Magneto-transport in the zero-energy Landau level of single-layer and bilayer graphene

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Abstract. We present recent low-temperature magnetotransport experiments on single-layer and bilayer graphene in high magnetic field up to 33 T. In single layer graphene the fourfold degeneracy of the zero-energy Landau level is lifted by a gap opening at filling factor $\nu = 0$. In bilayer graphene, we observe a partial lifting of the degeneracy of the eightfold degenerate zero-energy Landau level.

1. Introduction

Graphene is the purely two dimensional form of carbon arranged in a honeycomb-lattice [1]. Initially, this material was believed not to be stable thermodynamically [2]. However, in 2004 Novoselov et al. succeeded in producing an ambipolar field effect transistor made from one layer of graphene using mechanical exfoliation of graphite [3]. Maybe even more spectacular than the sole existence of a material which should not exist are its unique physical properties [1]. Charge carriers in graphene behave relativistically like massless chiral Dirac fermions rather than massive electrons in conventional materials. These relativistic properties of graphene are revealed most clearly in high magnetic fields where the energy spectrum splits up into non-equidistant Landau levels with energies given by

$$E^\text{SLG}_N = \text{sgn}(N)\sqrt{2\hbar c^2 e B|N|} \quad \text{and} \quad E^\text{BLG}_N = \text{sgn}(N)\frac{\hbar e B}{m^*}\sqrt{N(N-1)}$$

for single-layer graphene (SLG) [4] and bilayer graphene (BLG) [5], respectively. The velocity $c = \sqrt{3\gamma_0 a / 2\hbar} \approx 10^6 \text{ ms}^{-1}$ is given by the intra-layer coupling $\gamma_0 = 3.2 \text{ eV}$ and the lattice constant $a = 2.46 \text{ Å}$. The effective mass $m^*$ in BLG is determined by $c$ and the inter-layer coupling $\gamma_1 = 0.4 \text{ eV}$ as $m^* = \gamma_1 / c^2 \approx 0.035 m_e$. In both cases, $N$ is a negative integer for holes and positive for electrons. Due to these relativistic Landau-level structures, the well-known integer quantum Hall effect (IQHE) [6] observed in conventional two-dimensional electron systems transforms to a relativistic half-integer quantum Hall effect in SLG [7,8] and an new type of unconventional IQHE in BLG [9].

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A particularity of this Landau level spectrum is the existence of a Landau level at zero energy (independent on the magnetic field) which is shared equally between electrons and holes. In SLG this level is fourfold degenerate, just like all other Landau levels with \(|N| \geq 1\). In BLG, the zero-energy Landau level is eightfold degenerate whereas higher Landau levels with \(|N| \geq 2\) are fourfold degenerate.

In this paper we present recent magnetotransport data on SLG and BLG performed at the High Field Magnet Laboratory in Nijmegen. For SLG we will show a narrowing of the this level in high fields \([10]\) and the opening of a gap at \(\nu = 0\) \([11]\). In BLG we start to lift the eightfold degeneracy in the highest-fields and observe minima in the conductance at \(\nu = 3\) and 2.

2. Gap opening at \(\nu = 0\)

The fourfold degeneracy of the zero-energy Landau level around the charge neutrality point (CNP) is visualized in magnetotransport experiments by a peak in \(\rho_{xx}\) at \(\nu = 0\) neighboured by zero-minima at \(\nu = \pm 2\) \([7,8]\). At the same time, the Hall resistivity \(\rho_{xy}\) passes through zero at \(\nu = 0\) from \(\rho_{xy}(\nu = -2) = -\hbar/2e^2\) to \(\rho_{xy}(\nu = 2) = +\hbar/2e^2\). Using the tensor inversions \(\sigma_{xx} = \rho_{xx}/(\rho_{xx}^2 + \rho_{xy}^2)\) and \(\sigma_{yx} = -\rho_{xy}/(\rho_{xx}^2 + \rho_{xy}^2)\) this implies a maximum in the conductivity \(\sigma_{xx}\) accompanied by a zero-crossing of the Hall conductivity \(\sigma_{yx}\), a behaviour which is indeed found back in the high temperature data of Figure 1.
The occurrence of a zero $\rho_{xy}$ at the CNP already proposes that the lowest Landau level of graphene has to be treated as a (partially) compensated semiconductor with a finite number of electrons and holes present at the CNP. In contrast, for a conventional system, with one type of carriers present simultaneously, the carrier concentration at the CNP is zero and, as a consequence, $\rho_{xy}$ diverges to $\pm \infty$ when approaching the CNP from the electron side or from the hole side, respectively.

