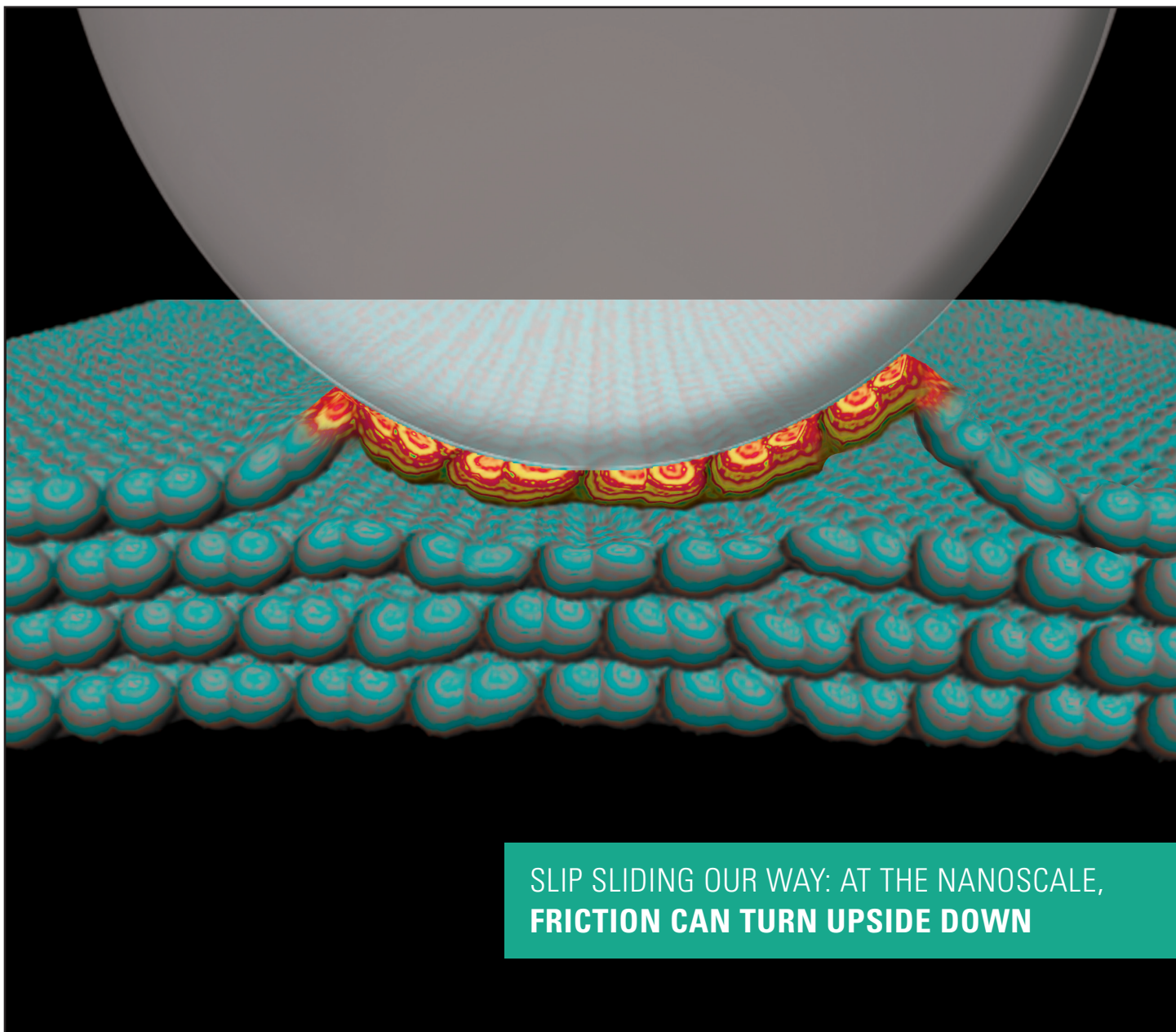


THE CNST NEWS

FALL 2012



SLIP SLIDING OUR WAY: AT THE NANOSCALE,
FRICTION CAN TURN UPSIDE DOWN

INSIDE

A PLASMONIC CALORIMETER FOR NANOLITER-SCALE FLUID SAMPLES

STRAIN-INDUCED QUANTUM DOTS IN GRAPHENE

TRACKING NANOPARTICLES IN THREE-DIMENSIONS

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

IN THIS ISSUE

From the Director	2
Nanoliter-Scale Calorimeter for Drug Discovery	3
Group Demonstrates Heralded Single Photon Source	4
At the Nanoscale, Graphite Turns Friction Upside Down	5
Entrepreneur Builds MEMS Pressure Sensor	6
Surface Conduction in a Topological Insulator	6
Creating Strain-Induced Quantum Dots in Graphene	7
Nanoparticle Dynamics in Three Dimensions	8
Determining the Optimum Path for Tracking Fluorescent Nanoparticles Using a Laser	8
Imaging Defects in Magnetic Nanodevices	9
A Low-Noise, Chip-Based Optical Wavelength Converter	10
A Fast and Sensitive Nanophotonic Motion Sensor	10
CNST Summer Students Gain Hands-On Research Experience	11
CNST's Shaffique Adam Receives Singapore National Research Foundation Fellowship	11

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FROM THE DIRECTOR



The vision of the CNST's NanoFab is to provide researchers with a comprehensive, state-of-the-art suite of tools and process for nanofabrication and measurement, supported by hands-on training, extensive tool and process development and assistance, and access to NIST-wide expertise in nanoscience and nanotechnology. This fall we added one of the last major tools in that suite — an ASML i-Line Stepper — bringing us closer to achieving our vision.

The stepper is at the heart of the new photolithography suite in our class 100 cleanroom that also includes an automatic developer, enabling researchers to use the NanoFab to prototype processes at a production scale. The ASML i-Line Stepper can expose 80 to 120 wafers per hour, with alignment accuracy of 40 nm and overlay resolution down to 280 nm, on substrates from small pieces up to 200 mm-diameter (8 inch) wafers. To our knowledge, it is the only such stepper available at a shared-use nanofabrication facility in the United States that, in addition to front-side alignment, provides three-dimensional back-side alignment so that overlay resolution and alignment accuracy are not degraded by wafer processing.

This cutting edge commercial tool complements the advanced metrology and patterning tools available outside the cleanroom nearby. The Titan analytical transmission electron microscope (TEM) provides nanoscale imaging and chemical analysis of a variety of materials, including semiconductors, photovoltaics, quantum structures, nanostructures, and biological samples. Three focused ion beam systems can be used for nanomachining, nanoscale structural and chemical characterization, circuit editing, three-dimensional tomography, TEM sample preparation, and *in situ* electrical measurements. Finally, a direct write electron beam lithography system is available to pattern electron sensitive materials or resists with a nanometer-diameter spot size.

