Nano Focus

Perspectives provided on graphene for electronic and photonic devices

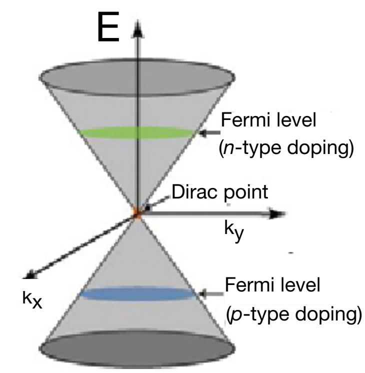
With the 2010 Nobel Prize awarded to K.S. Novoselov and A.K. Geim, for their study of graphene, a perspective by P. Avouris, at the IBM T. J. Watson Research Center, published in the November 10th issue of *Nano Letters* (DOI: 10.1021/nl102824h; p.4285) on graphene's electronic and photonic properties and devices is particularly timely. Extensive research has resulted from Novoselov and Geim's work, reflected in the atypical short amount of time between discovery and award.

As an ideal two-dimensional system with single atom thickness and noninteracting π and π* states, graphene possesses striking properties that not only enable validation of physical theory but also appear to make possible a variety of new materials for electronics and photonics applications. Although graphene shares many electrical properties with carbon nanotubes (CNTs), Avouris said that, from a practical, device point of view, the biggest difference is dimensionality; CNT's many different chiralities prevent it from being a well-defined starting material unlike graphene, whose planar geometry is suitable for the highly advanced techniques already in place in the semiconductor industry.

For energies appropriate for electron transport, Avouris said that graphene's hexagonal honeycomb lattice, with two atoms per unit cell, leads to a band structure represented by two cones that touch at and are symmetric about the Dirac energy (see figure). This demonstrates that graphene has zero bandgap, and that electrons and electron holes have the same properties. Another unusual property is that the density of states increases linearly with energy. Avouris summarized the outstanding transport properties of graphene, for example, in the ballistic regime, carriers exhibit a Fermi velocity of about 10^6 m/s with forbidden backscattering from long-range interactions resulting in elastic mean-free paths on the order of 100 nm.

Avouris discussed the challenges of using graphene in field-effect transistors due to its lack of a bandgap and made a persuasive case that graphene is an ideal material for radio frequency analog electronic devices. Current devices and approaches to fabrication problems were also presented. Methods for opening a bandgap in graphene were summarized, including cutting graphene into strips in order to reduce its dimensionality, and applying a strong electric field to graphene bilayers.

Avouris said that the combination of high light transmission and high conductivity should make graphene an excellent conductive electrode for solar cells, flat panel displays, touch screens, and organic light-emitting diodes but additional progress in producing large-area graphene multilayers with increased conductivity is required to replace the indium tin oxide currently used in these applications. Even with a zero bandgap, graphene can be used as the active element in photodetectors.



For low energy, the band structure of graphene is approximated by two cones touching at the Dirac point. The nature of the doping and the transport carriers is determined by the Fermi level. Reproduced with permission from *Nano Letters* **10** (2010) DOI: 10.1021/nl102824h; p. 4285
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Avouris concluded by saying that, "A requirement for high-end applications of graphene, particularly in electronics and photonics, is the complete control over the structure of the material, i.e., lateral size, layer thickness homogeneity, and purity. Progress in graphene research has been explosive. It is hoped that the enthusiasm will continue and that graphene will become the basis of new technologies."

Steven Trohalaki

Nano Focus

Ultrafast pump-probe measurement of electron spin relaxation of single atoms

A magnetic atom on a surface can exchange energy and angular momentum with its environment, giving it excited spin states of finite lifetime. Measuring the relaxation of these atomic states is potentially useful for quantum information processing, but achieving sufficient resolution in both space and time is a challenge.

S. Loth of IBM, M. Etzkorn of the École Polytechnique de Lausanne, and their colleagues have used a spin-sensitive scanning tunneling microscope (STM) to observe the relaxation of individual atoms with nanosecond resolution. Described in the September 24th issue of *Science* (DOI: 10.1126/science.1191688; p. 1628), their work looks at Fe atoms on a layer of Cu_2N over a Cu(100) surface. These adatoms show high magnetic anisotropy, which gives rise to long spin relaxation times, particularly when the Fe has formed a dimer with an adjacent Cu atom. A spin-polarized STM tip can be used both to probe the spin state of the dimers and to excite them to higher energy states. The researchers apply a high voltage "pump" pulse with the tip to create an excited spin state, followed by a weaker pulse to probe the state at a later interval. In its excited state the surface atom's spin is less aligned with the spin of the STM tip, giving a higher tunnel magnetoresistance and a weaker tunnel current than for the ground state atom.