We will first concentrate on the high-field behaviour of $\rho_{xx}$, an issue still subject to intensive debate [12]. Experiments performed in the zero-energy Landau level of high-mobility SLG (made from Kish-graphite) have shown a lifting of its chiral degeneracy by the appearance of a $\nu = 1$ state [13, 14] and recently also the lifting the eightfold degeneracy in BLG has been observed [15]. Most other experiments, however, did not find a $\nu = 1$ state in SLG [11,16,17]. Possibly, the disorder in these experiments was still too large, preventing a spontaneous symmetry breaking in the lowest Landau level [18]. Instead, only a divergence of $\rho_{xx}$ at the CNP is observed.

With the above tensor inversions a diverging $\rho_{xx}$ at the CNP, together with a zero crossing of $\rho_{xy}$, inevitably leads to a zero minimum in $\sigma_{xx}$ and a zero-value quantized plateau in $\sigma_{yx}$. Figure 1 visualizes the appearance of such a $\nu = 0$ quantum-Hall state where the Hall conductivity $\sigma_{yx}$ and the longitudinal conductivity $\sigma_{xx}$ of a SLG sample, deposited on a Si/SiO$_2$ substrate, are plotted as a function of filling factor. We performed these experiments for different temperatures at a magnetic field of 30 T [11]. The conductivities shown were calculated by tensor inversion from the measured resistivity $\rho_{xx}$ and $\rho_{xy}$ in a Hall-bar sample. The filling factor was varied by sweeping the carrier concentration at a constant magnetic field using the doped Si of the Si/SiO$_2$ substrate as a back-gate. The zero-energy Landau level is completely empty at $\nu = -2$ and is completely filled at $\nu = 2$.

As can been seen in the figure, $\sigma_{xx}$ starts to develop a zero-minimum with decreasing temperature and a quantized zero-plateau appears in $\sigma_{yx}$. This new quantum Hall state, however, is quite different compared to the conventional QHE [19]. It is caused by the zero crossing of $\rho_{xy}$ at the CNP together with a diverging $\rho_{xx}$, whereas conventionally $\rho_{xy} \gg \rho_{xx}$ and quantum Hall states are characterized by a zero-minima of both the resistivity $\rho_{xy}$ and the conductivity $\sigma_{xx}$ and by non-zero quantized plateaus in $\rho_{xx}$ and $\sigma_{yx}$.

The nature of the new $\nu = 0$ quantum Hall state can be elucidated further by investigating the temperature dependence of the $\sigma_{xx}$ minimum at the CNP. It shows an activated behaviour, with a gap roughly scaling linearly with magnetic field [11]. This observation might suggest that the splitting is spin related. And indeed, comparison with a simple Zeeman splitting (using a free-electron $g$-factor $g = 2$) and an offset due to a final level width yield a reasonable agreement between this simple expectation and the experimentally measured gaps.

### 3. Lifting of the eightfold degeneracy in BLG

Having observed a splitting of the zero-energy Landau level in SLG it is certainly of interest to also investigate the transport properties of BLG. Experimental results on a bilayer sample are shown in Figure 2. In high magnetic fields ($B > 20$ T) and at low temperatures ($T < 1$ K) a partial lifting of the eightfold degenerate zero-energy Landau level is indeed observed and clearly pronounced minima in the conductivity $\sigma_{xx}$ appear at filling factors $\nu = \pm 3$ and $\pm 2$. They are accompanied by quantum Hall plateaus in $\sigma_{xx} = \nu e^2/h$ (not shown). However, the quality of the samples is not yet high enough to observe a full splitting of the Landau level, and, interestingly no $\nu = 0$ quantum-Hall state appears yet, or, more specifically, no strongly diverging $\rho_{xx}$ can be observed at the CNP. Apparently, no narrowing of the zero-energy Landau level as in SLG [10,20] takes place and the finite level width still masks the effect of a possible Zeeman splitting.
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Figure 2. Conductivity $\sigma_{xx}$ in the zero-energy Landau level of a BLG sample at $B = 30$ T as function of carrier concentrations. At $\nu = \pm 4$ the level is entirely full or empty, respectively. The arrows at $\nu = \pm 3$ and $\pm 2$ indicate how the eightfold degeneracy of the Landau level starts to be lifted.
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