Graphene goes from strength to strength

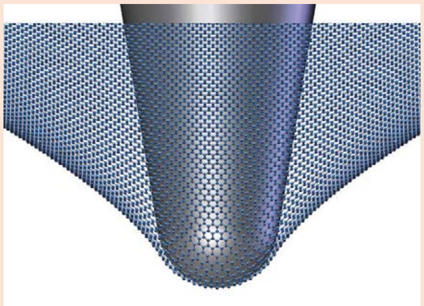
CARBON

Predictions about the phenomenal strength of defect-free graphene appear to be well-founded, according to new experimental data from researchers at Columbia University [Lee *et al.*, *Science* (2008) 321, 385].

Changgu Lee and colleagues used nanoindentation to measure the breaking strength and elastic properties of nano-sized flakes of graphene suspended over open wells. They probed free-standing monolayers of graphene with a diamond-tipped atomic force microscope (AFM) to determine the force-displacement behavior of the material.

The measurements reveal a material with second- and third-order elastic stiffnesses of 340 Nm^{-1} and -690 Nm^{-1}, breaking strength of 42 Nm^{-1}, a Young's modulus of 1 TPa, and an intrinsic strength of 130 GPa.

"This work demonstrates what has been predicted theoretically, namely that graphene is the strongest material," says Kostya Novoselov of the University of Manchester.



AFM tip deforming a graphene sheet. (Courtesy of James Hone.)

The fact that the breaking force tallies with predictions of the intrinsic strength of graphene suggests that the film in the vicinity of the AFM tip is defect-free.

These unique mechanical properties have enabled a team of researchers from the University of California at Berkeley and the Lawrence Berkeley National Laboratory to push transmission electron microscopy (TEM) toward the ultimate sensitivity [Meyer *et al.*, *Nature* (2008) **454**, 319].

The researchers have used single layers of graphene as sample-support membranes to enhance the signal-to-background ratio of light atoms such as C and H. Viewing such light atoms in the TEM is difficult because the low signal levels are drowned out by background signals from the substrate.

Graphene, however, is transparent to the electron beam. So when Alex Zettl and colleagues use it as a TEM membrane, they are able to see individual C and H atoms.

As well as imaging individual adatoms directly, the researchers also captured C chains and vacancies dancing across the surface of the membranes in real time. However, the technique is limited to atoms that are present in the TEM chamber and settle onto the graphene membrane. Adatoms have to be bound to the graphene surface to be visible.

Cordelia Sealy

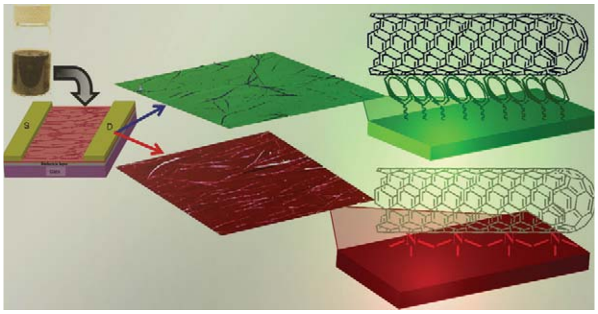
Promising future for nanotube-based electronics

ELECTRONIC MATERIALS

Semiconducting carbon nanotubes (CNTs) are promising for electronics because of their superior properties, particularly their suitability for flexible applications. But production methods yield a mixture of semiconducting and metallic tubes – so how do you deal with the problem of metallic tubes in devices?

Two recent reports outline different approaches to this conundrum. A team from Stanford University and Samsung Advanced Institute of Technology in South Korea take a 'bottom-up' approach to eliminate metallic nanotubes from devices entirely. They report a one-step process for depositing, aligning, and sorting CNTs on the surface of a Si wafer [LeMieux *et al*., *Science* (2008) **321**, 101].

The process relies on a surface oxide layer functionalized with amine- and phenyl-terminated silane groups. When a solution of single-walled CNTs is spincoated onto the wafer surface, semiconducting tubes preferentially stick to the amine-terminated areas.



Metallic carbon nanotubes (CNTs) are selectively absorbed onto phenyl functionalized surfaces (top) while semiconducting CNTs are primarily absorbed onto amine surfaces. (Credit: Melburne C. LeMieux and Zhenan Bao, Stanford University.)

"We have a simple way to separate semiconducting and metallic CNTs during deposition with control over their density and alignment," explains Zhenan Bao of Stanford.

The transistors show average on/off ratios of 900 000, with an average of ~200 000, and a field-effect mobility of 0.5-6 $cm^2V^{-1}s^{-1}$. "Since we have a much higher percentage of semiconducting tubes, we have high on/off ratios without having to burn off the metallic tubes. This will make it possible to manufacture high performance CNT transistors, sensors, and transparent electrodes," says Bao.

In contrast, John A. Rogers and colleagues at the University of Illinois at Urbana-Champaign and Purdue University [Cao *et al*., *Nature* (2008) doi: 10.1038/nature07110] do not try and eliminate metallic nanotubes from the mix, but have developed a 'top-down' approach to limit their ill effects.

By cutting patterns into the nanotube network using lithography and reactive-ion etching, the researchers limit the possibility of metallic nanotubes shorting the devices. The resulting transistors show mobilities as high 80 $cm^2V^{-1}s^{-1}$ and on/off ratios as high as 10^5.

"[This] approach enables, for the first time, fully integrated circuits based on CNTs," says Rogers. "Demonstrations on plastic substrates provide an example of the possible applications in flexible electronics."

Both approaches aim to eliminate the off-state current – either by eliminating metallic nanotubes from the device entirely or mitigating its effect. "It will be interesting to see which approach turns out to be the most valuable," says Rogers.

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