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News

## Graphene gets ready for the big time

Physicists are talking about how to make practical use of a former laboratory curiosity.

**Geoff Brumfiel**

### Pittsburgh, Pennsylvania

Physicists are in the grips of graphene madness. At last week's American Physical Society meeting in Pittsburgh, Pennsylvania, they packed conference rooms to hear about the atom-thick sheets of honeycombed carbon. Talks on graphene transistors, chemical sensors, electrodes, scales and frequency generators could all be heard, with participants from industry, notably IBM, in many of the sessions.

The ultra-thin carbon sheets have turned the normally staid community into "a herd of rhinos", says Andre Geim, a physicist at the University of Manchester, UK. And, he adds, "this year, I feel more like applications are what's driving the field."

Not everyone is sanguine about graphene's chances for going commercial. Graphene has several problems, notably a lack of an obvious 'band gap', a break in electron energy levels that would allow it to be easily used as a transistor, says Kenneth Shepard, an electrical engineer at Columbia University in New York. "There are a lot of problems with this stuff," he warns, fearing that starry-eyed researchers may overhype this latest material.

**"There have been great advances in making large-scale graphene."**

But others argue that graphene is much more promising than its predecessor, carbon nanotubes. Nanotubes, essentially rolls of graphene, have been difficult to control and integrate into existing electronics, says Tomás Palacios, an electrical engineer at the Massachusetts Institute of Technology in Cambridge. Graphene's uniformity and flatness make it easier to combine with current silicon technology, and many researchers who once worked on nanotubes are

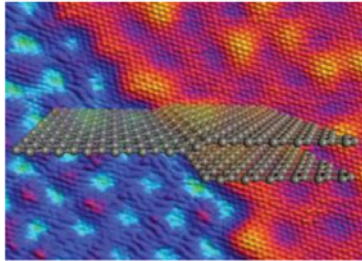
now focusing instead on graphene. The shift was evident at this year's meeting: there were 16 sessions on nanotubes, whereas graphene had 28.

Work on graphene — discovered by Geim and his colleagues almost 5 years ago (**K. S. Novoselov *et al.* *Science* 306, 666–669; 2004**) — heated up quickly as researchers realized that the material's two-dimensionality caused it to show unusual quantum behaviours (see ***Nature* 438, 201–204; 2005**). But graphene also has properties that make it alluring for certain applications. Electrical charge can fly through the sheets at high velocities, up to four times those in silicon. Large thin layers of graphene would be both flexible and transparent. Graphene ribbons might act as transistors, even though bulk graphene does not. And because graphene is so thin, even the slightest brush from neighbouring atoms can alter its mechanical and electrical properties. "It has been a fascinating material," says Marcus Freitag of IBM's T. J. Watson Research Center in Yorktown Heights, New York.

### Silicon transplant?

To turn graphene applications into reality, the material must first be synthesized in large quantities. Until now, it has often been grown on substrates of silicon carbide, a costly material that is available in only limited quantities from suppliers. But at last week's meeting, several new techniques were on display, including a way to grow graphene through chemical vapour deposition, a process widely used in the electronics industry. In one session, Byung Hee Hong of Sungkyunkwan University in South Korea reported using the technique to grow films up to 10 centimetres in diameter — a figure he soon hopes to double. "There have been great advances in making large-scale graphene," Freitag says.

While some researchers work on making more graphene, others hunt for ways to use it. The most immediate application would be as a simple electrode. Although transparent electrodes using materials



Sheet happens: graphene could have potential uses in solar cells or flexible displays.

A. WEE, NATL UNIV. SINGAPORE/H. HUANG

immediate application would be as a simple electrode. Although transparent electrodes using materials such as indium tin oxide are already commercially available, graphene's flexibility would give it an edge in solar cells and displays, says Philip Kim, a physicist at Columbia University.

Graphene also shows promise for broadband communications, in part because electrical charge can move so quickly through it. Graphene transmitters and receivers should be able to operate at frequencies on a scale of hundreds of gigahertz ( $10^9$  Hz) or even terahertz ( $10^{12}$  Hz), far better than silicon, which operates at several gigahertz, says Palacios. Higher frequencies allow for more bandwidth, and that means graphene could pave the way for broadband satellite communication. In early experiments on display at the conference, Han Wang, one of Palacios's graduate students, presented data up to one megahertz ( $10^6$  Hz), but Palacios is bullish: "We should be able to have competitive devices just a few months from now," he says.

Whether graphene can replace silicon as the basic unit of the electronics industry is another question; its lack of a band gap is a formidable problem. The most obvious solution is to cut the material into ribbons, which have discrete energy levels. But, as several groups showed in Pittsburgh, cutting the sheets creates a jagged edge of dangling chemical bonds that can pick up unwanted contaminants. Xinran Wang of Stanford University in California reported some success in using ammonia and other compounds to dope the edges of the graphene ribbons, allowing them to carry charge more easily. Even then, the scattering of electrons from the ribbon's ragged edges greatly reduces its performance. Based on these kinds of findings, Shepard believes that making these devices work will be extremely difficult. "Nothing's going to supplant silicon, not in my lifetime," he says.

Ultimately, it may be too early to tell just what graphene will — or won't — be able to do. As groups presented models and raw data from their early graphene gadgets, it became clear that many are still grappling with the latest addition to the pantheon of carbon materials. At the end of one talk, Andrea Carlo Ferrari of the University of Cambridge, UK, flashed a few slides onto the screen. Apparently, oxidizing graphene causes it to glow under infrared laser light, Ferrari told the crowd. The data are fresh, and the implications still unclear. "Will this lead somewhere?" Ferrari said afterwards with a shrug, "We don't know."

## Comments

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