Our NanoFab process engineers and technicians are available to provide expert training that will enable you to use most tools yourself. Training is economical and easy to schedule; our goal is to get you on the equipment as soon as possible. For example, in this issue (page 6) we feature a project by entrepreneur David DiPaola who was able to fabricate a MEMS sensor himself after receiving training on a variety of tools, including lithography and etching.

An unusual and noteworthy aspect of the NanoFab's operation is the ability to perform "remote projects." Researchers who need to get a job done but do not want to do it themselves can have the work performed by the NanoFab. The combination of our cost-reimbursement model and the extended hours that our expert staff members are available allow the work to be done at the usual cost of the tools and processes plus the staff costs required. As described on the opposite page, Draper Laboratory took advantage of this approach, with the NanoFab creating a prototype wafer to their specifications in less than a month with great success.

With our comprehensive tool set and expert staff, we are considering ways to expand our program to provide services remotely for researchers lacking convenient access to specific tools or processes. Two areas in which we have particularly strong capabilities and are poised to offer such assistance are electron beam lithography and fabrication of complex, three-dimensional nanophotonic devices. At this early stage, we would be eager to hear what you think. What fabrication tools or services would you find useful and why? Please email me your suggestions at Robert.Celotta@nist.gov.



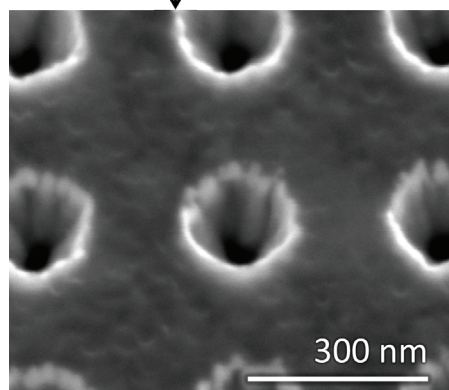
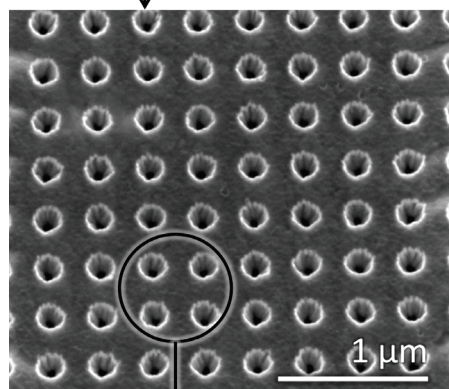
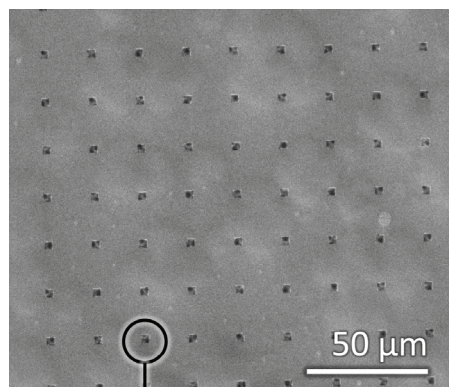
Robert Celotta

DRAPER LABORATORY BUILDS NANOLITER-SCALE CALORIMETER TO IMPROVE DRUG DISCOVERY

Working with CNST NanoFab engineers, researchers from Draper Laboratory, a not-for-profit research and development laboratory headquartered in Cambridge, MA, along with their collaborators at Northeastern University, have built nanohole array apertures for use in sensitive chip-scale temperature sensors. These sensors can be used to measure the heat of reaction in nanoliter-scale samples of fluid, opening a pathway to dramatically reduce the sample size needed and potentially enable calorimetry to be included in early stage drug screening, an improvement the researchers believe will greatly increase the chance of successfully choosing compounds for use in drugs.

Calorimetry is an excellent tool for judging the potential of chemicals for drug use. It is routinely used for characterizing molecular interactions and enzyme kinetics, for assessing the effect of structural changes on molecular binding mechanisms, and for measuring biological activity. However, it is usually reserved for use in late stage drug discovery because the large sample sizes required make it an expensive experimental tool. Current state-of-the-art commercial calorimeters require 200 μL fluid samples; Draper's nanoliter-scale experimental device could reduce the quantity of test sample needed by up to a factor of a thousand.

The research team, led by Dale Larson at Draper and Greg Kowalski at Northeastern, have designed an array of nanohole arrays to make an extremely high spatial resolution map of the whole temperature field across a fluid sample that is moving rapidly through a microfluidic channel. Draper's sensors detect temperature changes in the fluid sample by taking advantage of "extraordinary optical transmission," a plasmonic effect that causes the intensity of light transmitted through the fabricated array of subwavelength-diameter nanoholes to be greatly increased. As fluid close to the nanoholes heats or cools due to a chemical reaction, the fluid's index of refraction changes, causing variations in the intensity of the transmitted light that can be measured with a CCD camera on the opposite side of the nanohole array. The effect is extremely sensitive to temperature changes a few hundred nanometers



Each sensor site consists of a 10 x 10 array of 150 nm-diameter holes fabricated from a lithographic pattern made using direct-write electron beam lithography. The holes are milled through a gold film. The NanoFab's direct-write electron beam lithography system allowed Draper to move from 20 to 40 sensor arrays per channel to 30,000 while significantly lowering costs.

from the apertures, making this system ideally suited for nanoscale calorimetry. The researchers can continuously flow multiple series of reagents through two ports that allow liquids to have an interface along the length of the channel. The system allows them to observe a temperature map as the temperature field spreads, giving the information needed to characterize chemical reactions, including the reaction rate, the enthalpy, the entropy, and the contribution of the Gibbs free energy. Samples can be continuously renewed and washed away and conditions, including acidity or salinity, can be continuously changed.

Prior to coming to the CNST NanoFab, Draper's fabrication process used a focused ion beam to mill individual nanoscale holes. Each sensor site requires a 10 x 10 array of holes and each sensor channel required a minimum of 20 to 40 arrays. A researcher working one day could mill the 2,000 to 4,000 holes required for a proof-of-concept device. NanoFab Process Engineers Gerard Henein and Richard Kasica were able to use the NanoFab's direct-write electron beam lithography system to make a mask to produce devices with as many 30,000 sensor arrays covering the entire length of the reactor channel. Within a month of first receiving a CAD drawing from Draper, they fabricated a prototype wafer with 235,000,000 holes – enough to make 80 sensor chips.

