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# Quantum Hall effect in monolayer, bilayer and trilayer graphene

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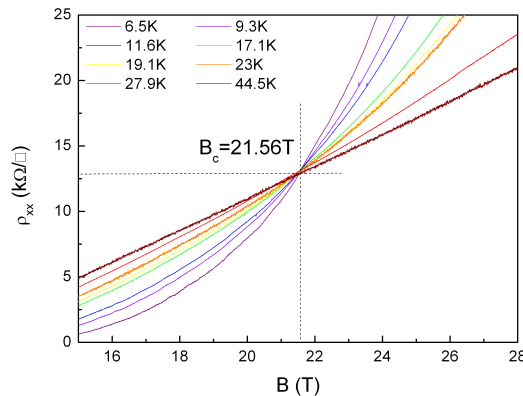
**Abstract.** We have performed magneto-transport experiments in monolayer, bilayer, trilayer and four layered graphene, at temperatures between 2 and 190 K and magnetic fields up to 28 T. In particular, in monolayer graphene we studied the quantum Hall effect and the metal-insulator transition. On the other hand, in bilayer graphene we observed quantum Hall plateaus at filling factor  $\nu = 4, 8, 12, 16, 20, \dots$  and the  $\nu = 6$  plateau in trilayer graphene, studying their temperature dependence. We have also studied the symmetry properties which are related with different contact configurations describing the method used to study inhomogeneous samples. Finally, four layered graphene we did not found quantum Hall plateaus, but we observed and investigated an ambipolar conduction effect.

Graphene is a material which has been studied in several investigations because of its unique electronic properties, which are interesting due to the theoretical concepts involved and its potential applications [1, 2, 3, 4, 5]. The electronic properties of graphene induced by its electronic band structure leads to unusual effects, such as the massless Dirac fermions and the anomalous quantum Hall effect (QHE) [1, 2, 3, 6, 4, 5, 7, 8], which results in the quantum Hall plateaus series  $\nu = \pm 2, \pm 6, \pm 10, \pm 14, \dots$  for monolayer graphene and  $\nu = \pm 4, \pm 8, \pm 12, \pm 16, \dots$  for bilayer graphene. Because of the experimental observation of these series for the QHE in graphene [6, 7, 8] the electronic properties of graphene and multilayer graphene has been extensively investigated. In particular, QHE in trilayer graphene (TLG) has also been investigated since its band structure depends on the interlayer stacking sequence [9, 10, 11, 12].

Here we study the QHE in monolayer, bilayer and trilayer graphene. In particular, we investigate the metal-insulator transition in monolayer graphene, the serie of the quantum Hall plateaus for bilayer graphene and the presence of the  $\nu = \pm 6$  quantum Hall plateau in trilayer graphene. Furthermore, we study an asymmetry of the conductivity arising from the presence of a density gradient, which has been previously observed in 2DEG [13] and more recently in graphene [14, 15]. Finally, we have also investigated the magnetotransport properties of four layered graphene.

The graphene flakes have been fabricated by means of mechanical exfoliation of natural





**Figure 1.** Longitudinal resistivities measured at gate voltage 0 V using the magnetic field as driving parameter at temperatures from 6.5 K to 44.5 K.

