Non-local transport and the hydrodynamic shear viscosity in graphene

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ACKNOWLEDGEMENTS

This work was partially supported by MIUR through the program “Progetti Premiali 2012” - Project “ABNANOTECH”. Free software (www.gnu.org, www.python.org) was used. We thank M.F. Crommie, This work was partially supported by MIUR through the program “Progetti Premiali 2012” - Project “ABNANOTECH”. Free software (www.gnu.org, www.python.org) was used. We thank M.F. Crommie, and observed in differential resistivity measurements at high current densities in both micrometer-scale ballistic transport even at room temperature, whereas local equilibrium in the system is provided by free electron-electron collisions. Under those conditions, electrons in doped samples behave as a highly viscous liquid and may exhibit hydrodynamic phenomena similar to classical liquids. Here [1] we present a theoretical study of dc transport in graphene in the hydrodynamic regime. By using the linearized continuity and Navier-Stokes equations, we demonstrate analytically that measurements of non-local resistance in multi-terminal Hall bar devices can be used to extract the hydrodynamic shear viscosity of the 2D electron liquid in graphene. Our approach is able to explain the experimental findings of Ref. [2] and can be straightforwardly generalized to any 2D electron liquid in the hydrodynamic transport regime.

HYDRODYNAMIC THEORY

The region of parameter space where hydrodynamics can be applied is determined by two inequalities between the characteristic length scales of the system:

\[ L_{c} \ll L_{W}, \]

where \( L_{c} \) is the \( ee \) mean free path, \( L_{W} \) is the momentum relaxation length and \( W \) is the sample size.

Near room temperature, \( L_{c} \) in graphene becomes of the order of \( \sim 10^{-9} \text{m} \) [3, 4], while \( L_{W} \) remains above \( \sim 1 \text{um} \) even at room temperature [5] in ultra-clean, h-BN encapsulated samples. Hydrodynamics is therefore useful in describing transport in micrometer-size graphene devices in a wide range of densities \( n \sim 10^{12} \text{cm}^{-2} \) at temperatures \( T \sim 150 \text{K} \).

The equations of hydrodynamics are the continuity and Navier-Stokes equations [6]. Here we use them in linearized form, including force terms in the Navier-Stokes equation arising from:

- electronic field;
- electric field;
- momentum-non-conserving collisions;

\[ \text{∇} \cdot \text{J}(r) = 0, \]

\[ \text{∇} \times \text{J}(r) = 0. \]

The shape of the solutions of Eqs. (2-3) is determined by the vorticity diffusion length:

\[ D_{\nu} \approx \sqrt{\nu \tau}. \]

This depends on \( ee \) interactions through the kinematic viscosity \( \nu \) and on momentum-non-conserving collisions through \( \tau \).

Hydrodynamic equations are supplemented with the following Boundary Conditions (BCs) on the normal and tangential components of the current at the boundaries of the system:

\[ J_{n}(x,y=\pm W/2) = J_{n}(x) \]

\[ \mu_{\nu} \frac{\partial J_{n}(x,y=\pm W/2)}{\partial x} = J_{n}(x,y=\pm W/2) \]

Here \( \mu_{\nu} \) is related to the friction exerted by the boundary of the system on the electron liquid.

LONGITUDINAL TRANSPORT

Electron liquid viscosity has in general little impact on normal four-point resistance measurements. For \( \mu_{\nu} \gg W, L_{\nu} \), no effect of viscosity is present and the four point resistance is controlled only by momentum-non-conserving interactions. Interestingly, if a certain amount of boundary scattering is present, viscosity is responsible for the anomalous decrease of the resistivity with temperature predicted by Gurzhi [7] and observed in differential resistivity measurements at high current densities in both GaAs [8] and graphene [2] devices.

REFERENCES