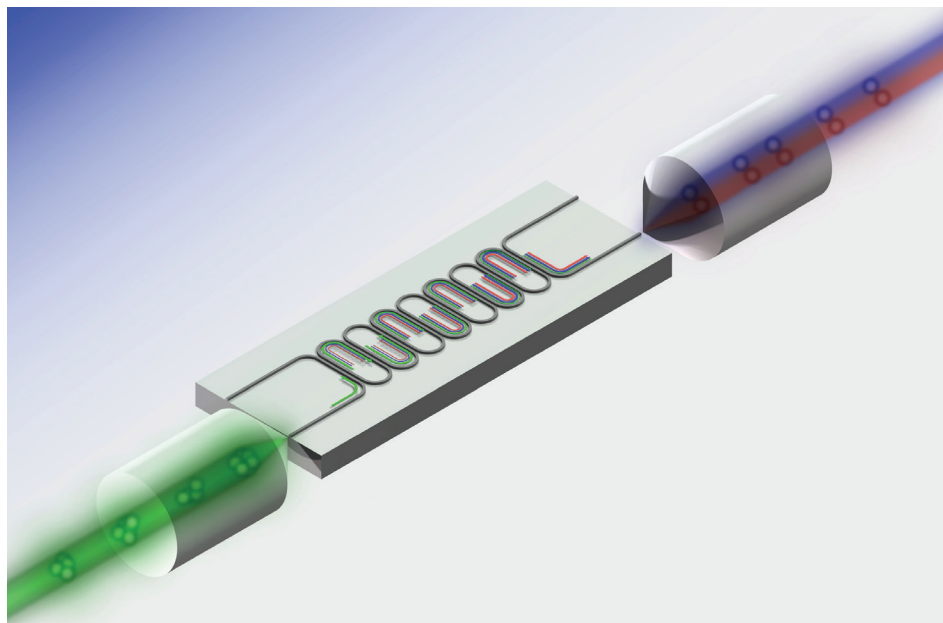
According to Draper's Jason Fiering, "with one wafer we have enough chips to move our work into the next round of demonstrations and improvements, rather than contending with producing each chip one at a time. The sensors have vastly improved spatial resolution and the cost is also significantly less." This fabrication technique allows Draper to show that these sensors "can be made economically and even as a disposable item. It allows us to include many design variations to determine which types of arrays give the best response." The researchers are using the chips to begin demonstrations with relevant biological molecules and are developing a microfluidic sample injection system to increase the speed with which they can change the reagents while minimizing waste. According to Fiering, "the working prototypes we got from the CNST allow us to viably talk to commercial partners."

GROUP DEMONSTRATES FIRST HERALDED SINGLE PHOTON SOURCE MADE FROM SILICON

In an important step towards more practical quantum information processing, researchers from the CNST, the University of California, San Diego, and the Politecnico di Milano in Milan, Italy, have demonstrated the first heralded single photon source from silicon. This silicon-based single photon source complements two other recently-developed silicon-based technologies—interferometers for manipulating the entanglement of photons and single photon detectors—needed to build a quantum optical circuit. In addition to their use in quantum computing, such circuits could be the backbone of secure quantum communication systems.

The line between “interesting” and practical in advanced electronics and optics often comes down to the ability to make the new technology compatible with existing systems. The new 0.5 mm x 0.05 mm-sized photon generator, made with devices known as coupled optical ring resonators, meshes with existing technology in three important ways: it operates at room temperature (some alternate techniques require very low temperatures); it produces photons compatible with existing telecommunications equipment (wavelengths of about 1550 nm); and it’s in silicon, and so can be built using standard, scalable fabrication techniques.

A “heralded” photon is one of a pair whose existence is announced by the detection of a partner that was generated at the same instant. To generate heralded single photons, the group built upon a technique previously demonstrated in silicon called photon pair generation. This is a process where a laser pumps photons into a material whose properties cause two incoming pump photons to spontaneously generate a special pair of new photons that emerge at precisely the same time, with one at a slightly lower frequency and the other a slightly higher frequency than the pump photons. The authors used a specially designed photonic structure in silicon that strongly increases the probability that such photon pairs are generated, although it remains impossible to determine exactly when they will simultaneously appear.



Schematic illustrating the process of photon pair generation. Heralding occurs after input pump photons spontaneously generate special pairs of new photons that emerge at precisely the same time, with one at a slightly lower frequency and the other a slightly higher frequency.

While there are many applications in which the photon pairs themselves are useful, according to the CNST’s Kartik Srinivasan, there are others in which the process of heralding itself is important; for example, in future quantum-based memory where heralding is needed to trigger the storage of information carried by a photon. Because it is impossible to know precisely when a pair of single photons is produced, the detection of one of the photons therefore lets the observer know to look for its complement and put it to work.

Using photon correlation measurements, an experimental method for confirming the generation of single photons and whether two photons are generated at the same time, the group verified that their silicon-based device very efficiently produced pairs of single photons, and clearly demonstrated they could herald the presence of one photon by the detection of the other in a pair. “In order to build optical circuits for quantum computing and communications, we need to have efficient single photon sources, and not just one, but a lot of

them,” says Srinivasan. “This is why building these devices using silicon is so great. Unlike some other types of sources, we don’t need to cool them and we can use standard fabrication techniques used in commercial microelectronics.”

Still, according to co-author Professor Shayan Mookherjee at UC San Diego, the device as built is not yet practical because a number of necessary operations, such as spectral filtering (to purify the light), entanglement, and detection will ultimately need to be integrated onto a single chip. Due to the nature of the photon pair generation process, there’s also a fundamental limitation to how bright these sources can be made. However, putting many of these sources together, along with their complementary components — something made possible by using silicon fabrication technology — could supply the performance needed for practical applications.

SLIP SLIDING OUR WAY: AT THE NANOSCALE, GRAPHITE CAN TURN FRICTION UPSIDE DOWN

If you ease up on a pencil, does it slide more easily? Sure. But maybe not if the tip is sharpened down to nanoscale dimensions. A team of CNST researchers has discovered that if graphite (the material in pencil “lead”) is sticky enough, as measured by a nanoscale probe, it actually becomes harder to slide a tip across the material’s surface as you decrease pressure—the exact opposite of our everyday experience.