By probing the state at varying

intervals after excitation, the researchers resolve an initially reduced tunneling current, which exponentially decays back to the ground state level with a relaxation time of between 50 ns and 250 ns. Control experiments in which either the tip or the surface adatom is spin inactive indicate that spin relaxation is indeed responsible for the change in current. The relaxation time is also strongly dependant on the magnetic field, which can further split the spin states and increase their lifetimes.

Significantly, it is possible to observe small differences in spin relaxation times for adatoms in slightly different surface environments. This versatile "pump-probe" technique could also be extended to monitoring the evolution of a range of surface states of suitable lifetime, such as conformational changes in molecular motors or even spin precession.

Tobias Lockwood

Energy Focus

Graphene nanosheet supercapacitor achieved high-frequency ac circuit-filtering capacity

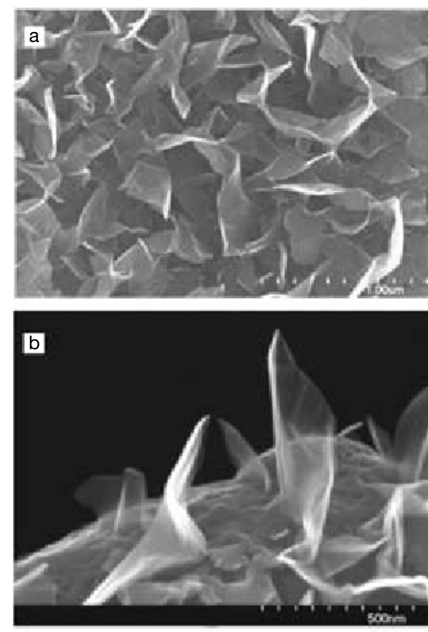
Supercapacitors, also called electric double-layer capacitors (DLC) are effective charge storage devices, and have applications ranging from electric vehicles to computer memory power backup. A major limitation of current DLCs is their inability to filter voltage ripple in rectified 120 Hz alternating current (ac) line power. The resistor-capacitor (RC) time constant, which is a measure of how fast the capacitor can be charged, is typically ~1 s for present capacitors, a value far too long for effective filtering when the period is ~8.3 ms. This limitation is caused by the highly porous nature of present electrodes, which behaves like a resistor rather than a capacitor at 120 Hz. Recently J. R. Miller of JME, Inc. and Case Western Reserve University; R.A. Outlaw of College of William and Mary, and B.C. Halloway from the Defense Advanced Research Project Agency have developed a graphene nanosheet DLC that achieved an RC time constant of 200 µs, along with other performance improvements.

As reported in September 24th issue of *Science* (DOI: 10.1126/science.1194372; p. 1637), the researchers synthesized vertically oriented graphene nanosheets on heated nickel (Ni) substrates using radio frequency, plasma-enhanced chemical vapor deposition. These graphene nanosheets were ~600 nm high and <1 nm thick. They have exposed edge planes and random open surfaces, but essentially no porosity.

This design is more effective for numerous reasons: edge planes provide higher capacitance compared to basal plane; exposed planes are directly accessible for charge storage; less porosity reduces ionic resistance; graphene is highly conductive; and ion intercalation on the edge sheet creates pesudocapacitance, another potential benefit.

The researchers prepared capacitors using these graphene nanosheet electrodes and KOH solution as electrolyte. The prototype capacitor was 2.5 cm diameter, ~175 µm thick, and weighs only ~0.8 g and at 120 Hz, showed a capacitance of 175 µF compared to 25 µF for bare nickel electrode. At a frequency less than 1 Hz, the capacitance was even greater. Use of organic electrolyte further increased the capacitance value.

The graphene DLC not only demonstrated fast response, but it also has less weight and smaller volume than competing technology, and thus very suitable for portable devices. It can be manufactured through standard semiconducting process techniques. The performance can be improved further by optimizing various parameters. The researchers are optimistic that graphene DLC will exceed the performance of current low-voltage capacitor technology.



(a) Plan scanning electron micrograph (SEM) of coated Ni electrode; (b) SEM of a coated fiber, showing plan and shallow-angle views. Reproduced with permission from *Science* **329** (2010) DOI: 10.1126/science.1194372; p. 1637. ©2010 AAAS.

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