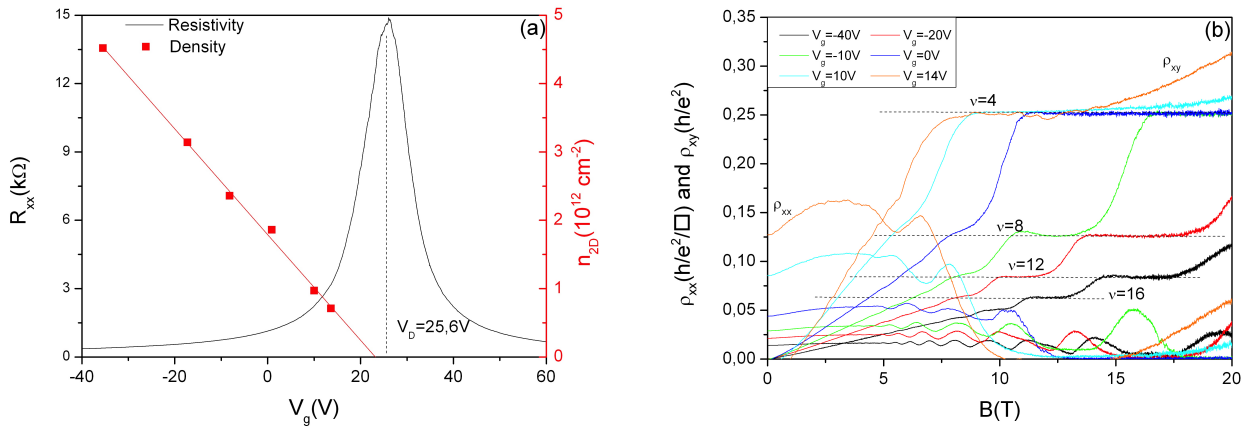
graphite and were placed on top of  $\text{SiO}_2$ . Their number of layer was determined by Raman spectroscopy. The processing of the samples was done as follows: the Hall bar geometry was defined by means of electron beam lithography and the contacts (50 Å of Ti followed by 500 Å of Au) were deposited by e-beam evaporation. The undesired parts of the flakes were removed using  $\text{O}_2/\text{Ar}$  plasma etching. The magneto-transport measurements have been carried out at temperatures between 1.9 K and 190 K, with sample placed in a  $^4\text{He}$  cryostat. All the measurements were performed using standard ac lock-in techniques and four probe measurements, using an excitation current of  $I = 50$  nA which was obtained by applying 5 V with frequency below 15 Hz to a 100 M $\Omega$  series resistance. This current flowed from contact S to D (see inset in Fig. 3(b)), pre-amplified with a gain of  $\simeq 100$ . We measured simultaneously the voltage drop  $V_{1-3}$ ,  $V_{1-2}$  and  $V_{3-4}$  between the contact pairs 1 – 3, 1 – 2 and 3 – 4 (see inset of Fig. 3(b)). A 10 MW resistive magnet was used to apply a magnetic field up to 28 T perpendicularly to the samples.

We measured the longitudinal resistivity using the back gate voltage as driving parameter of the charge density in a monolayer graphene sample on top of  $\text{SiO}_2$ , finding a charge neutrality point (CNP) at  $V_{CNP} = 4$  V. We placed the gate voltage enough close to the Dirac point in order to have only the last Landau Level  $\nu = -2$  below the Fermi energy, since  $\nu = nh/(eB)$ . We then studied, at different temperatures, the metal-insulator transition from the state  $\nu = -2 \rightarrow \nu = 0$  which is characterized by a crossing point at a critical magnetic field  $B_c$  (see Fig. 1).

The longitudinal resistance exhibits a temperature independent crossing point at  $B_c = 21.56$  T. Using the standard scaling theory analysis  $R_{xx} \propto \exp(\Delta\nu/\nu_0(T))$  with  $\Delta\nu = 1/B - 1/B_c$  (where  $\Delta\nu$  should not be confused with the filling factor) we have obtained the critical exponent of the transition  $\kappa = 0.58 \pm 0.01$  [16].

For the bilayer sample, the Dirac point was at 25 V (see figure 2(a)). We define the longitudinal resistance as  $R_{xx} = (V_{1-2}/I)$  whereas the Hall resistance is defined as  $R_{xy} = (V_{1-3}/I)$  (the labels of the contacts are shown in the inset in figure 3(b)). In figure 2(b) we show the QHE measured in the bilayer sample. This QHE differs from the QHE observed previously and reveals a new serie of plateaus  $\nu = \pm 4, \pm 8, \pm 12, \pm 16, \dots$  which have not been observed in monolayer graphene.

We characterized the bilayer sample by fitting the slope of the linear part of Hall resistances



**Figure 2. a)** Longitudinal resistance measured at zero magnetic field using the gate voltage as driving parameter. The Dirac point was found at  $V_G = 25$  V. The carrier density in the hole-like regime is shown in red.

**b)** Measurements of the quantum Hall effect performed in a bilayer graphene flake at 2 K using the magnetic field as driving parameter at different values of the gate voltage, from  $-40$  V up to  $14$  V. The series of quantum Hall plateaus  $\nu = 4, 8, 12, 16, 20, \dots$  is observed.

