Nano Focus

Room-temperature terahertz detectors fabricated using graphene field-effect transistors

Terahertz radiation penetrates many common dielectric materials that are opaque to visible and mid-infrared light, allowing for imaging of objects and identification of substances through their molecular fingerprints. A significant factor limiting the exploitation of this effect is the slow response of commercial terahertz detectors. Describing a new approach to overcome this problem, L. Vicarelli from Istituto Nanoscienze-CNR and Scuola Normale Superiore, Italy, D. Coquillat from Université Montpellier and CNRS, France, A. Lombardo from Cambridge University, UK, and their colleagues have recently demonstrated room-temperature terahertz detectors based on antenna-coupled graphene field-effect transistors (GFETs).

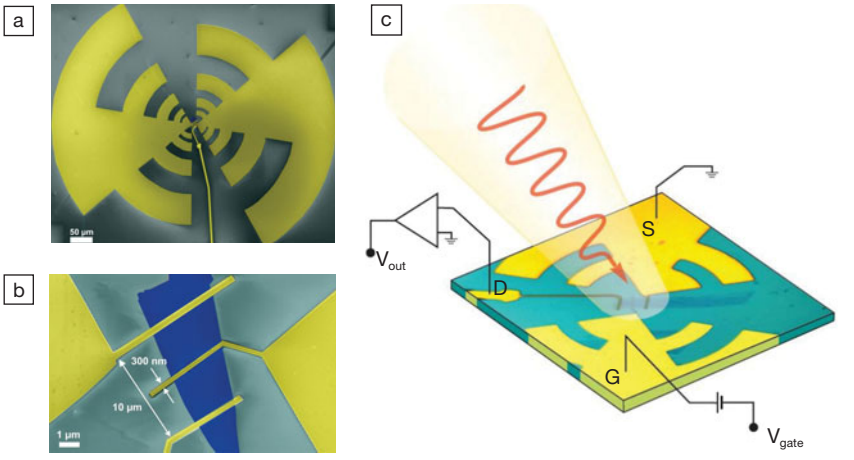
This new approach incorporates field-effect transistor, wherein terahertz detection is mediated by the excitation of plasma waves in the transistor channel. Because the two-dimensional electron gas in doped graphene has very high mobility (even at room temperature) and supports plasma waves that are weakly damped, GFET plasma-based photodetectors could outperform other terahertz detection technologies.

As described in the October issue of *Nature Materials* (DOI: 10.1038/NMAT3417; p. 865), Vicarelli and co-researchers mechanically exfoliated graphene on Si/SiO_2, and then used lithography to define a single lobe of a log-periodic circular-toothed antenna as the source contact and a metal line as a drain running to the bonding pad (see figure). After depositing an insulating layer of HfO_2, the researchers then used e-beam lithography to define an identical antenna lobe for the top gate. Calculation showed that the antenna has resonant frequencies of 0.4, 0.7, 1, and 1.4 THz.

The researchers then measured the conductivity and photoresponse to terahertz radiation at room temperature in single-layer and bilayer graphene devices while varying the gate voltage, and showed that even though a considerable fraction of the radiation field is not funneled into the GFETs, the nonlinear response to the oscillating radiation field at the gate electrode is exploited with both thermoelectric and photoconductive contributions. The noise equivalent powers (NEPs)—a figure of merit for photodetectors that corresponds to the lowest detectable power in a 1-Hz output bandwidth—are about 200 $nWHz^{-1/2}$ and 30 $nWHz^{-1/2}$ for single-layer and bilayer devices, respectively. Although these are one to two orders of magnitude larger than those for commercial detectors, the researchers said that these are upper limits; correcting for the coupling efficiency of the radiation into the nanosized transistor element would result in much smaller NEPs.

The researchers demonstrated that, even without optimization, their devices can perform large-area, fast imaging of realistic samples. Furthermore, the researchers said that their GFETs "have the potential for investigations of fundamental physics, such as the hydrodynamic behavior of chiral electron plasmas and their nonlinear instability, chirality-assisted electronic cloaking, and Zener-tunneling-induced negative differential conductivity."

Steven Trohalaki



False-color scanning electron micrographs in (a) and (b) show that the detector consists of a log-periodic circular tooth antenna located between the source and gate of a graphene field-effect transistor. The line running to the bonding pad is the drain. A Cr/Au top gate is located in the middle of the graphene channel, over the insulating layer. In (c), off-axis parabolic mirrors focus the terahertz radiation. Reproduced with permission from *Nature Mater.* **11** (2012), DOI: 10.1038/NMAT3417; p. 865. © 2012 Macmillan Publishers Ltd.

Smallest ice crystal revealed

Ice crystals have small beginnings—even smaller than previously believed. Challenging the existing belief that around 1000 molecules are required to generate a particle of ice with a true crystalline structure, a team of researchers working with Thomas Zeuch from the University of Göttingen, Petr Slavíček from the Technical University in Prague, and Udo Buck from the Göttingen-based Max Planck Institute for Dynamics and Self-Organization has now shown experimentally that crystalline order starts to form with just 275 water molecules, and that only 475 can generate a real crystalline structure.

