Electronic transport in graphene and bilayer graphene

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Graphene and bilayer graphene exhibit anomalous transport properties, in particular close to the charge neutrality point (CNP) where the conduction and the valence band touch. In the presence of long-range disorder the carrier density profile close to the CNP breaks up in electron-hole puddles. In this highly inhomogeneous density landscape the standard theoretical approaches to transport are not valid. In this work we present a theory to describe the transport properties of graphene and bilayer graphene that takes into account the strong disorder-induced carrier density inhomogeneities.

In most of the graphene samples charge impurities are the dominant source of scattering. The long-range disorder potential created by charge impurities induces strong density inhomogeneities. To characterize these inhomogeneities we have developed a functional approach, the Thomas-Fermi-Dirac (TFD) theory, [1], [2]. The method takes into account non-linear screening effects and is very efficient, allowing the calculation of the disorder-averaged properties of the density profile, Fig. 1. To calculate the transport properties we combine the TFD theory with the transfer-matrix approach and obtain a full quantum-mechanical transport analysis [3]. Fig.2 shows the dependence of the conductivity σ on the average doping n obtained with our theory. Fig. 3 shows the amplitude of the conductance (G) fluctuations $\langle(\delta G)^2\rangle$ as a function of n. In 2D the thermally activated motion of defects is one of the most likely causes of $1/f$ noise. In this case the strength of the $1/f$ noise can be shown to be proportional to $\langle(\delta G)^2\rangle/\langle G\rangle^2$. From Fig. 4 we see that our theory predicts that the $1/f$ noise depends non-monotonically on n as recently observed experimentally.

We have developed a qualitative understanding of transport in disordered gapped bilayer graphene (BLG) by calculating the disordered averaged fraction of the sample area, A_i, that is covered by insulating regions [4]. If $A_i > 50\%$ we expect the sample to be insulating, whereas if $A_i < 50\%$ we expect the sample to be metallic. We found the surprising result that in systems like gapped BLG in which the disorder strength is of the order of (or smaller than) than the band-gap Δ an increase of the disorder, i.e. of the impurity density $n_{\rm imp}$, can *reduce* the value of A_i. We have shown that most of the current experiments are expected to be in a regime, regime *IV* in Fig. 5, in which the disorder is strong enough to reduce A_i below 50% even at zero doping. In this regime, gapped BLG is expected to behave like a bad metal in which transport is dominated by hopping processes between electron and hole puddles that cover most of the sample. The most striking and counterintuitive consequence of our results is that in gapped BLG an *increase* of the disorder can drive the system from being an insulator to being a bad metal. This behavior is the opposite of what happens in standard large-gap two dimensional semiconductors for which regime *IV* is not present (Fig. 6).

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References

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[2] S. Das Sarma, S. Adam, E. H. Hwang, and E. Rossi, "Electronic transport in two dimensional graphene," *Rev. Mod. Phys.*, vol. 83, p. 407, 2011.

[3] E. Rossi, J. H. Bardarson, M. S. Fuhrer, and S. Das Sarma, "Universal conductance fluctuations in Dirac materials in the presence of long-range disorder," *ArXiv e-prints*, Oct. 2011.

[4] E. Rossi and S. Das Sarma, "Inhomogenous electronic structure, transport gap, and percolation threshold in disordered bilayer graphene," *Phys. Rev. Lett.*, vol. 107, p. 155502, 2011.

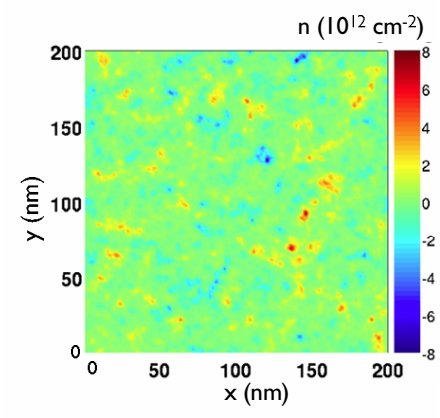

Fig. 1. Density landscape at the CNP for graphene on SiO_2 for $n_{\rm imp} = 10^{12}{\rm cm}^{-2}$

