Nano Focus

Perspectives provided on graphene for electronic and photonic devices

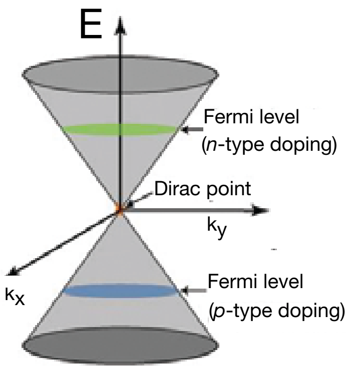
With the 2010 Nobel Prize awarded to K.S. Novoselov and A.K. Geim, for their study of graphene, a perspective by P. Avouris, at the IBM T. J. Watson Research Center, published in the November 10th issue of *Nano Letters* (DOI: 10.1021/nl102824h; p.4285) on graphene's electronic and photonic properties 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