Visualization of charge transport through Landau levels in graphene

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Band bending and the associated spatially inhomogeneous population of Landau levels play a central role in the physics of the quantum Hall effect (QHE) by constraining the pathways for charge carrier transport and scattering. Spatially inhomogeneous charge distributions, e.g., due to adsorbate-induced surface doping, are expected to be particularly pronounced in graphene due to the proximity of the carrier gas to the surface, and can cause significant deviations from pure edge-state transport. Progress in understanding such effects in low-dimensional carrier gases in conventional semiconductors has been achieved by real-space mapping using local probes. We have recently developed spatially resolved photocurrent microscopy in the QHE regime, i.e., at variable temperature from 300 K to 4 K and at high magnetic fields, to study the correlation between the distribution of Landau levels and the macroscopic transport characteristics in graphene [1].

The conductance of typical two-terminal graphene devices (fig. 1 a) shows series of local extrema associated with individual Landau levels, with maxima predicted to occur at quantized Hall conductances of 2, 4, 6, 10, and 14 e^2/h [2]. The observed maxima are consistently higher (fig. 1 c), suggesting deviations from ideal edge transport in these devices. We find that the gate-voltage dependent photocurrent at fixed locations is oscillatory, with polarity determined by the direction of the magnetic field (fig. 1 d). Such local oscillations are due to a recurring global photocurrent distribution across the device, synchronous with the filling of consecutive Landau levels, which can be used to visualize the gate-voltage dependent distribution of Landau levels in the graphene channel.

Based on an analysis of the photocurrent generation mechanism in graphene subject to a quantizing magnetic field, we conclude that quantum Hall transport in graphene is governed by a non-uniform potential distribution across the channel (fig. 2 a). Multiple inhomogeneously filled Landau levels are populated simultaneously, with the dividing boundaries (traced in the experimental map of fig. 2 b) expected to form incompressible barriers that profoundly affect the electrostatic landscape and current pathways in the device. Besides Landau level mapping at low temperatures, we discuss the extension of photocurrent microscopy to imaging the temperature-dependent quantum Hall transport in graphene up to room temperature, and for characterizing the energy landscape across the graphene channel.

References

[1] G. Nazin, Y. Zhang, L. Zhang, E. Sutter, and P. Sutter, Nature Physics, **6** (2010) 870.

[2] J.R. Williams, L. DiCarlo, and C.M. Marcus, Science, **317** (2007), 638.

Figures

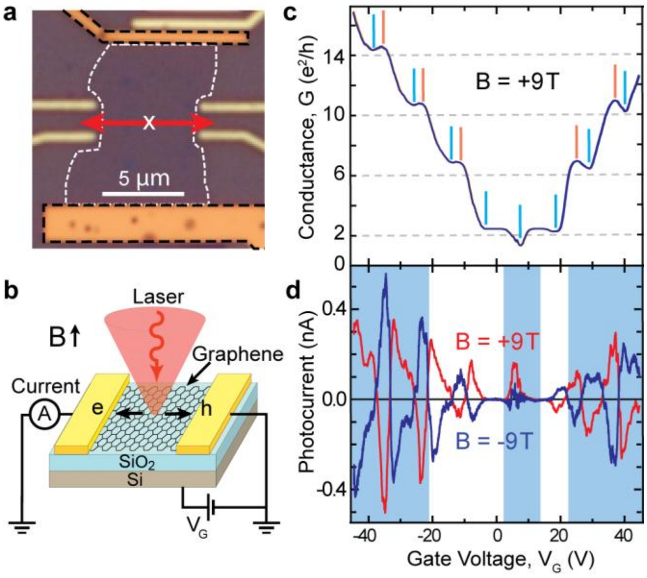

***Figure 1 – Low-temperature photocurrent measurements on graphene devices. a** – Optical image of a typical two-terminal device. Dashed outlines mark the channel and the two connected electrodes. **b** – Schematic diagram of the photocurrent measurement. **c** – Conventional two-terminal conductivity, G, as a function of gate voltage, V_G, measured at T = 4.2 K. Blue and red lines mark local conductivity minima and maxima. **d** – Photocurrent measured with laser spot at the center of the graphene channel (cross in **a**) for B = ±9 T.*

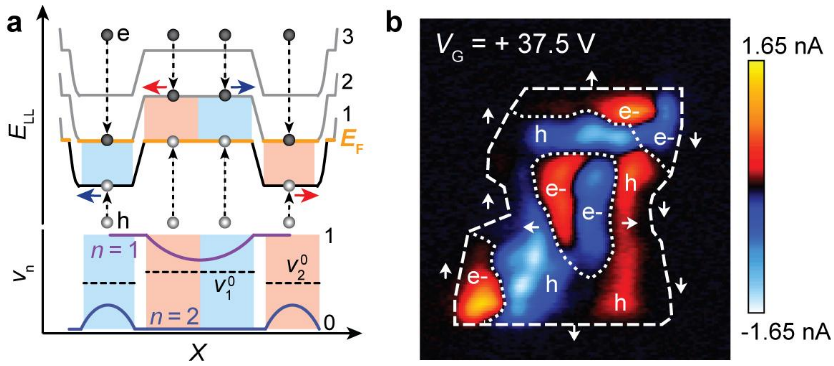

***Figure 2 – Mapping photocurrent collection and the distribution of Landau levels in graphene. a –** Dominant pathways of charge carrier relaxation and collection across the graphene channel (spatial dimension: X), for n-doped graphene in the case of two Landau levels (n = 1, 2) at E_F inside the channel, and local filling factors, ν_n, of these levels across the device. Colored rectangles connect the Fermi level with the Landau levels responsible for carrier transport; the color indicates the resulting photocurrent polarity. **b –** Experimental photocurrent map at gate voltage V_G = +37.5 V and magnetic field B = 9 T, measured on the device of fig. 1 a. The distributions of individual Landau levels at E_F, and of the incompressible boundaries between them are indicated as dotted contours.*