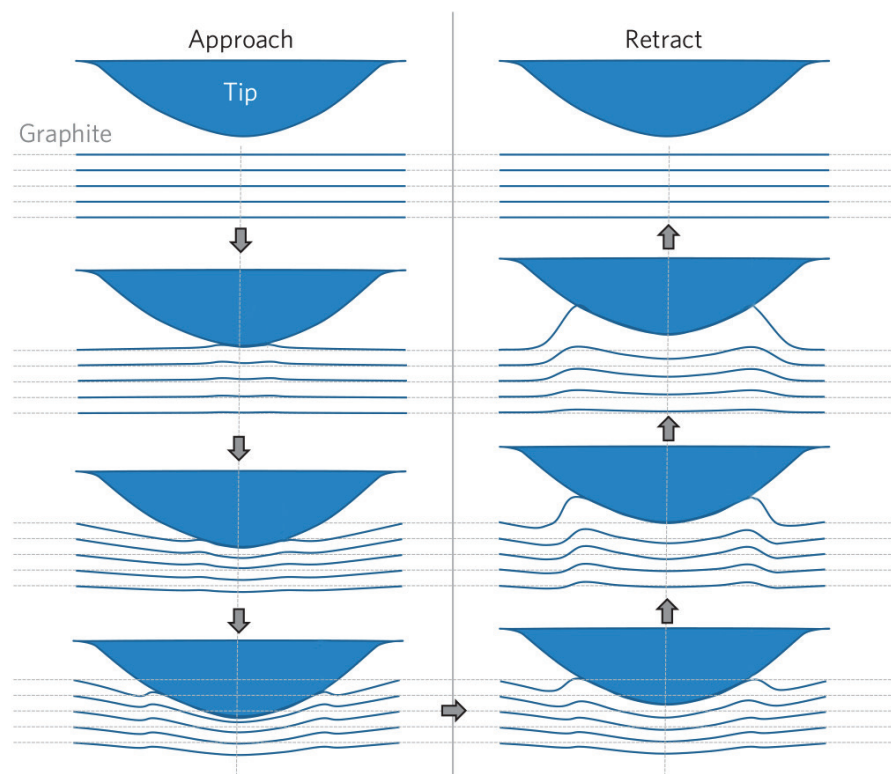
Technically, this leads to an effectively “negative coefficient of friction,” something that has not been previously seen, according to team leader Rachel Cannara. Graphite, Cannara explains, is one of a special class of solids called “lamellar” materials, which are formed from stacks of two-dimensional sheets of atoms. The sheets are graphene, a single-atom-thick plane of carbon atoms that are arranged in a hexagonal pattern. Graphene has a number of exotic electrical and material properties that make it attractive for micro- and nanoelectromechanical systems with applications ranging from gas sensors and accelerometers to resonators and optical switches.

Zhao Deng, a University of Maryland postdoctoral researcher at the CNST, noted some odd data while experimenting on graphite with an atomic force microscope (AFM). Deng was measuring the friction forces on the nanoscale tip of an AFM tracking across the graphite as he modified the “stickiness” of the surface by allowing tiny amounts of oxygen to adsorb to the topmost graphene layer.

Deng found that when the adhesive force between the graphene and the stylus became greater than the graphene layer’s attraction to the graphite below, reducing the pressure on the stylus made it *harder* to drag the tip across the surface—a negative differential friction.

Backed by theoretical simulations performed by collaborators from NIST and Tsinghua University in Beijing, China, Cannara’s team found that, after the AFM tip has been pressed into the graphite surface, if the attractive force is high enough, the tip can pull a small localized region of the surface layer of graphene away from the bulk material, like raising a nanoscale bubble from the surface. Pushing that deformation around takes more work than sliding over a flat surface. Therefore, whenever the researchers pressed the AFM tip against the sticky graphite surface and then tried to pull the two apart, they measured an increase in friction force with a sensitivity in the tens of piconewtons.

“Once we have a complete model describing how these graphene sheets deform under repeated loading and sliding at the nanoscale—which we’re working on now—friction force microscopy may be the most direct way to measure the energy that binds these layered materials together. And, since it’s nondestructive, the measurement can be performed on working devices,” Cannara says. Understanding how the sheets interact with each other and with other parts of a device would help quantify the energy required to produce individual sheets from bulk material, assess device operation, and assist in formulating new structures based on layered materials, she says.



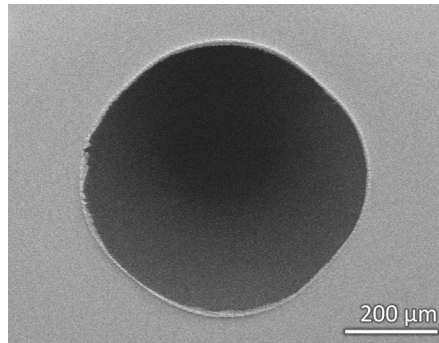
Schematic of the approach–retract cycle of the AFM tip causing the deformation of several surface and subsurface layers. As the tip presses into the sample, the contact area increases. If the attraction between the tip and the graphite is greater than the interlayer attraction, the topmost layer(s) can conform to the tip and remain attached to it on retraction. Once the tip begins to retract, it can pull a small localized region of the surface layer of graphene away from the bulk material, raising a nanoscale bubble under the surface. Pushing that deformation around takes more work than sliding over a flat surface and increases the friction force.

ENTREPRENEUR BUILDS MEMS PRESSURE SENSOR TO IMPROVE AUTOMOTIVE TRANSMISSIONS

David DiPaola, an entrepreneur whose engineering consulting company, DiPaola Consulting, LLC., is located in Gaithersburg, MD, has built a microelectromechanical (MEMS) sensor for use in an automobile transmission to detect the pressure inside of each channel that controls each gear clutch. The device is designed to allow closed loop control of automatic transmissions. This should allow automakers to cut the cost of producing transmissions by reducing the complexity of their calibrations during manufacturing.

DiPaola is developing the sensor at the request of an automobile manufacturer. The manufacturer is initially planning to use the device for calibrating transmissions and ultimately wants to incorporate it into cars as an operating component. Once it is built into transmissions, they anticipate that it will improve “shift feel.”

According to DiPaola, his greatest challenge before discovering the CNST was that, “foundries were not interested in initial development without a contract that includes non-recurring engineering costs of up to \$500,000 to bring a device into production. A small business doing early-stage development cannot guarantee a contract like



Scanning electron micrograph of a pressure sensor. A deep reactive ion etch is used to form a hole in a silicon-on-insulator wafer, leaving behind a silicon membrane which flexes as pressure changes in the transmission.

that until feasibility is shown.” However, for a few thousand dollars, plus his time, DiPaola is working in the NanoFab to create a proof-of-concept sensor and show that it can withstand the difficult conditions inside a car’s transmissions.

The prototype device is designed to withstand three times a transmission’s operating pressure or 4.55 MPa (660 pounds per square inch). By using a low profile MEMS design, DiPaola will

be able to have the sensor operate directly above the manifold inside the transmission without interfering with the transmission’s operation. He believes he can produce over 6,000 devices on a single 150 mm-diameter wafer.

His initial prototype includes all the mechanical features, and he is now working on incorporating the electronics into the next revision. The pressure sensor uses a simple silicon membrane sitting over an etched hole fabricated using deep reactive ion etching into a silicon-on-insulator wafer. The finished sensor package will consist of four to seven pressure sensors with a Wheatstone bridge attached to a piezoresistive layer on each one to measure changes in resistance due to motion in the sensor membrane. Readout from each pressure sensor will go to a custom central processing unit for signal conditioning. DiPaola anticipates he will be able to finish a packaged prototype for \$30,000, enabling him to show proof-of-concept to his customer and work with a commercial foundry to scale-up production.

