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Site Search GO

Home About Scientific Press Room Contact Us

- ScienceWatch Home
- Interviews

Featured Interviews
Author Commentaries
Institutional Interviews
Journal Interviews
Podcasts

- Analyses

Featured Analyses
What's Hot In...
Special Topics

- Data & Rankings

Sci-Bytes
Fast Breaking Papers
New Hot Papers
Emerging Research Fronts
Fast Moving Fronts
Research Front Maps
Current Classics
Top Topics
Rising Stars
New Entrants
Country Profiles

- About Science Watch

Methodology
Archives
Contact Us
RSS Feeds

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TRACKING TRENDS & PERFORMANCE IN BASIC RESEARCH

Interviews Analyses Data & Rankings

What's Hot In... : What's Hot in Physics Menu : With Applications Looming, Is Graphene the New Silicon?

WHAT'S HOT IN... PHYSICS , September/October 2008

With Applications Looming, Is Graphene the New Silicon?

by Simon Mitton

PDF

Physicists and materials scientists are excited about potential applications in the semiconductor industry for a new form of carbon, known as graphene. Whenever you use an ordinary lead pencil, flakes of graphene slide off the graphite and leave their mark. Graphene is a form of carbon that is only one atom thick. The atomic structure of this two-dimensional crystal resembles a chicken wire of benzene rings, with one carbon atom residing at each 120° corner. Carbon nanotubes are graphene cylinders, and buckyballs are graphene spheres. Although nanotubes exhibit enormous strength, they are difficult to make on an industrial scale, and it is hard to incorporate them into electronic circuits. It's entirely possible that graphene technology can overcome both of these problems.

Physics Top Ten Papers

Rank	Papers	Cites Mar-Apr 08	Rank Jan-Feb 08
1	D.N. Spergel, *et al.*, "Three-year *Wilkinson Microwave Anisotropy Probe* (*WMAP*) observations: Implications for cosmology," *Astrophys. J. Suppl. Ser.*, 170(2): 377-408, June 2007. [13 U.S. and Canadian institutions] *178TD	201	1
2	C. Berger, *et al.*, "Electronic confinement and coherence in patterned epitaxial graphene," *Science*, 312(5777): 1191-6, 26 May 2006. [Georgia Tech., Atlanta; CNRS, Grenoble, France] *048OW	44	5
3	F.H.L. Koppens, *et al.*, "Driven coherent oscillations of a single electron spin in a quantum dot," *Nature*, 442(7104): 766-71, 17 August 2006. [Delft U. Technol., Netherlands] *074DK	39	7
4	L. Page, *et al.*, "Three-year *Wilkinson Microwave Anisotropy Probe* (*WMAP*) observations: Polarization analysis," *Astrophys. J. Suppl. Ser.*, 170(2): 335-76, June 2007. [13 U.S. and Canadian institutions] *178TD	35	†
5	K. Mitsuda, *et al.*, "The X-ray observatory Suzaku," *Pub. Astron. Soc. Japan*, 59(SP1): S1-7, 25 January 2007. [42 institutions worldwide] *139ON	35	†

Graphene has been around in the lab only since 2004, when scientists from the University of Manchester first isolated and named it. (Note: see the recent interview with Manchester's Andre Geim, *Science Watch*, 19[4]: 3-4, July/August 2008.) The pioneers produced graphene by repeated exfoliation, or peeling, of graphite crystals. Once graphene films were in the lab, their remarkable properties became apparent: almost no electrical resistivity, and very high electron mobility at room temperatures. These features alone mark out graphene as an attractive alternative to silicon, because the semiconductor industry has just about reached the limit of what can be achieved with silicon. Graphene's electrical qualities exceed all known materials, thus offering the potential of cooler, smaller, faster circuits.

Graphene produced by exfoliation consists of tiny flakes that are not fixed to anything. Researchers with an eye to applications and ease of handling have therefore been turning to epitaxial graphene (EG)—that is to say, graphene deposited as a film on a substrate. There's no surprise that the substrate is silicon, since the technology to handle this element is well established. Graphitic films can be grown on hexagonal SiC crystals heated to 1300° C in ultra-high vacuum. EG is multi-layered, which makes it a more complex material than exfoliated graphene. The two materials are rather different, and the electronics community is now focused on EG as a platform for nanoelectronics.

