Universal Dynamic Conductivity and Quantized Visible Opacity of Suspended Graphene

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Recommended with a Commentary by Francisco Guinea, Instituto de Ciencia de Materiales de Madrid

New, and larger, graphene flakes, and more refined experimental techniques have made possible a better understanding of the properties of graphene.

It is by now possible to obtain graphene membranes of up to 100 microns, see **Macroscopic graphene membranes and their extraordinary stiffness**, by T. J. Booth, P. Blake, R. R. Nair, D. Jiang, E. W. Hill, U. Bangert, A. Bleloch, M. Gass, K. S. Novoselov, M. I. Katsnelson, A. K. Geim, arXiv:0805.1884, **Impermeable Atomic Membranes from Graphene Sheets**, by J. Scott Bunch, Scott S. Verbridge, Jonathan S. Alden, Arend M. van der Zande, Jeevak M. Parpia, Harold G. Craighead, Paul L. McEuen, arXiv:0805.3309. These membranes can be suspended in vacuum, or over metallic gates, so that they can be doped, see **Temperature dependent transport in suspended graphene** by K. I. Bolotin, K. J. Sikes, J. Hone, H. L. Stormer, P. Kim, arXiv:0805.1830, **Suspended Graphene: a bridge to the Dirac point**, by Xu Du, Ivan Skachko, Anthony Barker, Eva Y. Andrei, arXiv:0802.2933. The mobility of carriers in suspended sheets can be significantly higher than in samples deposited on a SiO_2 substrates.

Among the experiments whose interpretation is less ambiguous is the measurement of the optical absorption of graphene, reported in the paper mentioned at the beginning of this comment. Large membranes of sizes of a few microns and different thickness were attached to copper-gold films with small apertures. The samples were annealed in an hydrogen-argon atmosphere, in order to remove hydrocarbon molecules which are easily attached to graphene.

The graphene samples are nearly transparent for light in the visible range.

The absorption is a few percent, and easily measurable. It grows linearly with the number of layers in the sample.

The well known linear dispersion of the electronic bands in graphene near the neutrality point can be described by a single material parameter, the velocity, $\mathbf{v} \approx 10^6 m/s$. This parameter drops out of the expression which gives the optical conductivity, because of the cancellation of its occurrence in the square of the matrix element of coupling to light, $\propto [\mathbf{v} \cdot \mathbf{A}]^2$ and the density of states. The result is that the optical transmision of a single graphene plane is given by $T \approx 1 - \pi\alpha$, where $\alpha = e^2/(\hbar c) = 1/137$, the fine structure constant, see **Universal dynamical conductance in graphite** by A. B. Kuzmenko, E. van Heumen, F. Carbone, D. van der Marel, arXiv:0712.0835, Phys. Rev. Lett. **100**, 117401 (2008), and **The optical conductivity of graphene in the visible region of the spectrum**, by T. Stauber, N. M. R. Peres, A. K. Geim, arXiv:0803.1802. The measured absorption fits very well this expression, providing a simple procedure for determining the value of the fine structure constant. Samples with more than one layer behave as a stack of independent graphene monolayers. This is not so obvious.

The observations have been done in the visible range, with energies of a few electronvolts. Absorption at these energies is due to transitions between the valence and conduction bands, so that the involved electron states are separated from the Dirac point by 1-3 eV. The Dirac equation in graphene is a linearization of the bands, which are derived from a tight binding model defined by a nearest neighbor tight binding energy of $t \approx$ 3eV. Hence, the bands are expected to deviate from a linear dependence of momentum on energy at energies comparable to t. It is interesting to note that these devations are rather small, of a few percent, even for transition energies of order 3eV, see **The optical conductivity of graphene in the visible region of the spectrum**, by T. Stauber, N. M. R. Peres, A. K. Geim, arXiv:0803.1802.

The band structure of multilayered graphene is modified due to the interlayer hopping of the electrons. In its simplest version, interlayer hopping is described by a term $t_\perp \sim$ 0.3eV. The value of this scale is much less than the transition energies probed in the experiments studied in the paper mentioned here. Hence, it is explainable that stacks of a few layers behave as sets of independent monolayers, leading to the discrete steps mentioned in the title of the paper.

Complementary experiments, measuring the infrared reflectance of samples with a finite number of carriers, are reported in **Dirac charge dynamics in graphene by infrared spectroscopy**, by Z. Q. Li, E. A. Henriksen,

Z. Jiang, Z. Hao, M. C. Martin, P. Kim, H. L. Stormer, D. N. Basov, Nature Phys., doi: 10.1038/nphys989. These experiments do not allow for an absolute determination of the absorption, although its dependence on different parameters can be measured. At low energies, shifts in the chemical potential lead to shifts in the absorption threshold, and change the reflectance. It is interesting to note that this absorption threshold is significantly broadened. This broadening suggests the existence of inhomogeneities in the distribution of the charge of the carriers. This observation is consistent with earlier measurements of the broadening of optical phonons due to the creation of interband electronic excitations, measured by Raman spectroscopy, see **The Raman Fingerprint of Graphene**, by A. C. Ferrari, J. C. Meyer, V. Scardaci, C. Casiraghi, Michele Lazzeri, Francesco Mauri, S. Piscanec, Da Jiang, K. S. Novoselov, S. Roth, A. K. Geim, arXiv:cond-mat/0606284, Phys. Rev. Lett. **97**, 187401 (2006) and **Electric Field Effect Tuning of Electron-Phonon Coupling in Graphene**, by Jun Yan, Yuanbo Zhang, Philip Kim, Aron Pinczuk, arXiv:cond-mat/0612634, Phys. Rev. Lett. **98**, 166802 (2007). Charge inhomogeneities in graphene, "puddles", have also been measured by monitoring the local charge compressibility, see **Observation of Electron-Hole Puddles in Graphene Using a Scanning Single Electron Transistor** by J. Martin, N. Akerman, G. Ulbricht, T. Lohmann, J. H. Smet, K. von Klitzing, A. Yacoby, arXiv:0705.2180, Nature Phys. **4**, 144 (2008).