Unveiling the Landau Levels Structure of Graphene Nanoribbons

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In the present work we show the first experimental evidence of Hall quantization in graphene nanoribbons along with the impact of the 1-D confinement of Dirac fermions.

Carbon-based nanoelectronics is, in the actuality, one of the most promising subjects of nanotechnology. The challenging task for technologists is the achievement of clean devices with an engineered energy gap. The lateral confinement in graphene nanoribbons leads to a series of 1-D electronic sub-bands with a confinement gap. In presence of a large enough magnetic field, the band structure evolves to magneto-electric sub-bands and graphene-like Landau levels are expected to develop. The presence of these Landau levels makes itself evident with the appearance of Shubnikov-deHaas (SdH) oscillations and conductance quantization plateaus.

Up to now, Hall quantization in graphene nanoribbons (GNRs) remains puzzling since no experimental evidence has been found for widths smaller than 200 nm [1-4]. The absence of Hall quantization in GNRs has been attributed to disorder, which is suspected to crosslink the chiral edge currents and impede the conductance quantization.

Lithographically patterned GNRs of 100 and 70 nm widths are made using oxygen plasma etching and a PMMA etching mask. These GNR present a high conductance, a high field effect mobility and a weakly diffusive transport regime with presence of Fabry-Perot oscillations at low temperature. Magneto-resistance (MR) measurements show the first experimental evidence of Hall quantization in GNRs (Fig. 1) for filling factors ν = 2 and 6. On the other hand, anomalies in the magneto-transport measurements are evidenced:

(i) At high electrostatic doping level SdH oscillations show a clear departure from the regular linear behaviour of the Landau index as a function of 1/B (Fig. 1(a) inset). This is a direct signature of the electronic confinement that starts to overcome the magnetic confinement.

(ii) The maxima of MR for all the ribbons, fingerprint of the Landau levels depopulation [5], present an up-shift of several Tesla compared to the theoretical value [6].

(iii) The narrower ribbons exhibit the expected $6G_0$ conductance maxima for a two-terminal measurement [5] but the $2G_0$ plateau is absent and the depopulation of the N=2 Landau level goes along with an unusual double peak of the resistance (Fig. 1(b)).

To unveil the origin of the singular Landau spectrum we performed numerical simulations of the GNR band structure as a function of the perpendicular magnetic field and self-consistent calculations of the carrier distribution under magnetic field. We directly compared the oscillatory behaviour of the magneto-resistance and the onset of the magneto-electric sub-bands (Fig. 2). The simulations give evidence of magneto-oscillations of the Fermi energy (blue line in Fig. 2) which consistently explains the broadening of the magneto-resistance peaks and their up-shift lo larger magnetic field. The presence of a second peak in the MR spectrum (Fig. 2 (b)) also finds a natural explanation: this is the clear signature of the orbital degeneracy lifting enhanced by the magnetic field and the pinning of the Fermi energy.

References

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Figures

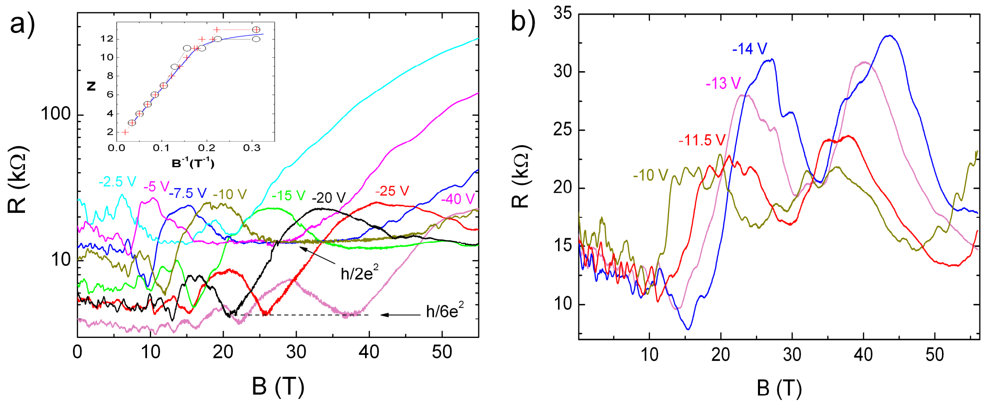

Fig 1. Two terminal magneto-resistance measurements in a) GNR of 100nm width exhibiting the h/2e^2 and h/6e^2 quantization Hall resistance. Inset: Landau level index as a function of 1/B from: experimental magneto-resistance (circles) at high electrostatic doping, band structure calculations (crosses) and calculations of occupied sub-bands in a hard-wall confinement.

b) Magneto-resistance of a GNR of 70nm width with the presence of a double resistance peak in the crossing of N=2 Landau level.

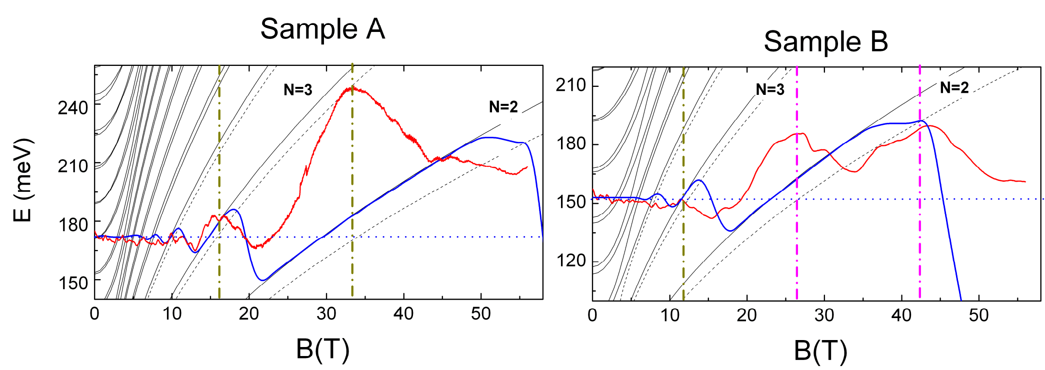

Fig 2. Numerical simulation of the band structure (black lines) in 814-aGNR (100 nm, Sample A) and 571-aGNR (70 nm, Sample B), self-consistent calculations of the Fermi energy under magnetic field (blue curve) and direct comparison with magneto-resistance measurements (red curve).