RESEARCHERS DEMONSTRATE AND EXPLAIN SURFACE CONDUCTION IN A TOPOLOGICAL INSULATOR

Researchers at the University of Maryland and the CNST have for the first time experimentally demonstrated surface-only charge conduction in a topological insulator [1], and have theoretically explained the conduction using techniques previously applied successfully to the understanding of graphene [2]. The research team found that the thin Bi_2Se_3 crystals studied have unusual magneto-electronic properties that should allow such topological insulators to be used in new types of devices, including high-performance transistors, magnetic sensors, and optical

detectors. A topological insulator is an unusual type of three-dimensional material theoretically predicted to carry electric charge only on a two-dimensional boundary. As recently verified by experiment, topological insulators behave as an electrical insulator in their interior but conduct electrons on their surface. Topological insulators have also been predicted to have an unusual Dirac-type electronic band structure (shared by graphene), where the electron energy has a linear dependence on momentum as seen in photons. By directly measuring the charge

transport on the surface of thin Bi_2Se_3 crystals, the researchers showed that the behavior at the surface is consistent with a Dirac band in which the electrons are weakly interacting and disordered. These features of the Dirac band imply that, unlike graphene, the conducting electrons at the surface of topological insulators have a unique coupling between their spins and charges. This coupling could give rise to new kinds of solid state devices, including smaller magnetic components whose logic can be switched using nanoscale spin currents.

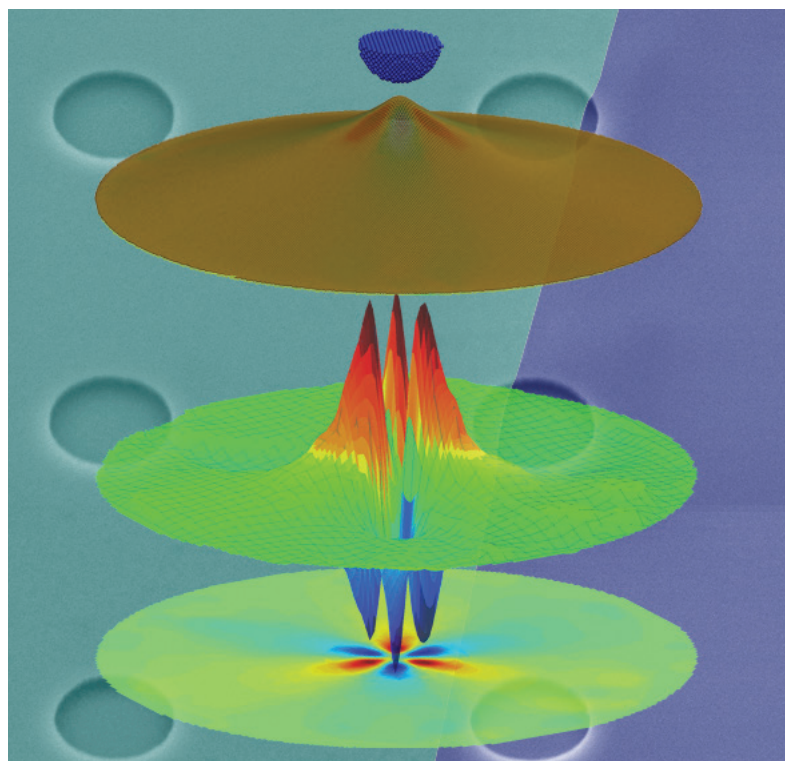
[1] Surface conduction of topological Dirac electrons in bulk insulating Bi_2Se_3 , D. Kim, S. Cho, N. P. Butch, P. Syers, K. Kirshenbaum, S. Adam, J. Paglione, and M. S. Fuhrer, *Nature Physics* **8**, 460-464 (2012).

[2] Two-dimensional transport and screening in topological insulator surface states, S. Adam, E. H. Hwang, and S. Das Sarma, *Physical Review B* **85**, 235413 (2012).

CREATING STRAIN-INDUCED QUANTUM DOTS IN GRAPHENE

Tightening or relaxing the tension on a drumhead will change the way the drum sounds. The same goes for drumheads made from graphene, only instead of changing the sound, stretching graphene has a profound effect on the material's electrical properties. As reported in *Science* [1], a team of researchers from the CNST, the NIST Physical Measurement Laboratory, and the University of Maryland have shown that subjecting graphene to mechanical strain can mimic the effects of magnetic fields and spatially confine the electrons in the membrane. This region of confined electrons forms a quantum dot, a nanoscale electronic structure with possible applications in a variety of new graphene devices, including diode lasers, amplifiers, and biological sensors.

Graphene is a single layer of carbon atoms arranged in a honeycomb lattice. Able to conduct electricity with little resistance at room temperature, graphene is a prime candidate for applications ranging from flexible displays to high-speed transistors. However, when graphene is put into device geometries, its conductivity can be reduced. The research team had previously shown that proximity to substrates changes the behavior of electrons as they move through graphene [2], leading the researchers to try to remove the substrate altogether. Nikolai Klimov, a University of Maryland Postdoctoral Researcher at the CNST, built a model system suspending the graphene over shallow holes in a substrate of silicon dioxide to make a set of graphene “drumheads.” The team then used a unique, ultra-low temperature scanning probe microscope designed and built at the CNST to probe the drumheads and found that the graphene rose up to meet the probe's tip — a result of the van der Waals force, a weak electrostatic force that attracts objects that are very close to each other. “While our instrument was telling us that the graphene was shaped like a bubble clamped at the edges, the simulations run by our colleagues at the University of Maryland showed that we were only detecting the graphene's highest point,” says Nikolai Zhitenev, who co-led the study with CNST colleague, Joseph Strosio. “Their calculations



NIST researchers showed that straining a graphene membrane creates pseudomagnetic fields that confine the graphene's electrons and create quantized quantum dot-like energy levels. The background is a false color image of the graphene drumheads made from a single layer of graphene over 1 micron-sized pits etched in a silicon dioxide substrate.

showed that the shape was actually more like the shape you would get if you poked into the surface of an inflated balloon, like a teepee or circus tent.” The researchers discovered that they could tune the strain in the drumhead using the conducting plate upon which the graphene and substrate were mounted to create a countervailing attraction and pull the drumhead down. This allowed the graphene to be pulled into or out of the hole below it. By changing the degree of strain, they could change the material's electrical properties: when they pulled the graphene membrane into the tent-like shape, the region at the apex acted just like a quantum dot, a type of semiconductor in which electrons are confined to a small region of space. The researchers believe that creating spatially confined regions like quantum dots in graphene by modifying its shape might enable new electronic applications. While the electrons normally flow

through graphene by following the segments of the material's hexagonal lattice of carbon atoms, stretching the hexagons lowers the energy near the apex of the tent-like shape and causes the electrons to move in closed, clover-shaped orbits. These orbits mimic nearly exactly how the electrons would move in a vertically varied magnetic field. “This behavior is really quite remarkable,” says Zhitenev, “while there is a little bit of electron leakage, it can be eliminated by complementing the pseudomagnetic field with an actual magnetic field.” “Normally, to make a graphene quantum dot, you would have to cut out a nanosize piece of graphene,” adds Strosio. “Our work shows that you can achieve the same thing with strain-induced pseudomagnetic fields, without the need to use bulky magnets. It's a great result, and a significant step toward developing future graphene-based devices.”

