# Spin-splitting in graphene

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The Landau levels in graphene are spin and valley degenerate. In order to lift the spin degeneracy completely, fields of a few hundred Tesla are necessary. However, even in fields of 30 T spin splitting already becomes visible as a reduction of Shubnikov-de Haas (SdH) oscillations. We present recent results exploring the spin-splitting by means of tilted-field magnetotransport experiments at magnetic fields up to 30 T.

The Landau level splitting in a graphene flake increases with a magnetic field $B_n$ perpendicular to the flake. It follows a square root dependence in single layer graphene (SLG) [1] and an almost linear dependence in bilayer graphene (BLG) [2,3]. Spin-splitting of each Landau level increases linearly with the total magnetic field $B$. Therefore, tilting a sample in a magnetic field increases the ratio between the Zeeman splitting and the Landau level splitting and, as a consequence, reduces the amplitude of the SdH oscillations.

To observe the spin-splitting we have measured the longitudinal resistance as a function of charge carrier concentration in SLG and BLG in tilted magnetic fields. Our measurements show that increasing the total magnetic field $B$ at a constant perpendicular field $B_n$ leads to a damping of the SdH oscillation amplitudes (Fig.1). We fitted the experimental dependences by the Lifshitz-Kosevich formula and determined the SdH oscillation amplitudes, reduced by the Zeeman splitting with an added in-plane field. The amplitudes found for BLG are plotted in Fig.2 as a function of total field $B$ for a constant perpendicular field $B_n = 8$ T and for different Landau level indices $N$. The reduction of the SdH amplitude can be quantitatively described by a factor $cos\left(\frac{\pi\ g^* m^* B}{2m_e B_n}\right)$ [4] for particles with an effective $g$-factor $g^*$ and a cyclotron mass $m^* = \frac{\hbar^2}{2\pi}\frac{dS(E)}{dE}$, where $S(E) = \pi k^2$ is the area in $k$-space of the Landau orbits at the Fermi energy. This allows us to extract $g^* m^*$ from our measurements.

Assuming a parabolic dispersion at low magnetic fields for BLG and using a constant effective mass $m^*=0.032\ m_e$ [5] results in the effective $g$-factors $g^*$ plotted in the inset of Fig.2. The experimental $g^*$ are enhanced compared to the free electron $g$-factor with increasing enhancement for the higher Landau levels. We note that such an enhancement can also be caused by increasing the cyclotron mass with carrier concentration [6]. For SLG preliminary results suggest that $g^*$ is comparable to free electron $g$-factor for low Landau levels ($N = \pm 1$), though we cannot yet exclude an enhancement for the higher levels as seen in BLG.

**References**


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**Figures**

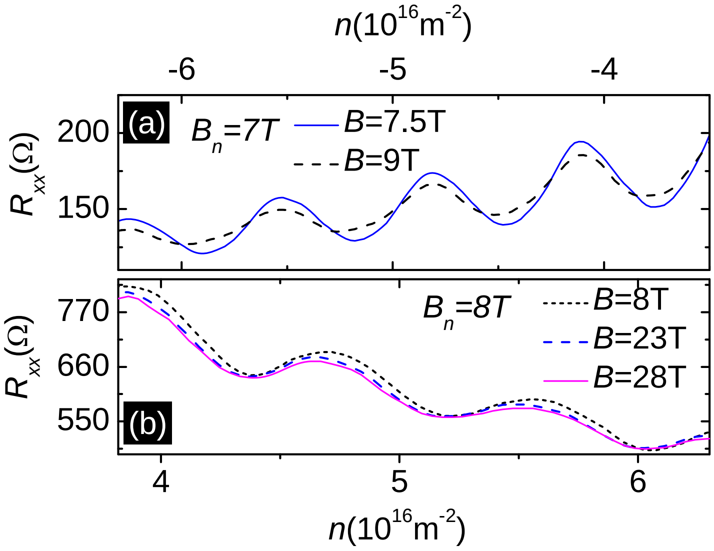


**Figure 1**: *(color online) SdH oscillations of longitudinal resistance as a function of carrier concentration in SLG (a) and BLG (b). The traces are recorded for different tilt angle/total field and a constant perpendicular field $B_n$ at T=0.4 K*

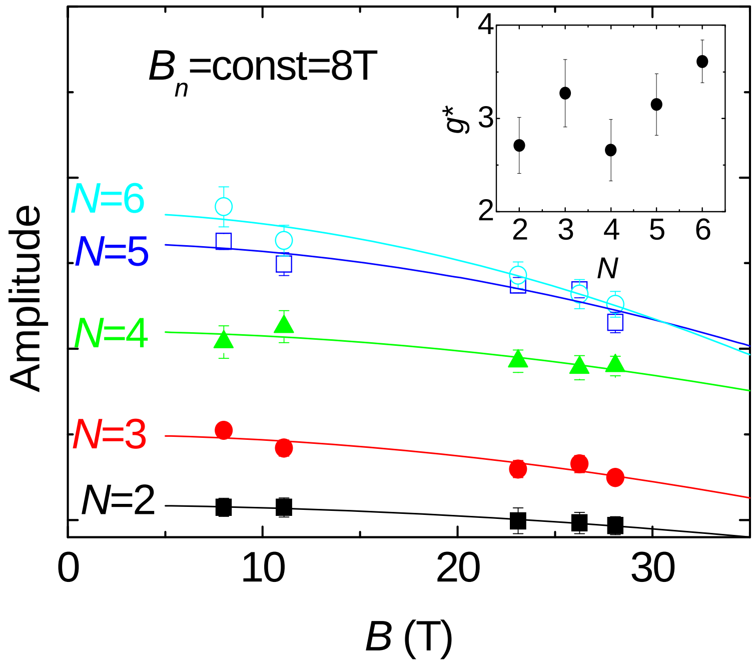


**Figure 2**: *(color online) Oscillation amplitude as a function of total field B at a constant perpendicular field $B_n$=8 T in BLG. Solid lines are fits by* $\cos\left(\frac{\pi g^* m^* B}{2m_e B_n}\right)$*, the $g^*$ extracted from this is shown in the inset as a function of Landau level index N*