Experimental Evidence to the Hydrodynamic Electron Flow in Graphene

D. A. Bandurin[1], **R. Krishna Kumar[1,4]**, **I. Torre[2,3]**, **M. Ben Shalom[1,5]**, **L. A. Ponomarenko[1,4]**, **I. V. Grigorieva[1]**, **M. Polini[3,6]**, **A. K. Geim[1]**
[1]*School of Physics & Astronomy, University of Manchester, Oxford Road, Manchester M13 9PL, UK*
[2]*National Enterprise for nanoScience and nanoTechnology, Scuola Normale Superiore, I-56126 Pisa, Italy*
[3]*Istituto Italiano di Tecnologia, Graphene labs, Via Morego 30 I-16163 Genova (Italy)*
[4]*Physics Department, Lancaster University, Lancaster LA14YB, United Kingdom*
[5]*National Graphene Institute, University of Manchester, Manchester M13 9PL, United Kingdom*
[6]*National Enterprise for nanoScience and nanoTechnology, Istituto Nanoscienze-Consiglio Nazionale delle Ricerche and Scuola Normale Superiore, I-56126 Pisa, Italy*
denis.bandurin@manchester.ac.uk

Theoretical and experimental studies of systems in which particles undergo frequent mutual collisions date back to more than two centuries ago. Transport in such systems is described by hydrodynamic theory that was found very successful in explaining the response of classical liquids and gases to external fields [1]. It has been argued for a long time that collective behaviour of charge carriers in solids can be also treated by hydrodynamic approach. However, there has been almost no direct evidence to hydrodynamic electron transport so far [2]. This is because the conditions at which the hydrodynamic effects become observable are very strict: the electron-electron scattering length should provide the shortest spatial scale in the problem. First of all, this requires ultra clean systems where the scattering at impurities is diminished. Second, the electron-phonon scattering rate should be smaller than that of electron-electron scattering.

Due to weak electron-phonon coupling high mobility graphene devices offer an ideal system to study electron hydrodynamics. To amplify the hydrodynamic effects we employed a special measurement geometry shown in Fig. 1C [3]. The idea is that in case of hydrodynamic electron flow, vortices emerge in the spatial electric current distribution near the current injection contact (Fig.1 B). That results in a development of a negative voltage drop at the nearby contacts (Fig. 1E). We were able to detect such negative signal over the range of temperatures when the electronic system is in a hydrodynamic regime. Finally, we performed a rheological study of electron liquid in graphene. The electron viscosity was found to be an order of magnitude larger than that of honey which is in good agreement with many-body calculation.

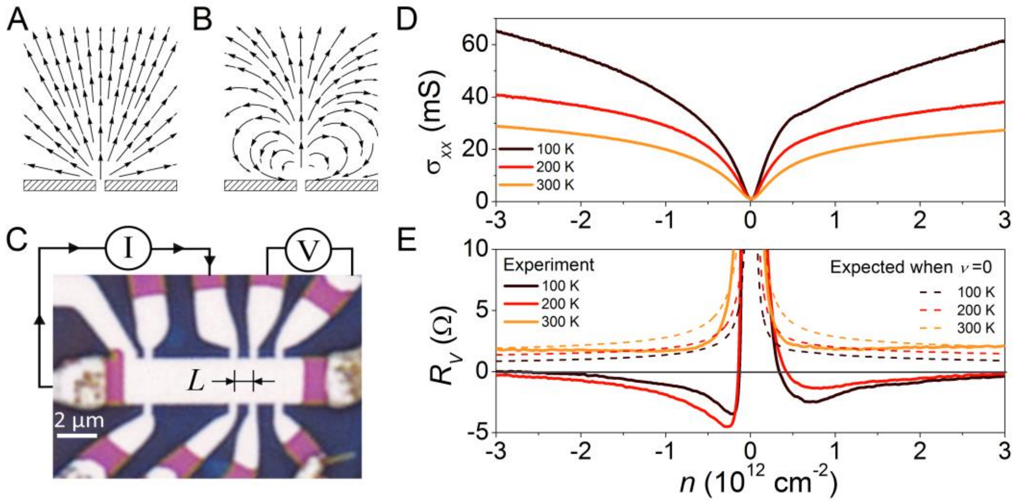

Fig. 1. (A,B) Steady-state distribution of current injected through a narrow slit for a classical conducting medium with zero viscosity (A) and a viscous Fermi liquid (B). (C) Optical micrograph of one of our SLG devices. The schematic explains the measurement geometry for vicinity resistance. (D,E) Longitudinal conductivity and vicinity resistance for this device as a function of the carrier density induced by applying voltage to top and back gates. Dotted lines correspond to the expected values in case of zero viscosity.

[1]L. D. Landau & E. M. Lifshitz. *Fluid Mechanic*, (Pergamon, New York, 1987).
[2] M. J. M. de Jong, L. W. Molenkamp. Hydrodynamic electron flow in high-mobility wires. Phys. Rev. B **51**, 13389 (1995).
[3]D. Bandurin et al., Science, **351**, 2016.