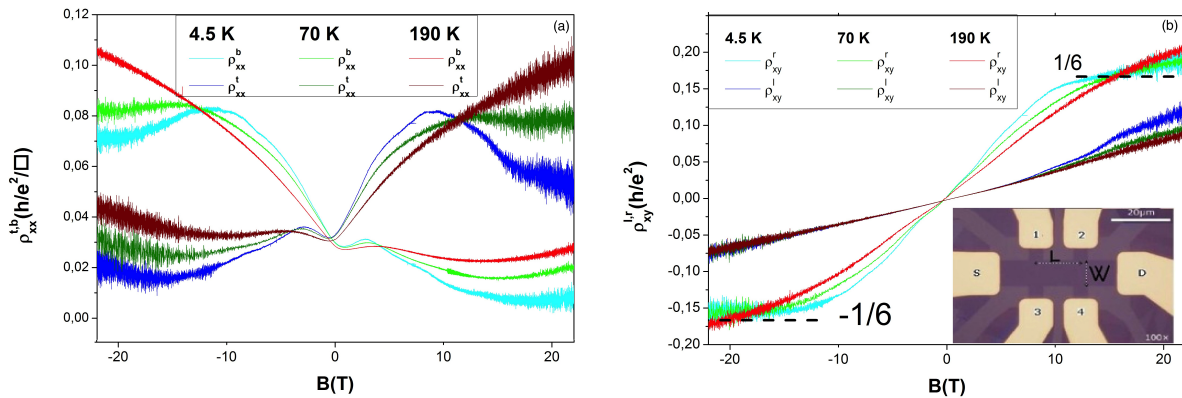
measured at different gate voltages, since, at low magnetic field, it can be assumed that  $R_{xy} \sim B/(ne)$  (figure 2(a)). The values of both the mobility (given by  $\mu = 1/(neR_0)$ ) and the density at the different gate voltages are reported in the following table:

$V_{gate}$ (V)	-40	-20	-10	0	10	14
$n_{2D}$ ( $10^{12}\text{cm}^{-2}$ )	4.5	3.2	2.4	1.6	0.9	0.7
$\mu$ ( $\text{cm}^2/\text{Vs}$ )	3800	3600	3557	3400	3217	2800

For the trilayer sample, we obtain the Hall resistivities (denoted as “left” and “right”) using  $\rho_{xy}^l = V_{1-3}/I$  and  $\rho_{xy}^r = V_{2-4}/I$ ; whereas the longitudinal resistivities (denoted as “top” and “bottom”) are obtained using  $\rho_{xx}^t = (V_{1-2}/L)/(I/W)$  and  $\rho_{xx}^b = (V_{3-4}/L)/(I/W)$ . In Fig.3 we show the Hall and longitudinal resistivities as a function of the magnetic field.

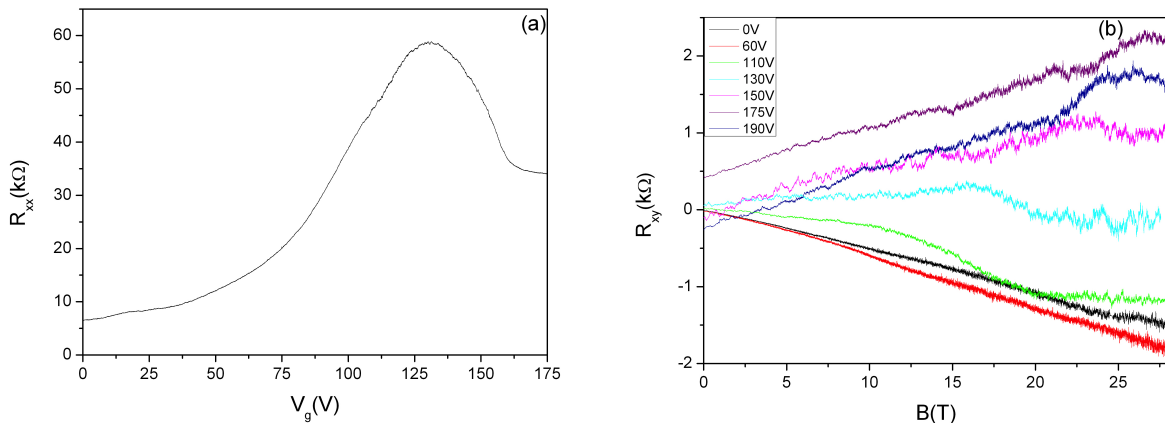
We obtain the mobility  $\mu$  and 2D carrier density from the Hall and the longitudinal resistances at low magnetic field, finding that the carrier density increases with increasing temperature, as expected for the semi-metallic TLG [9]. At the base temperature of 4.5 K the density and the mobility of the sample were  $n_{2D} = 2.04 \times 10^{12}\text{cm}^{-2}$  and  $\mu = 3750 \text{ cm}^2/\text{Vs}$ . Unfortunately a leak in the  $\text{SiO}_2$  layer did not allow the use of the back gate in order to change the carrier density. In Fig. 3(b) we show that the “right” Hall resistivity shows the QHE with the presence of the  $\nu = \pm 6$  plateau. It is also observed that the slope of  $\rho_{xy}^r$  ( $s^r$ ) is higher than the slope of  $\rho_{xy}^l$  ( $s^l$ ), such that  $s^r \sim 3s^l$ . This fact indicates a large inhomogeneity along the sample, since the density follows  $n_{2D} \propto 1/s$ . This inhomogeneity results in the asymmetry of the longitudinal resistivity upon the reversal of the magnetic field (namely,  $\rho_{xx}(-B) = \rho_{xx}(B)$ ), since, as it is shown in figure 3(a),  $\rho_{xx}^{t,b}(B) \neq \rho_{xx}^{t,b}(-B)$ , but  $\rho_{xx}^{t,b} = \rho_{xx}^{b,t}(-B)$  [17]. That is, when the polarity of the magnetic field is inverted, the “top” longitudinal resistivity and the “bottom” longitudinal resistivity are swapped.