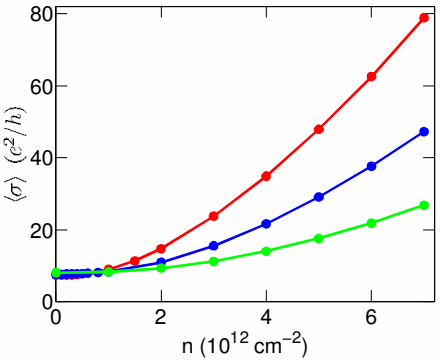

Fig. 2. Conductivity $\langle\sigma\rangle$ as a function of n for $n_{\rm imp} = (3, 5, 9) \times 10^{12}{\rm cm}^{-2}$ from top to bottom.

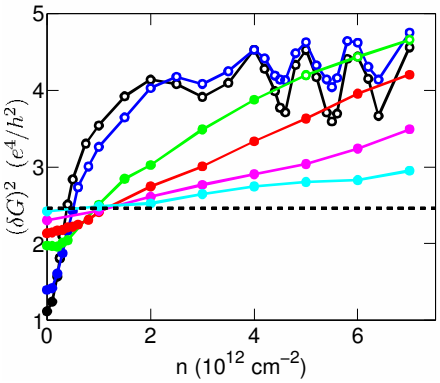

Fig. 3. $\langle(\delta G)^2\rangle$ as function of n and different values of $n_{\rm imp}$. From top to bottom (for $n = 2 \times 10^{12}{\rm cm}^{-2}$): $n_{\rm imp} = (0.682, 1, 3, 5, 9, 16) \times 10^{12}{\rm cm}^{-2}$

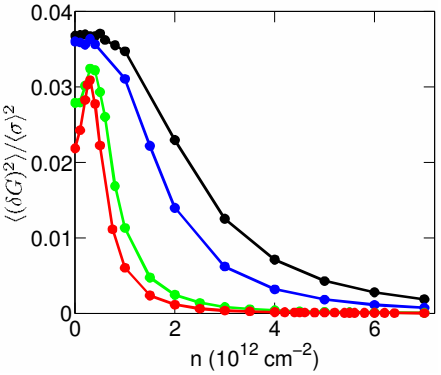

Fig. 4. $\langle(\delta G)^2\rangle/G^2$ as function of n and different values of $n_{\rm imp}$. From top to bottom (for $n = 2 \times 10^{12}{\rm cm}^{-2}$): $n_{\rm imp} = (5, 3, 1, 0.682) \times 10^{12}{\rm cm}^{-2}$.

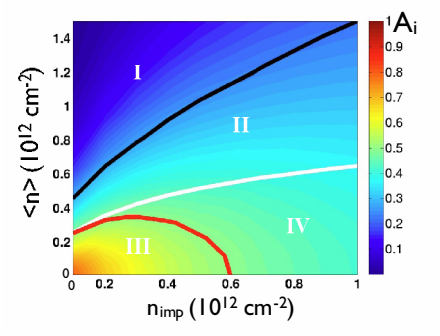

Fig. 5. Color plot showing disorder averaged A_i for gapped BLG as a function of $n_{\rm imp}$ and $\langle n\rangle$ for $\Delta = 125$ meV

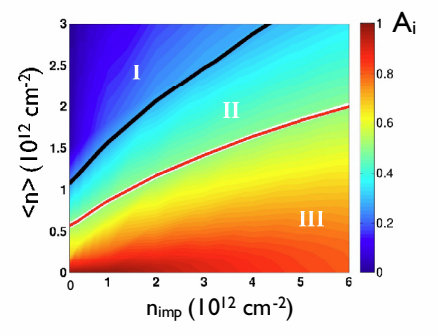

Fig. 6. Color plots showing disorder averaged A_i for gapped BLG as a function of $n_{\rm imp}$ and $\langle n\rangle$ for $\Delta = 500$ meV,