[1] Electromechanical properties of graphene drumheads, N. N. Klimov, S. Jung, S. Zhu, T. Li, C. A. Wright, S. D. Solares, D. B. Newell, N. B. Zhitenev, and J. A. Strosio, *Science* **336**, 1557–1561 (2012).

[2] Evolution of microscopic localization in graphene in a magnetic field from scattering resonances to quantum dots, S. Jung, G. M. Rutter, N. N. Klimov, D. B. Newell, I. Calizo, A. R. Hight-Walker, N. B. Zhitenev, and J. A. Strosio, *Nature Physics* **7**, 245-251 (2011).

RESEARCHERS TRACK NANOPARTICLE DYNAMICS IN THREE DIMENSIONS

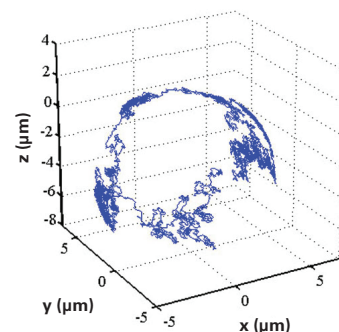
Using three-dimensional single-particle tracking, CNST researchers have measured the dynamic behavior of individual nanoparticles adsorbed at the surface of micrometer-scale oil droplets in water. The results revealed that the diffusion of the particles depends on their size, with smaller particles diffusing much more slowly than expected. A detailed understanding of how colloidal nanoparticles interact with interfaces is essential for designing them for specific applications in fields ranging from drug delivery to oil exploration and recovery. The researchers developed a feedback control system with real-time control electronics to actuate a piezoelectric stage, moving the sample in order to lock the moving nanoparticle in the observation volume of an optical microscope. The technique, which triggers off of photons collected *in situ* from an individual fluorescing nanoparticle, provides high resolution three-dimensional position information with excellent time resolution and with the added benefit of sensitivity to chemical activity.

Particles ranging in size from 20 nm to 2000 nm were followed in real-time as they diffused

freely in water and over the curved surfaces of variously-sized oil droplets. As expected, the diffusion coefficients scaled with particle size for the freely diffusing particles. However, there was a significant and unexpected decrease in the diffusion coefficients for smaller (< 200 nm) nanoparticles when they diffused at the oil-water interface. Furthermore, for a given particle size, the researchers observed a large spread in the diffusion coefficients measured at the interface, while no such effect was observed for the freely diffusing particles. In order to better fit the measurements, the basic model that works well for larger particles diffusing at a fluid-fluid interface needed to be modified to account for line tension (the one-dimensional analogue of surface tension) at the interface between the smaller nanoparticles, the oil, and the water.

The researchers believe that the variability in the diffusion coefficients of the particles adsorbed at the interface is most probably a reflection of subtle variations in the surface chemistry of the particles, suggesting that diffusion measurements may provide a new way to compare particle surface

chemistries. Whereas following the dynamics of isolated particles provides many useful insights into their behavior, typical man-made and natural systems are usually far more complex, with heterogeneous fluids, crowded environments, and strong particle-particle interactions. The researchers believe that using real-time, three-dimensional particle tracking to observe intentionally inserted, single tracer particles may provide an ideal tool to probe complicated fluid systems, such as the interior of cells, or oil/water mixtures trapped inside porous rock.



Tracked three-dimensional trajectory of a 200 nm polystyrene particle diffusing on the spherical surface of an oil-microdroplet in an aqueous solution.

Three-dimensional real-time tracking of nanoparticles at an oil–water interface, K. Du, J. A. Liddle, and A. J. Berglund, *Langmuir* **28**, 9181–9188 (2012).

RESEARCHERS DETERMINE THE OPTIMUM PATH FOR TRACKING FLUORESCENT NANOPARTICLES USING A LASER

CNST researchers Gregg Gallatin and Andrew Berglund (now at Quantifind in Palo Alto, CA) have determined the optimum path in which to scan a laser beam in order to track a fluorescing nanoparticle as the particle moves inside a fluid or gas in two or three dimensions. The ability to accurately track nanoparticles is extremely useful in biology, in fluid dynamics at the nanoscale, and in nanotechnology generally. In biology, for example, if one or more fluorescing nanoparticles are attached to a protein inside a cell then the position and orientation of that protein can be tracked as it performs its functions inside the cell. In nanofabrication, many techniques involve

nanoparticles or nanostructures coalescing to form useful materials or devices and optimizing these processes requires accurate data on how these nanostructures move. The path derived by the researchers is considered optimal because it yields the most accurate possible data on the nanoparticle's position as a function of time. The researchers developed a simple formula for determining the overall positional accuracy as a function of various standard laser beam parameters such as beam intensity and beam size. The formula for the optimum path was derived using a classical mathematical technique, the calculus of variations, and the resulting solution was verified by showing

that it satisfies the conditions of global optimality (i.e. it is the best solution among all possible solutions) using the theory of optimal experimental design. The positional accuracy was determined using classical statistical methods. Interestingly, although the path can be smooth in two dimensions, in three dimensions the beam needs to hop to achieve optimality. While the accuracy formula was derived for the most common laser beam shape, a Gaussian, the researchers are expanding the work to show how changing the laser beam's shape can further improve the tracking accuracy.

Optimal laser scan path for localizing a fluorescent particle in two or three dimensions, G. M. Gallatin and A. J. Berglund, *Optics Express* **20**, 16381–16393 (2012).

