Observation of Electron-Hole Puddles in Graphene Using a Scanning Single Electron Transistor

Authors: J. Martin, N. Akerman, G. Ulbricht, T. Lohmann, J. H. Smet, K. von Klitzing, and A. Yacoby

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One of the reasons behind the recent explosion in interest in the physics of graphene is the number of unexpected features that makes this system different from other materials. They mostly arise from the extreme two dimensional character of graphene, and its semimetallic electronic structure.

The electronic properties of graphene at the neutrality point are not well understood. One of the main puzzles is the fact that the measured conductivity tends to a value which seems sample independent, and which is higher than the theoretically predicted conductivity in the limit of few carriers and small disorder (an experimental value which was smaller than the theoretical prediction would be much less of a problem). On theoretical grounds, the Fermi wavelength should diverge at zero doping, making quasiclassical models of the transport properties invalid. In addition, the lack of screening, due to the semimetallic character of graphene, implies the existence of strong corrections to the electronic properties due to the Coulomb interaction.

The experiments reported in the paper discussed here address many of these questions. The authors probe the electronic compressibility locally, making use of a small capacitor (a single electron transistor), which allows them to measure the electrostatic potential in a small region of the sample, and to monitor the induced change in the electronic density. The device combines the versatility of the Scanning Tunneling Microscope with the sensitivity to changes in the charge of the Single Electron Transistor.

The first unexpected result coming from these experiments is that the compressibility of the electrons and holes in graphene, at high dopings, can be very well explained without including interaction corrections. So far, there is no good theoretical explanation for this.

Even more striking, the authors report that the charge distribution near the neutrality point is highly inhomogeneous, The changes in electronic density are of the order of $4 \times 10^{10}\mathrm{cm}^{-2}$. These fluctuations have a length scale $l \sim 10^2$nm, which is comparable to the resolution of the experiment. A better estimate can be obtained from the inhomogeneities observed at high magnetic fields, where disorder separates the system into localized regions, where the electron compressibility is low, and delocalized regions. This analysis gives for the actual density fluctuations a value of order $2 \times 10^{11}\mathrm{cm}^{-2}$. The associated changes in the chemical potential are in the range $0.05 - 0.1$eV. At zero field, the SET averages over these fluctuations over an scale comparable to the experimental resolution. Using the central limit theorem, one obtains that the puddles should have a typical size of order 30nm. This length is comparable to the mean free path obtained from conductivity measurements. Note that the estimates of the electron density and the electron mean free path imply that $k_{\mathrm{F}} l \sim 1$.

The existence of these charge puddles near the neutrality point is consistent with Raman experiments, see **Electric Field Effect Tuning of Electron-Phonon Coupling in Graphene**, J. Yan, Y. Zhang, P. Kim, and A. Pinczuk, arXiv:cond-mat/0612634, and Phys. Rev. Lett. **98**, 166802 (2007). The measured shift of the optical phonon frequencies depends on the carrier density of the graphene layer. In order to explain the shifts near the neutrality point, the authors of this paper postulate the existence of a finite charge density of order $3 \times 10^{11}\mathrm{cm}^{-2}$.

Other experiments have detected inhomogeneities in single layer graphene, asociated to fluctuations in the height of the layer, the graphene ripples. These modulations have been observed in free standing sheets and in layers attached to a SiO_2 substrate, see:

The structure of suspended graphene sheets, J. C. Meyer, A. K. Geim, M. I. Katsnelson, K. S. Novoselov, T. J. Booth, and S. Roth, arXiv:cond-mat/0701379, and Nature **446**, 60 (2007).

On the roughness of single- and bi-layer graphene membranes , J. C. Meyer, A. K. Geim, M. I. Katsnelson, K. S. Novoselov, D. Obergfell, S. Roth, C. Girit, and A. Zettl, arXiv:cond-mat/0703033.

Atomic Structure of Graphene on SiO_2, M. Ishigami, J. H. Chen, W. G. Cullen, M. S. Fuhrer and E. D. Williams, Nano Letters **7**, 6 (2007).

High-Resolution Scanning Tunneling Microscopy Imaging of Mesoscopic Graphene Sheets on an Insulating Surface , E. Stolyarova, K. T. Rim, S. Ryu, J. Maultzsch, P. Kim, L. E. Brus, T. F. Heinz, M. S. Hybertsen and G. W. Flynn, arXiv:0705.0833, and Proc. Nat. Acad. Sci. **104**, 9209 (2007)

Many researchers in graphene see a connection between the charge inhomogeneities found by J. Martin *et al*, and the existence of ripples. The origin and properties of these puddles have motivated a lively theoretical debate, which probably should be discussed elsewhere.