Thinnest generator of electricity

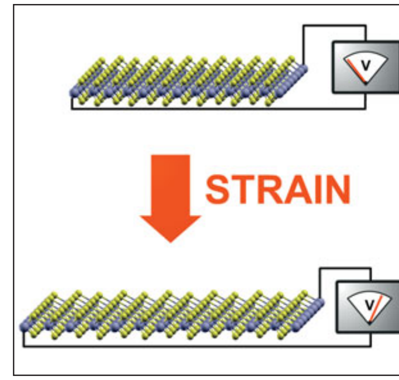
A single layer of molybdenum disulfide (MoS_2), 0.6 nm thick, generates a peak electrical output of 15 mV and 20 pA when strained by 0.53%, which corresponds to a mechanical-to-electrical energy conversion of 5.8%. These observations were made by a research team from Georgia Institute of Technology (Georgia Tech) and Columbia University, who published their results in the October 15 online edition of *Nature* (DOI:10.1038/nature13792).

The accumulation of electric charge in a material when it is stressed is known as piezoelectricity, a phenomenon discovered in 1880 by the brothers Pierre and Jacque Curie. MoS_2 (molybdenite in its mineral form) was studied as a source of molybdenum by Scheele in 1778. However, this material in bulk form cannot be piezoelectric because it has a center of symmetry, and charges from the layers cancel each other out. But in the form of a monolayer—that is a single atomic layer of Mo sandwiched between two adjacent atomic layers of S packed in a hexagonal lattice—it is no longer centrosymmetric and hence becomes piezoelectric. Theoretical work has suggested this possibility for many transition-metal dichalcogenides. Karel-Alexander Duerloo, Mitchell Ong, and Evan Reed at Stanford University calculated the piezoelectric coefficient of the MoS_2 monolayer to be 364 pC/m, using density functional theory. A research team from the University of California–Berkeley and Lawrence Berkeley National Laboratory posted a value of 290 pC/m on the arxiv.org website on August 29, 2014, from inverse piezoelectric measurements (i.e. apply voltage and measure change in force).

Electronics fabricated using piezopotential as a gate voltage to tune or control the charge-transport behavior across a metal/semiconductor interface or a *p–n* junction are called piezotronics. Transport measurements show for the first time a strong piezotronic effect in single-layer MoS_2, but not in bilayer and bulk MoS_2. According to Zhong Lin Wang of Georgia Tech, a corresponding author of the article in *Nature*, "Proof of the piezoelectric effect and piezotronic effect adds new functionalities to these two-dimensional materials." These properties greatly expand the application of layered materials for human-machine interfacing, robotics, microelectromechanical systems, and active flexible electronics.

James Hone, whose team at Columbia prepared the MoS_2 flakes and determined their crystal orientations, says, "This material—just a single layer of atoms—could be made as a wearable device, perhaps integrated into clothing, to convert energy from your body movement to electricity and power wearable sensors or medical devices, or perhaps to supply enough energy to charge your cell phone in your pocket."

The study demonstrates that the piezoelectric output can be controlled according to the number of MoS_2 atomic layers (n). When n is even the material is centrosymmetric and does not show a piezoelectric response. An odd number of layers gives rise to a piezoelectric output, where this is large and decreases roughly as the inverse of n. It also shows that serial connection of individual single-layer MoS_2 crystals flakes in a circuit can be used to boost the piezoelectric output for energy conversion.



Piezoelectricity in a monolayer of MoS_2. The larger atom is Mo. Credit: Evan Reed at Stanford University.

Reed, Duerloo, and Ong, who have studied monolayers and bilayers of two-dimensional solids, extensively describe Wang and Hone's work as creative because it has looked at the problem from many angles, and has rigorously characterized the material, which should bring it closer to device fabrication.

They point out that there are many other two-dimensional materials whose monolayer properties may turn out to be superior to those of currently used materials.

N. Balasubramanian

Digital metamaterial bits for simpler optical elements

In this Information Age, digital electronics have become a crucial part of our everyday lives. Binary, or Boolean, logic has become ubiquitous in a society so closely affiliated with personal electronics. The deceptively simple nature of the mathematical structure that uses 1s and 0s has enabled applications across a range of varied scientific fields.