The water molecules in ice crystals arrange themselves in a hexagonal lattice in which each water molecule forms hydrogen bonds to four adjacent molecules, and which occupies more space than liquid water, which is an unusual behavior. In the experiments performed, clusters below the minimum size for a crystal are generated with temperatures of around −180°C to −160°C. As they are

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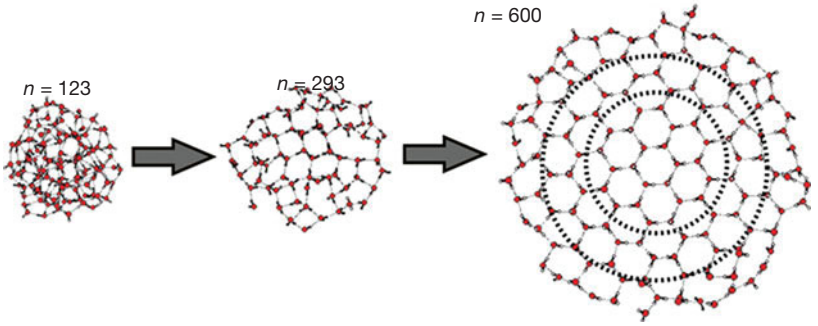

With increasing size, very cold clusters of water molecules arrange themselves as a real ice crystal. (a) When there are 123 water molecules, clusters are still completely unstructured—like a rigid liquid; (b) when there are just under 300 molecules, the hexagonal structure of the ice crystal is already discernible in the cluster's core; (c) when there are 600 molecules, the interior of the ice crystal is already perfectly formed, only the outer layer is still amorphous.
Credit: Udo Buck

too small to crystallize, they instead form a disordered, amorphous spatial lattice.

As such clusters increase in size, the water molecules at their core can change at some stage from a disordered into an ordered crystalline structure. This was first observed with 275 water molecules, where the first crystalline structure is observed in the interior of the cluster and comprises a ring of six hydrogen-bonded water molecules in a tetrahedral configuration.

To begin with, this structure is still slightly deformed. However, as the cluster increases in size, this interior grows to become a nicely ordered ice crystal, while the outer layers remain amorphous. "When there are 475 molecules, the very core is already perfect," says Buck.

As reported in the September 21 issue of *Science* (DOI: 10.1126/science.1225468; p. 1529), the researchers doped the cluster with a sodium atom and used IR excitation–modulated photoionization spectroscopy to pinpoint the onset of crystallization. Zeuch says that the sodium atom enables the cluster to be gently ionized, sorted with an electric field, and measured specifically.

The sodium atom on the surface of the water cluster also has a second function. "It acts as a type of photographic paper," says Zeuch. "We initially irradiate the clusters containing the sodium atom with the infrared light. Then we 'develop' it with a laser pulse of ultraviolet light." The sodium atom provides an infrared spectrum of the tiny water cluster. This decisive trick was the breakthrough.

The researchers now want to experimentally investigate the crystallization of other substances and their surface properties as well—accurate to one molecule, where possible.

Nano Focus

Germanium lasers may close Moore's Gap

An international team of researchers has investigated the mechanisms necessary for enabling germanium to emit laser light. As a laser material, germanium together with silicon could form the basis for innovative computer chips in which information would be transferred partially in the form of light. This technology would revolutionize data streaming within chips and give a boost to the performance of electronics. Hans Sigg of the Paul Scherrer Institute (PSI) and Jérôme Faist of ETH Zurich in Switzerland, Giovanni Isella of Politecnico di Milano in Italy, and their colleagues have demonstrated that germanium must be put under strain by an external force in order to turn it into a laser material.

While much progress has been made to increase the number of transistors in computer chips, the overall performance of processors has not been able to follow Moore's law for the past decade, and specialists are now talking about "Moore's Gap." The reason for this is that modern chips have more cores—individual processors—that can only relatively slowly communicate with each other using current technology.

"Actually, we do know a way in which this gap can be closed. The key concept is 'optical data transfer between the different cores on the chip," says Sigg. "This means partially transferring information inside a chip with the aid of laser pulses, which would significantly speed up the information exchange." In order to do this, tiny lasers are needed that can be built into chips to send out light pulses.

As reported in the August 3 issue of *Physical Review Letters* (DOI: 10.1103/PhysRevLett.109.05740; 057402), the researchers investigated those properties of germanium that are important for the generation of laser light, and compared them with those of currently available laser materials. Specifically, they quantified optical gain as a function of carrier density, strain, and doping, and highlighted the role of valence intraband absorption in limiting optical amplification for lasing.

"Our results are, on the one hand, encouraging, because germanium behaves similarly to traditional laser materials, and therefore the possibility of it emitting light cannot be excluded," says Sigg, "but with the limitation that the balance between amplification and loss is still so unfavorable in the germanium layers investigated so far that the material does not yet fulfill the condition for emitting laser light." But it has been demonstrated that this condition can be more closely approached the more the germanium is put under strain using an external force.

Correction
In the October 2012 issue of *MRS Bulletin*, Reference 27 should be cited for Figure 2 on page 933: M.J. Maloney, in *Turbine Forum* (Forum of Technology, Germany, Nice-Port St. Laurent, France, 2006).

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