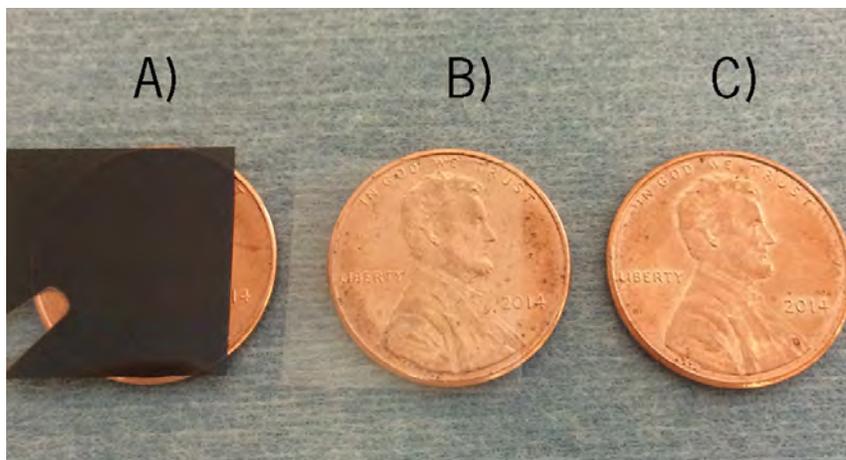
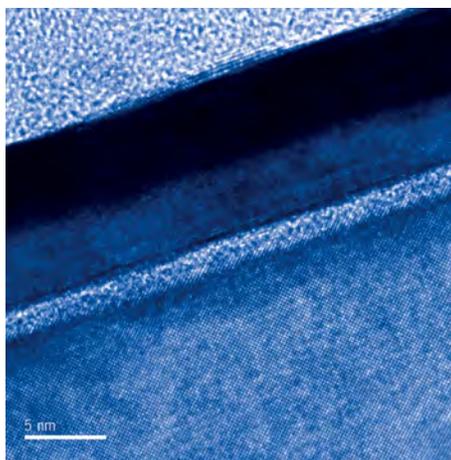
Indium Tin Oxide (ITO) is a standard material used to produce a transparent electrical contact for applications such as liquid crystal, flat panel and plasma displays, organic LEDs, solar cells and electromagnetic interference shielding.

The ITO film is typically opaque and insulating when deposited using the magnetron sputtering or the electron beam evaporation methods. Post-annealing at 300 °C or higher is needed to achieve transparency and conductivity. The SCS's ion beam deposition technique, or IBD, makes it possible for the first time in the NanoFab to deposit transparent and conductive ITO films at room temperature without post-annealing. This is clearly an advantage for devices sensitive to

elevated temperature processing. Presently, the ITO film obtained in the IBD chamber can achieve a resistivity of 9×10^{-4} ohm-cm with 95% transmissivity in the visible range, comparable to that of films obtained by the other two techniques. The graphic below, right, compares the transparency of the ITO film using the magnetron sputtering technique with the IBD technique. The ITO film thickness is 100 nm. It is obvious that the ITO film deposited using the IBD technique shows significantly improved transparency.

Silicon dioxide films are commonly used in passivation, hard masking for reactive ion etching and electrical isolation applications. High quality pinhole-free films are always desired and typically grown at around 1000 °C using the thermal oxidation method. Films deposited at room or near-room temperature via magnetron sputtering, electron beam evaporation or plasma-enhanced chemical vapor deposition always have a pinhole problem.

The SCS makes it possible to obtain pinhole-free SiO₂ films at room temperature. The etch rate of ion-beam-deposited oxide in Buffered Oxide Etch (6:1 BOE) is consistent with that of thermal oxide (1.6 nm/s – 2 nm/s). In addition, the film is denser than thermally grown oxide (2.4 g/cm³ versus thermal oxide 2.2 g/cm³) and its electrical resistivity is greater than 2×10^7 ohm-cm. The optical qualities (refractive index *n* and extinction coefficient *k*) are very similar to thermal oxide. These characteristics make such films an attractive alternative to thermal oxide.



Left: TEM image of a Cr/Pt film sputter-deposited on a silicon substrate using the new Sputter Cluster System and the biased target deposition technique. **Right:** A) Using magnetic sputtering, an ITO film deposited on a penny is opaque B) Using the new IBD technique, an ITO film deposited on a penny is essentially transparent C) Bare penny.

MULTILINGUAL CIRCUIT: NIST'S "OPTOMECHANICAL TRANSDUCER" LINKS SOUND, LIGHT AND RADIO WAVES

Researchers at CNST have developed a "piezo-optomechanical circuit" that converts signals among optical, acoustic and radio waves. A system based on this design could move and store information in next-generation computers.

The team's work, published in *Nature Photonics*, was also presented at the March 2016 meeting of the American Physical Society in Baltimore, Md.