In the September 14 issue of *Nature Materials* (DOI: 10.1038/NMAT4082), researchers at the University of Pennsylvania have proposed new methods of producing optical system designs using digital metamaterial "bits" and "bytes." Using simulations constructed with the COMSOL Multiphysics software, the researchers simulated the effective permittivity of two-component structures they label as metamaterial bytes; these were generated in both two-dimensional (2D) rectangular and concentric core–shell configurations. Each byte consisted of two bits, here comprising Ag and SiO_2. It was seen that by altering factors such as bit order, relative bit size, and orientation of the incident wave's electric-field polarization, significant changes in the effective permittivity of the byte could be achieved. Additionally, permittivity values could

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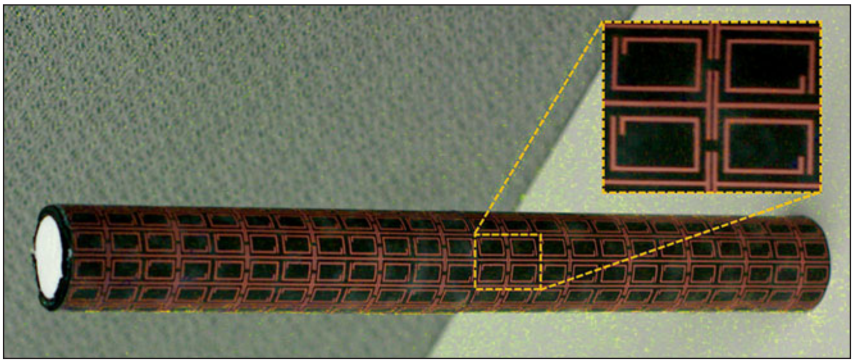
be produced anywhere between the values of the two bits or even outside that range. Thus, it was demonstrated that, given the right conditions, a wide range of effective permittivity values could be produced from just two materials. Furthermore, the electromagnetic wave scattering from the digital bytes was found to be comparable to analogous homogenized structures.

The researchers substantiated the use of these digital metamaterial bytes in a number of design structures. The core–shell digital bytes performed well in an arrangement designed to mimic a dielectric convex lens with a hyperbolic profile. By altering the order and thickness of the material bits within these core–shell bytes, a 2D graded-index flat lens architecture could also be produced. By constructing the grading in this lens from discrete, subwavelength cross-sections, spatial variation of permittivity can be controlled to a greater degree. With confirmation that these digital metamaterial bytes function well in a number of system designs, this work opens up the possibility of developing simpler, more controllable device architectures.

Ian McDonald

Tailored flexible illusion coatings hide objects from detection



Antenna covered with copper patterned dielectric substrate creates a flexible metasurface that acts as an illusion coating, cloaking the antenna or making it appear to be something entirely different. Image: Zhi Hao Jiang/Penn State.

Developing the cloak of invisibility would be wonderful, but sometimes simply making an object appear to be something else will do the trick, according to a research team at The Pennsylvania State University (Penn State).

"Previous attempts at cloaking using a single metasurface layer were restricted to very small-sized objects," says Zhi Hao Jiang, postdoctoral fellow in electrical engineering at Penn State. "Also, the act of cloaking would prevent an enclosed antenna or sensor from communicating with the outside world."

Jiang and Douglas H. Werner, the John L. and Genevieve H. McCain Chair Professor of Electrical Engineering, employ coatings made up of a thin flexible substrate with copper patterns designed to create the desired result. They can take a practical size metal antenna or sensor, coat it with the patterned film, and when the device is probed by a radio frequency source, the scattering signature of the enclosed object will appear to be that of a prescribed dielectric material like silicon or Teflon. Conversely, with the proper pattern, they can coat a dielectric and it will scatter electromagnetic waves the same as if it were a metal object. Furthermore, as they reported in the October 9 online edition of *Advanced Functional Materials* (10.1002/adfm.201401561), the metasurface is two-dimensional and lightweight rather than three-dimensional and bulky.

The researchers take the object they want cloaked and surround it with a spacer, in the form of either air or foam. They then apply the ultrathin layer of dielectric with copper-patterning designed for the wavelengths they wish to cloak. In this way, antennae and sensors could be made invisible or deceptive to remote inspection.

Another application of this material would be to protect objects from other emitting objects nearby, while still allowing electromagnetic communication between them. This was not previously possible because the cloaking mechanism electromagnetically blocked the cloaked object from the outside. However, this new coating allows the object surrounded to continue working while being protected. In an array of antennas, for example, interference from the nearby antennas can be suppressed.

The metasurface coating consists of a series of geometric copper patterns on a flexible substrate formed using the standard lithographic methods currently used to create printed circuit boards. Each illusion coating must be designed for the specific application, but the designs are optimized mathematically. This method of manufacture is low cost and well established.

Another advantage of this method is that it continues to operate properly within a 20° field of view, making it a better angle-tolerant shield than previous attempts that employed bulky metamaterials. Currently, the metasurface coatings only work on narrow bands of the spectrum for any application, but can be adapted to work in other bands of the electromagnetic spectrum including the visible spectrum.

"We haven't tried expanding the bandwidth yet," says Werner. "But the theory suggests that it should be possible and it will probably require multiple layers with different patterns to do that."

Illusion coatings could enhance the way radio-frequency ID tags work or could redistribute energy in different, controlled patterns making things more visible rather than less visible. The materials shielding ability can also be used to protect any type of equipment from stray or intentional electromagnetic interference, according to the researchers. □

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