Summary of pannel discussion on transport in graphene - Moderation by A. Geim

B. HOROVITZ (BEN-GURION UNIVERSITY) PRESENTATION

B. Horovitz (B.H.) made a short presentation on the theory of shot-noise in graphene and how it can be used to experimentally determine the influence of the electron-electron interaction in a graphene sample subjected to voltage applied on the long edges of the sample. For the non-interacting case, it is shown that the electron distribution at position x between the electrodes is a z-step function, i.e. a superposition of the distribution in the two leads with coefficients that are linear in x. A tunneling experiment is suggested, in analogy with experiments on dirty wires (Pothier et al., PRL 79, 3490, 1997). In the case where Coulomb interactions are present, the shot noise at temperatures above the voltage determines the correction to the minimum conductivity at the Dirac point. At temperatures below the voltage, the shot noise is also corrected by the Coulomb interaction. The frequency dependence of the renormalised interaction allows for an experimental probe of the Coulomb interaction. Prof. Horovitz also mentioned the fact that the Fano factor remains 1/3 in this case.

A. Savchenko (A.K.): Why does one need to measure the shot-noise at finite frequency?

B.H.: As the frequency goes to zero, the influence of the interaction on the shot noise also goes to zero.

A.K.: What kind of geometry are you using and does the result depend on it?

B.H.: We consider large aspect ratio, with contacts on the wide edge, while distance between contacts is short.

A.K.: What is the influence of disorder on the value of the Fano factor? Does it still remain 1/3?

B.H.: We did not consider the effect of disorder. Other researchers (Herbut et al.) have considered the influence of random gauge fields and in this case minimum conductivity does not change.

M. Titov (M.T.): What is the relation between the frequency ω and the system size L?

B.H.: The best regime is when $\omega \ll v_F/L$, where the non-interacting part is frequency independent.

A. Geim (A.G.) from Manchester University made a presentation on the experimental measurement of the mobility of graphene on a substrate, embedded on dieletric media with high κ

A.G. refered to experiments by M. Fuhrer's group where graphene is covered with a thin layer of ice and where a 30% increase in the value of the mobility is observed. A.G. does not disagree with these results, but he does disagree with the conclusion of the cited work that there is agreement of experiment with theory, as the thickness of the ice layer is small compared to the electron's wavelength at the Dirac point and therefore the screening of charged impurities does not occur in that regime. He also mentioned the results of two publications by Tao's group (Nanoletters 2009) which stated that a 3 order of magnitude increase of mobility was observed, but on samples that presented a low very mobility in vacuum (100 $\mathrm{cm}^2/\mathrm{Vs}$). Geim's group has also made measurements on graphene embedded on glycerol and ethanol, which permit a control of the dielectric constant through a change in the temperature of the assay. A.G. warned against some pitfalls that may lead to (incorrect) observations, particularly in the case of the estimation of the electron density and that can be overcomed by Hall measurements. Taking such caveats into account, Geim's group observed an increase in mobility by a factor of two, when theory predicts that this factor should be of order ten. In summary, A. G. stated that no significant increase in mobility was seen, except on samples with very low mobility. Moreover, $\mu \leq 20,000$ $\mathrm{cm}^2/\mathrm{Vs}$ for non-suspended devices. He placed the question of which factor limits μ. The candidates were:

- Charged impurities?
- Substrate?
- Corrugations/Strain?
- Resonant scatterers?
- Something else?

A.S.: What is the effect of ripples on the mobility?

A.G.: The contribution explains the results observed within 1 order of magnitude. The strain-strain correlation functions due to ripples measured are not the ones required to explain the results. If one is pessimistic, one will say that ripples do not explain the experimental results at all. If one is optimistic one may say that are underlying, yet to be observed ripples that can explain the results. Strain measurements are needed.

A.S.: Ripples as observed until now are too smooth to explain the experimental results.

A.G.: I agree.

Phillip Kim (P.K.): High-κ media may not screen charge impurities because the impurity may be below the graphene sheet (on the substrate).

M. Kastnelson (M.K.): The Coulomb interaction due to impurities in 2d is of the form $V(q) = \frac{2\pi Z e^2}{q} e^{-qh}$, where h is the position of the impurity along the vertical direction. The exponential term is negligible if $h < 1/2k_F \approx 10$nm. In the experiments, $h \approx 1$ nm. Thus, the placement of the impurities is irrelevant.

P.K.: Yes, but for impurities located below the substrate, could it not happen that the metallic character of graphene decreases the effect of the screening due to the dielectric media above?

A.G.: Das Sarma says is the same, to have the charges above or below...

M.K.: Relevant wavevectors are of the order of k_F. Graphene is not a conductor in such a regime.

Maria Vozmediano (M.V.M): Is mobility dependent on doping?

A.G.: Doping induced is 10^{12} e/cm^2. The electron-electron distance is still large...

L. Levitov (L.L.): Is the mobility dependent on the temperature?

A.G.: We did not observe any temperature dependence.

Paco Guinea (P.G.): What is the influence of thermal annealing?

A.G.: Anealing removes PMMA from the surface. It shifts the Dirac point to $V_D = 0$ or even further as an overshoot. μ increases a little.

M. Potemski (M.P.): Did someone measure the scattering times from transport and Shubnikov-de Haas oscillations and hence determined whether scattering is long or short-ranged?

A.G.: There is one French group that has done such measurements (see poster by Monteverde et al. on this conference) and they have found that scattering is short-ranged.

M. Polini (M.Po): Self-consistent Kohn-Sham-Dirac calculations give typically very small sized e-h puddles when impurities are less than 1 nm away from the graphene flake.

A. S.: What did AG meant by clusters of impurities in his presentation, early today?

P.G.: A cluster acts like a metal contact in that it shifts the chemical potential. If its radius $R < k_F^{-1}$, the cluster is transparent to Dirac electrons (Klein's paradox). If $R > k_F^{-1}$ the mean free path l of the electrons is $l \approx k_F/n_i$ where n_i is the cluster concentration, so clusters act as single Coulomb scatterers.

Member of the audience: Do transport experiments show influence of ripples?

A.G.: It is difficult to perform such experiments.

M.K.: The ripples observed are not enough to justify results, except possibly for recent experiments...

C. Stampher (C.S.): Could you clarify what is meant by a resonant scatterer?

A.G.: It just a vacancy, for instance.