Finally, we have measured the magnetotransport properties of a four layered graphene sample at a base temperature of 4.5 K. We measured the longitudinal resistivity  $\rho_{xx}$  using the back gate voltage as a driving parameter at zero magnetic field. We found that the longitudinal resistance



**Figure 3. a)** Longitudinal resistivities  $\rho_{xx}$  versus magnetic field at temperatures 4.5, 70 and 190 K.

**b)** Hall resistivity ( $\rho_{xy}$ ) versus  $B$  at  $T = 4.5, 70$  and  $190$  K. The quantum Hall plateau at  $\nu = \pm 6$  corresponding to  $\rho_{xy} = h/6e^2$  is visible up to 70 K.



**Figure 4. a)** Longitudinal resistivity versus the back gate voltage at a temperature of 4.5 K. It can be seen a maximum, the so called charge neutrality point, at 130 V.

**b)** The Hall resistivities versus the magnetic field at different back gate voltage and at a temperature of 4.5 K. We note the linear behavior with the magnetic, with different positive and negative slopes, indicating that the density and the sign is tuned by the gate voltage.

shows a maximum at  $V_G = 130$  V, followed by a saturation regime, as shown in figure 4(a). We believe that this feature indicates the presence of the CNP and that the saturation is caused by the inhomogeneities of the sample.

We think that the maximum located at 130 V is indeed the CNP point since, as we observe in figure 4(b), for back gate voltages below the CNP the Hall resistivity shows a linear dependence with the magnetic field with a negative slope. Nonetheless, we observe that for gate voltages closer to the CNP the Hall resistivity deviates slightly from this non linear behaviour. When the back voltage is exactly at the CNP, the Hall resistivity is almost constant with the magnetic

field; which is an indication of the presence of the electron-hole puddle regime. As the gate voltage is further increased, the resistance shows again a linear dependence with the magnetic field, but with a positive slope, which is the expected behaviour found in graphene when the back gate voltage passes through the Dirac peak and the transition from the hole-like regime to the electron-like regime.

In conclusion, we have measured the quantum Hall effect in monolayer, bilayer and trilayer graphene samples observing the presence of the corresponding Hall plateaus.

We have observed the quantum Hall plateaus resulting for monolayer graphene  $\nu = \pm 2, \pm 6, \pm 10, \dots$  and the metal-insulator transition. We have measured the critical exponent of this transition, resulting in  $\kappa = 0.58 \pm 0.01$  [16].

The resulting series of the quantum Hall plateaus for bilayer graphene is  $\nu = \pm 4, \pm 8, \pm 12, \pm 16, \pm 20, \dots$

We have observed the  $\nu = \pm 6$  plateaus for trilayer graphene and studied the asymmetry of the longitudinal resistances, which arises from an inhomogeneity of carrier density along the sample [17].

Finally, we have studied the magnetotransport properties of a four layered graphene flake, observing an ambipolar effect.

Thus, we remark that the quantum Hall effect is a notable tool to distinguish monolayer, bilayer and trilayer graphene, since their plateaus series are different. As far as four layered graphene is concerned, more experiments with higher quality samples are required.

### Acknowledgment

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