NEW METHOD FOR IMAGING DEFECTS IN MAGNETIC NANODEVICES SYSTEM

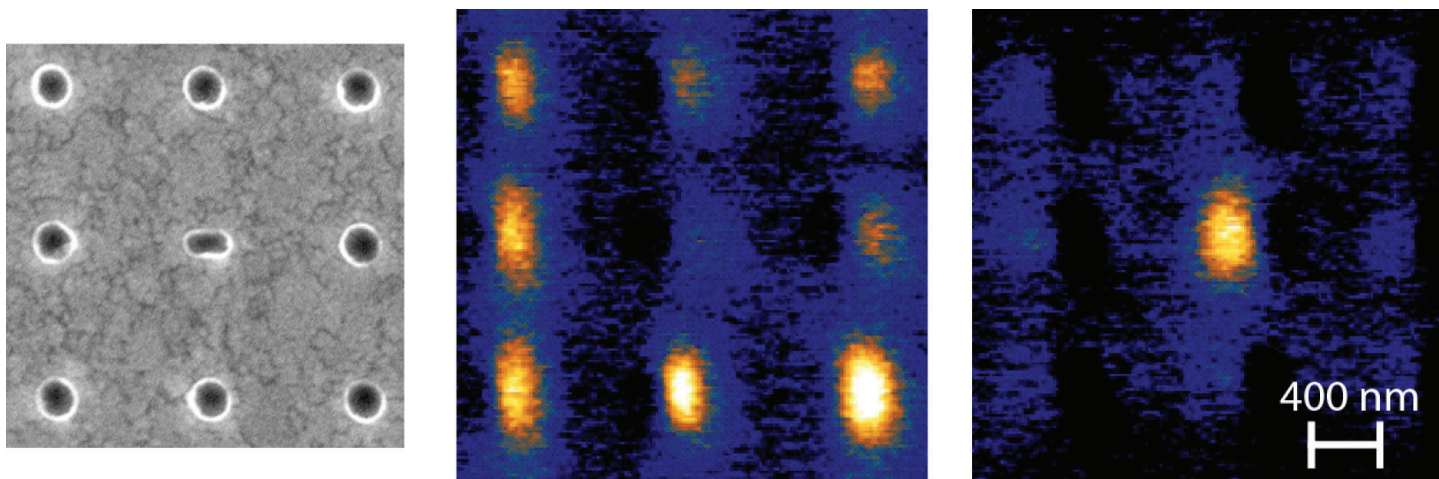
An international collaboration led by CNST researcher Robert McMichael has demonstrated a microscopy method to identify magnetic defects in an array of magnetic nanostructures. The method represents an important step towards identifying, measuring, and correcting the magnetic properties of defective devices in future information storage technologies.

The ability to detect and understand sources of defects in arrays of magnetic nanostructures is one of the key criteria in the development of future technologies that use the electron spin state to transmit and/or store information ("spintronics"). As in existing information technology, future spintronic devices for information processing will likely require large arrays of magnetic nanodevices with highly uniform magnetic properties; limiting defects will be critical to manufacturing these

arrays with tolerable yields. Minute variations in the properties between individual bits will dramatically alter the reliability of the device. Traditional metrology tools such as scanning electron microscopy (SEM) and atomic force microscopy (AFM) can detect geometrical defects but are blind both to buried devices and magnetic properties. Much more information can be obtained through spectroscopic imaging techniques such as ferromagnetic resonance force microscopy (FMRFM), a technique being developed at the CNST that combines the scanned-probe and buried-device analytical capabilities of magnetic force microscopy with ferromagnetic resonance spectroscopy. In FMRFM, a scanned cantilever probe with a magnetic tip is used to detect magnetic resonances in a sample as it is excited by microwave-frequency magnetic fields from a nearby antenna. These resonances produce small variations in the static magnetization which

change the magnetic force on the tip, providing the image contrast.

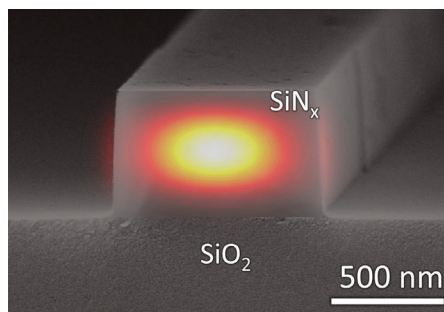
In the current work, the CNST team used FMRFM to image a magnetic nanostructure array with an intentional magnetic defect created by altering one particle's shape to an oval. In addition to demonstrating that the technique can resolve the intentional shape-induced variations, the researchers were able to measure smaller differences between unaltered, circular dots in the array. The researchers are continuing to improve the new method's sensitivity and spatial resolution, with the long-term goal of enabling wafer-level metrology for future spintronic devices.



Left: Scanning electron micrograph of an array of magnetic nanodisks with an oval-shaped "defect" structure at center. **Middle:** Ferromagnetic resonance force microscopy (FMRFM) image of the array at the resonance of the nanodisks. **Right:** FMRFM image at the resonance of the oval-shaped "defect."

RESEARCHERS DEMONSTRATE LOW-NOISE, CHIP-BASED OPTICAL WAVELENGTH CONVERTER

Researchers from the CNST have demonstrated a low-noise device for changing the wavelength of light using nanofabricated waveguides created on a silicon-based platform using standard planar fabrication technology. Optical wavelength conversion is an important resource for applications in both classical and quantum information processing: it can connect physical systems operating at different wavelengths, and facilitate improved light detection by converting light to wavelengths for which highly sensitive detectors are available. However, for many such applications the conversion process must not introduce additional noise. The researchers were able to demonstrate noise-free wavelength conversion using silicon nitride waveguides fabricated on a silicon substrate.



Scanning electron micrograph of the cross-section of a silicon nitride waveguide designed for low-noise frequency conversion with a simulation of the device's optical field profile superimposed.

These waveguides were designed based on electromagnetic simulations to determine an appropriate device geometry for a process called four-wave-mixing Bragg scattering, where an

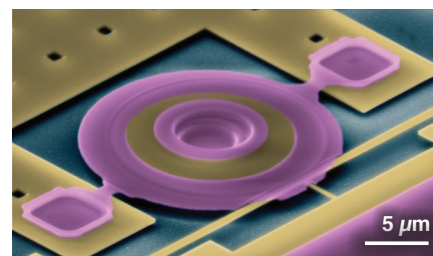
input signal field is converted to an output field whose frequency is shifted from the original by an amount equal to the difference in the frequencies of two applied pump fields. Measurements show conversion efficiencies in these devices as high as a few percent, approaching the levels needed for some applications, and with no excess noise added during the conversion process. These new noise-free frequency converters are dramatically smaller than the nonlinear crystals and optical fibers used in previous work (by several orders of magnitude), and can be created in arrays and integrated with other on-chip devices using scalable silicon-based fabrication methods. Future work will focus on increasing the conversion efficiency levels by optimizing the waveguide geometry and incorporating the waveguides into optical resonators.

Low-noise chip-based frequency conversion by four-wave-mixing Bragg scattering in SiN_x waveguides, I. Agha, M. Davanco, B. Thurston, and K. Srinivasan, *Optics Letters* **37**, 2997–2999 (2012).

