Temperature Dependence of Electric Transport in Few-layer Graphene under Strong Electrochemical Gating: Scattering and Weak Localization

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The temperature dependence of electric transport properties of single-layer and few-layer graphene (FLG) at large charge doping is of great interest both for the study of the scattering processes dominating the conductivity at different temperatures and in view of the theoretically predicted possibility to reach the superconducting state in such extreme conditions [1, 2].

Here we present the results of electric transport measurements in 3-, 4- and 5-layer exfoliated graphene samples with Bernal stacking (3LG, 4LG and 5LG in the following) down to 3.5 K and up to an induced surface charge density that ranges from about $5 \cdot 10^{14}$ cm^{-2} in 3LG to about $7 \cdot 10^{14}$ cm^{-2} in 5LG. This huge charge doping was obtained by using a novel polymer electrolyte solution (PES) of improved efficiency for the electrochemical gating [3]. Figure 1a shows a picture of one of the devices with the indication of the electric contacts for the four-wire measurements and the application of the gate voltage. The induced charge density was determined by comparing the results of a well-known electrochemical technique called double-step chronocoulometry (DSCC) [4] with the ones of classic Hall-effect measurements.

In all these experiments the increase of the charge density (both positive and negative) produces a strong decrease of the sheet resistance, but no trace of superconducting transition has been observed (see Figure 1b).
However, in contrast with recent results obtained in single-layer graphene [5], the temperature dependence of the sheet resistance between 20 K and 280 K reproducibly shows a low-temperature dominant T^2 component – that can be interpreted as being due to electron-electron scattering – and, at about 80 - 100 K, a crossover to the classic electron-phonon linear regime [6], as can be seen in Figure 1c. Unexpectedly this crossover temperature – that can be associated to the Bloch-Grüneisen temperature of the material – does not show any dependence on the induced charge density, i.e. on the large tuning of the Fermi energy [6].

References

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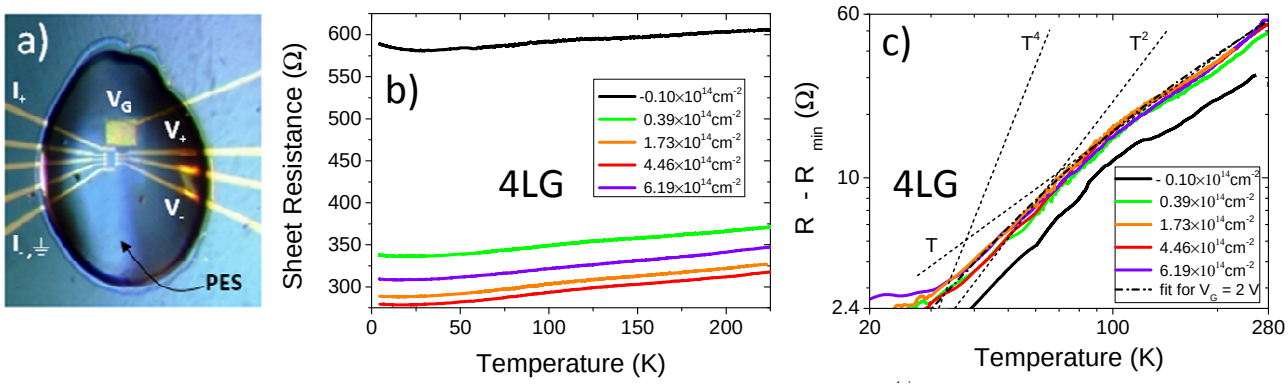

Figure 1: a) Micrograph of one of the FLG devices; b) T dependence of the sheet resistance at different gating-induced surface charge densities in a 4LG device for electron doping; c) Log-log plot of the increase of the sheet resistance in the range 20–280 K for the same 4LG device

At very low temperature (< 20 - 30 K) a logarithmic upturn of the sheet resistance is observed in all the FLG devices, that strongly depends on the induced charge density n_{2D} as shown in Figure 2a. This behaviour and the measured low-T dependence of the sheet resistance in presence of magnetic field is unambiguously interpreted in terms of weak localization (WL) of electrons in few-layer graphene, i.e. the quantum correction to the conductivity due to constructive interference between pairs of time reversed electron trajectories [7].

By fitting the low-T magnetic-field dependence of WL with models for graphene we conclude that the term depending on the parity of the number of layers can be neglected in the equation for the T dependence of WL. We can thus express this dependence only as a function of the ratio τ_ϕ/τ_i , where τ_ϕ is the phase coherence lifetime associated to inelastic scattering processes and τ_i is the intervalley scattering time. Figure 2b shows this ratio as a function of T for the 4LG device. By using the results of ab-initio DFT and tight-binding calculations, together with the experimental conductance in the intermediate T range (20 – 90 K), we are then able to determine $\tau_\phi(n_{2D}, T)$ and the transport scattering time, $\tau_{tr}(n_{2D})$. Finally $\tau_i(n_{2D})$ can be determined from the ratios τ_ϕ/τ_i [7]. Figure 2c shows the dependence on charge doping of the characteristic scattering times in the 4LG at 4 K. Unexpectedly $\tau_{tr}(n_{2D})$ and $\tau_\phi(n_{2D})$ decrease at the increase of n_{2D}, probably due to the introduction of extra point-like scattering centers.

In conclusion the multiband nature of FLGs and the important role of intervalley scattering ($\tau_i \approx \tau_\phi$) make their electronic properties quite different from the ones of SLG at a doping close to the intrinsic maximum fixed by the quantum capacitance of devices. One possible side effect of our electrochemical gating is the introduction of point-like scattering centers.

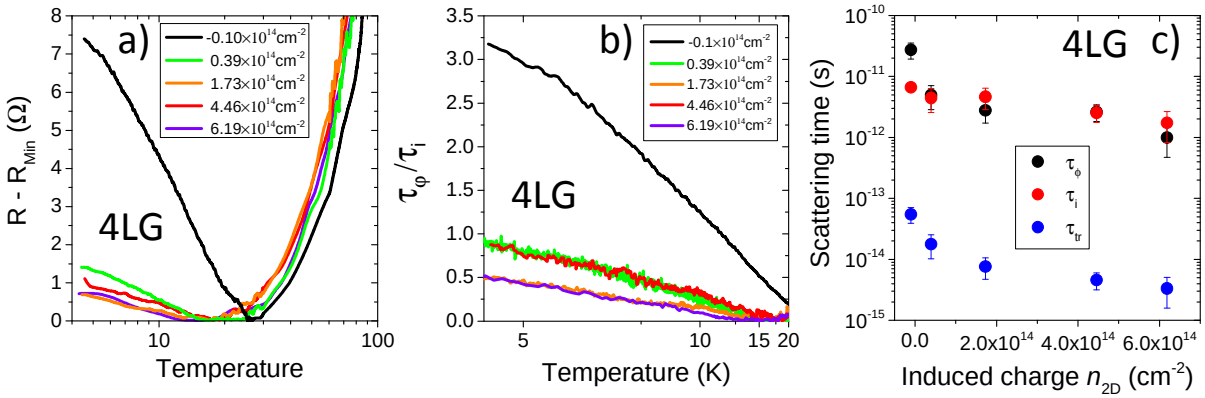

Figure 2: a) Semi-log plot of the low-T increase of the sheet resistance for the 4LG device shown in Fig. 1b; b) Temperature dependence (in reciprocal scale) of the ratio τ_ϕ/τ_i for the same device; c) Charge-doping dependence of the scattering times for the same device.