The way ahead is marked out in Hot Paper #2 from Walt de Heer's nanotechnology group at the Georgia Institute of Technology. They have investigated the electronic properties of a single layer of EG sandwiched between a SiC substrate, and an overburden of graphite. Paper #2 gives clear instructions for making EG on diced (3 mm by 4 mm) commercial SiC wafers. The later stages of the production process include electron-beam patterning, oxygen plasma etching, and wire bonding. These techniques enabled the production of a variety of devices.

6	G. Sansone, *et al.*, "Isolated single-cycle attosecond pulses," *Science*, 314(5798): 443-6, 20 October 2006. [Politec. Milan, Italy; CNR-IMIP, Rome, Italy; U. Padua, Italy; U. Naples, Italy] *096MW	33	†
7	J.B. Pendry, D. Schurig, D.R. Smith, "Controlling electromagnetic fields," *Science*, 312(5781): 1780-2, 23 June 2006. (Imperial College London, U.K.; Duke U., Durham, NC] *055LS	30	4
8	M. Tegmark, *et al.*, "Cosmological constraints from the SDSS luminous red galaxies," *Phys. Rev. D*, 74(12): no. 123507, December 2006. [36 institutions worldwide] *121QJ	29	6
9	K. Koyama, *et al.*, "X-ray imaging spectrometer (XIS) on board Suzaku," *Pub. Astron. Soc. Japan*, 59(SP1): S23-33, 25 January 2007. [12 Japanese and U.S. institutions] *139ON	29	†
10	J.K. Adelman-McCarthy, *et al.*, "The fifth data release of the Sloan Digital Sky Survey," *Astrophys. J. Suppl. Ser.*, 172 (2): 634-44, Octobre 2007. [73 institutions worldwide] *212HY	27	†

SOURCE: Thomson Reuter's Hot Papers Database. Read the Legend.

Ribbons of EG have remarkable properties. For example, electron transport is via electromagnetic waves, as in a waveguide. The width of a ribbon and its crystallographic structure can be tuned to make the material behave as either a metal or a semiconductor. The team at Georgia Tech have already demonstrated that EG can survive the processing necessary for the creation of patterned ribbons.

The results in #2 show that EG electronics can be delivered on a nanoscale and at high temperature. The material and its transport properties are suitable for electronic devices and their interconnections. Mass production of real devices requires the precision use of standard lithographical and chemical methods, and the signs are that EG will handle these requirements.

Just outside the Top Ten, the papers ranked at #11 and #12 are steadily advancing, and both tell us more about graphene in practice. In #11, Taisuke Ohta and four colleagues give the properties of the electronic band structure in bilayer graphene deposited on SiC (*Science*, 313[5789]: 951-4, 2006; with 23 citations during March-April 2008). They show how the energy gap between the valence and conduction bands can be controlled.

The band gap theme is taken up in #12, with Melinda Han as lead author, which reports on electronic transport in lithographically patterned graphene ribbons (*Phys. Rev. Lett.*, 98[20]: no. 206805, 2007; also cited 23 times this period). They find that the energy gap scales inversely with the ribbon width, thus demonstrating the ability to engineer the band gap of graphene nanostructures by lithographic processes.

Control of the band gap will be of critical importance in switching devices made from graphene, because switching functionality is indispensable in applications to computers. All three papers make a strong case for graphene electronics being just around the corner. Certainly the citations show that the race is on. The blue skies phase is already over for this field, with the research groups now chasing potential applications.

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Keywords: graphene, epitaxial graphene, Walt de Heer, Melinda Han, graphitic films, alternative to silicon.

PDF

back to top

What's Hot In... : What's Hot in Physics Menu : With Applications Looming, Is Graphene the New Silicon?

Scientific Home | About Scientific | Site Search | Site Map

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