A FAST AND SENSITIVE NANOPHOTONIC MOTION SENSOR FOR SILICON MICRODEVICES

Using a microscopic optical sensor that can be batch-fabricated on a silicon chip at low cost, CNST researchers have measured the mechanical motion between two nanofabricated structures with a precision close to the fundamental limit imposed by quantum mechanics. Combining a microelectromechanical system (MEMS) with a sensitive optical resonator that can be accessed using conventional optical fibers, the device provides a model for dramatically improving MEMS-based sensors such as accelerometers, gyroscopes, and cantilevers for atomic force microscopy. Traditional MEMS sensors depend on integrated electrostatic transducers with slow response times and low signal-to-noise ratios, and most scientific instruments that detect motion use bulky optics that require costly instrumentation, careful alignment, and mechanical isolation. To overcome these difficulties, the researchers created a highly sensitive position detector that relies on a silicon microdisk optical cavity that is only ten micrometers in diameter and has a similarly-sized silicon nitride ring suspended a few hundred nanometers above it. The close

proximity allows the evanescent light at the surface of the disk to interact with the ring, and changes in the strength of this interaction can be used to measure changes in the distance between them. The cavity has a high optical quality factor, meaning that light from an optical fiber can persist for several thousand resonant cycles. Combined with the high sensitivity of the optical mode to the disk-ring distance, this property enables precision displacement measurements close to the limit imposed by the quantum mechanical uncertainty principle. By using the signal from the optical cavity as an input to an electronic feedback circuit controlling a MEMS actuator that moves the ring, the researchers are able to reduce the Brownian motion of the actuator (the displacement caused by random molecular motion) by a factor of 1000. This feedback system effectively increases the mechanical force-sensing bandwidth by more than a factor of 2000, reducing the system response time to ten microseconds. The overall device achieves a combination of speed and



False-color scanning electron micrograph of a nanophotonic motion sensor. Vertical motion of the silicon nitride ring changes an evanescent light field of the silicon disk optical cavity a few hundred nanometers below it.

precision that is completely unreachable with conventional MEMS sensors. It combines extraordinary sensing performance, low power dissipation, and wide tunability with the high stability and practicality of a fully integrated silicon microsystem. The researchers are now working to integrate these sensors and actuators into highly sensitive, stable and compact cantilever probes for atomic force microscopy.

A microelectromechanically controlled cavity optomechanical sensing system, H. Miao, K. Srinivasan, and V. Aksyuk, *New Journal of Physics* **14**, 075015 (2012).

CNST SUMMER STUDENTS GAIN HANDS-ON RESEARCH EXPERIENCE

The CNST welcomed its 2012 class of summer student researchers. Nine Summer Undergraduate Research Fellowship (SURF) students, two Undergraduate Researchers who came to the CNST through the Student Temporary Employment Program, two graduate student researchers, and two High School students learned about the latest nanotechnology fabrication and measurement techniques. They participated in a wide variety of research projects ranging from characterizing photovoltaic materials using a near-field optical source to evaluating a new lateral force calibration technique for atomic force microscopy. The SURF program is sponsored by NIST and the National Science Foundation.



The CNST SURF students were among 176 at NIST, performing research, attending seminars, going on lab tours, and presenting their work at an end of summer colloquium. Left to right, top row: Janiszewski, Epstein, Lintel, Brooks, and Guss. Bottom row: Savikhin, Gianfrancesco, and Barkley.

Summer Undergraduate Researchers

Sarice Barkley, St. Olaf College

Sterling Brooks, Savannah State University

Stephen Epstein, Virginia Polytechnic Institute and State University

Anthony Gianfrancesco,
Worcester Polytechnic Institute

Summer Undergraduate Researchers

Brian Janiszewski,
University at Albany–SUNY

Eugene Kim, University of Michigan

Anton Lintel, University of Nebraska–Lincoln

Victoria Savikhin, Purdue University

Boda Song, Vanderbilt University

Bryce Thurston, Colorado School of Mines

Graduate Researchers

Tiffany Cheng, Cornell University

Kohei Ueda, Kyoto University, Japan

High School Researchers

Cory Latham, Poolesville High School, MD

Nusrat Molla, Poolesville High School, MD

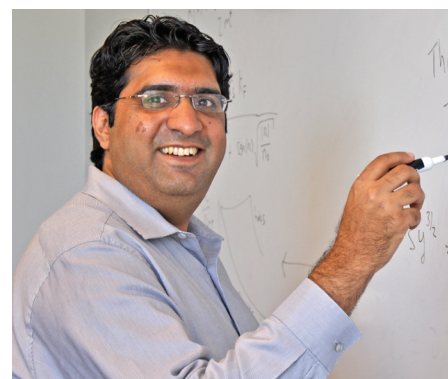
CNST'S SHAFFIQUE ADAM RECEIVES SINGAPORE NATIONAL RESEARCH FOUNDATION FELLOWSHIP

Shaffique Adam, who was an NRC Postdoctoral Research Associate in the CNST, has been awarded a 2012 Singapore National Research Foundation (NRF) Fellowship. The Fellowship provides an opportunity for a small number of “brilliant young researchers from all over the world to carry out independent research” in Singapore, and includes a five-year research grant totaling approximately \$3 million to support research on a topic of the Fellow’s choice. The NRF Fellowship is a globally competitive program, open to all nationalities, aimed at recruiting outstanding young scientists and researchers to conduct independent research in Singapore. Ten fellows were chosen out of 120 applicants from all areas of science and technology, including life sciences, physical sciences, computer science, and engineering.

Shaffique received a B.S. in Physics from Stanford University, with departmental honors and a university distinction, and a Ph.D. in Theoretical

Physics from Cornell University, where he studied the properties of nanoscale magnetic materials. Prior to joining the CNST, he was a Postdoctoral Research Associate in the Department of Physics at the University of Maryland, College Park. At the CNST, Shaffique worked with NIST Fellow Mark Stiles on theoretical studies of the physical mechanisms at play in a variety of technologically important nanomaterials, including graphene and topological insulators. His research seeks to understand these systems, and also to find a pathway to control their behavior in order to enable the development of future electronic devices. Shaffique has published over 30 manuscripts in prominent journals, including *Nature*, *Nature Physics*, *Proceedings of the National Academies of Sciences*, and *Physical Review Letters*.

In July, Shaffique joined the inaugural faculty of Yale-NUS College as an Assistant Professor



of Science, with a joint appointment in the Department of Physics at the National University of Singapore (NUS). Yale-NUS College is a joint project of Yale University and NUS, designed to create a twenty-first century model of undergraduate liberal arts and sciences education for Asia that draws on the best elements of the American liberal arts tradition.



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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National Institute of Standards and Technology
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E-mail: cnst@nist.gov



ANNOUNCEMENTS

VISIT THE CNST BOOTH AT THE



MATERIALS RESEARCH
SOCIETY FALL MEETING

Hynes Convention Center
Boston, Massachusetts
November 25 – 30, 2012



SPIE

**SPIE ADVANCED
LITHOGRAPHY SYMPOSIUM**

San Jose Convention Center
San Jose, California
February 24 – 28, 2013

NANOFAB USERS MEETING THURSDAY, DECEMBER 6, 2012 | 2 PM – 4 PM BUILDING 215/C103

Current and potential NanoFab researchers and others interested in NanoFab operations are invited to the quarterly NanoFab Users meeting. Topics typically include safety, policy changes, new equipment purchases or upgrades, research highlights, and new standard processes. Every meeting also includes an open discussion to allow users to bring ideas and suggestions to our attention. Anyone wishing to have a specific item added to the agenda, contact Vincent Luciani, 301-975-2886, vincent.luciani@nist.gov