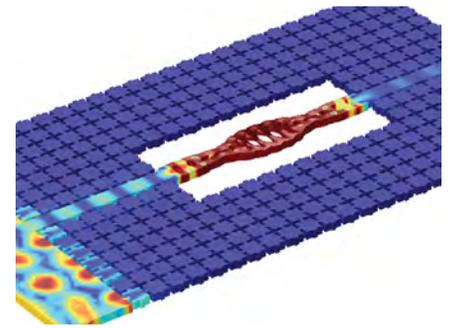
While Moore's Law, the idea that the number of transistors on an integrated circuit will double every two years, has proven remarkably resilient, engineers will soon begin to encounter fundamental limits. As transistors shrink, heat and other factors will begin to have magnified effects in circuits. As a result, researchers are increasingly considering designs in which electronic components interface with other physical systems that carry information such as light and sound. Interfacing these different types of physical systems could circumvent some of the problems of components that rely on just one type of information carrier, if researchers can develop efficient ways of converting signals from one type to another (transduction).

For example, light is able to carry a lot of information and typically doesn't interact with its environment very strongly, so it doesn't heat up components like electricity does. As useful as light is, however, it isn't suited to every situation. Light is difficult to store for long periods, and it can't interact directly with some components of a circuit. On the other hand, acoustic wave devices are already used in wireless communications technology, where sound is easier to store for long periods in compact structures since it moves much more slowly.

To address such needs, CNST researchers and their collaborators built a piezoelectric

optomechanical circuit on a chip. At the heart of this circuit is an optomechanical cavity, which in their case consists of a suspended nanoscale beam. Within the beam are a series of holes that act sort of like a hall of mirrors for light (photons). Photons of a very specific color or frequency bounce back and forth between these mirrors thousands of times before leaking out. At the same time, the nanoscale beam confines phonons, that is, mechanical vibrations, at a frequency of billions of cycles per second (gigahertz or GHz). The photons and phonons exchange energy so that vibrations of the beam influence the buildup of photons inside the cavity, while the buildup of photons inside the cavity influences the size of the mechanical vibrations. The strength of this mutual interaction, or coupling, is one of the largest reported for an optomechanical system.

One of the researchers' main innovations came from joining these cavities with acoustic waveguides, which are components that route sound waves to specific locations. By channeling phonons into the optomechanical device, the group was able to manipulate the motion of the nanoscale beam directly. Because of the energy exchange, the phonons could change the properties of the light trapped in the device. To generate the sound waves, which were at GHz frequencies (much higher than audible sounds; not even your dog could hear them), they used piezoelectric materials, which deform when an electric field is applied to them and vice versa. By using a structure known as an "interdigitated transducer" (IDT), which enhances this piezoelectric effect, the group was able to establish a link between radio frequency electromagnetic waves and the acoustic waves. The strong optomechanical links enable them to optically detect this confined coherent acoustic energy down to the level of a fraction of a phonon.



Acoustic waveguide channels phonons into the optomechanical cavity, enabling researchers at CNST to manipulate the motion of the suspended nanoscale beam directly.

They also observed controllable interference effects in sound waves by pitting electrically and optically generated phonons against each other. According to one of the paper's co-authors, CNST physicist Kartik Srinivasan, the device might allow detailed studies of these interactions and the development of phononic circuitry that can be modified with photons.

"Future information processing systems may need to incorporate other information carriers, such as photons and phonons, in order to carry out different tasks in an optimal way," says Srinivasan. "This work presents one platform for transducing information between such different carriers."

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.

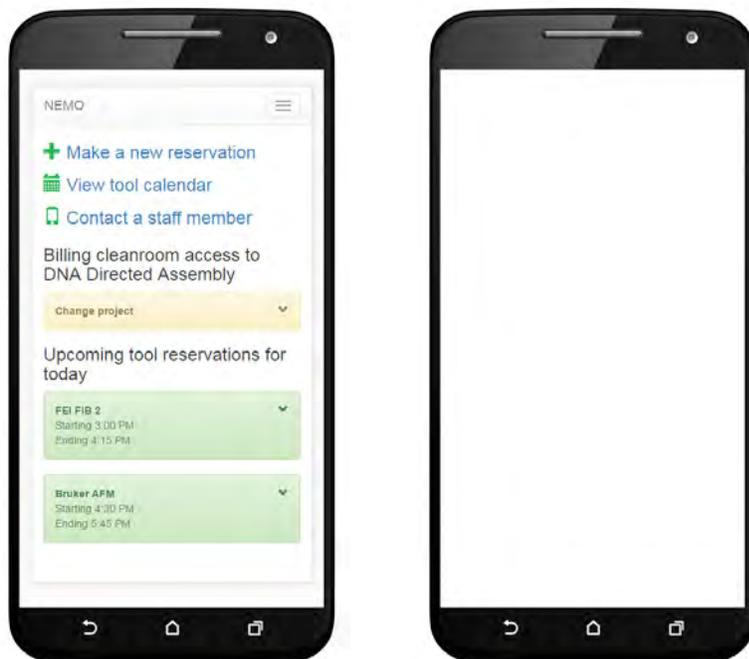
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A SMART WAY TO RESERVE TIME AT THE NANOFAB

Reserving time on an advanced nanoscale fabrication or measurement tool at the NanoFab is now about as easy as making an online reservation at your favorite restaurant. As of April 18, users can use a mobile device while off campus to access the NanoFab website, known as NanoFab Equipment Management and Operations, or NEMO. The website allows users to schedule reservations and view the operating status of instruments to ensure they'll have what they need when they need it. Through NEMO, customers can also seek assistance from staff if a problem arises with a tool or when additional supplies, such as silicon wafers, are needed.



Screen shots of NEMO, which is now available on phones off campus.