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Spin splitting in graphene studied by means of tilted magnetic-field experiments

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We have measured the spin splitting in single-layer and bilayer graphene by means of tilted magnetic field experiments. Applying the Lifshitz-Kosevich formula for the spin-induced decrease of the Shubnikov de Haas amplitudes with increasing tilt angle we directly determine the product between the carrier cyclotron mass $m^*$ and the effective $g$-factor $g^*$ as a function of the charge carrier concentration. Using the cyclotron mass for a single-layer and a bilayer graphene we find an enhanced $g$-factor $g^* = 2.7 \pm 0.2$ for both systems.

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The half-integer quantum Hall effect in single-layer graphene (SLG) [1,2] and the unconventional quantum Hall effect in bilayer graphene (BLG) [3] reveal spin- and valley-degenerate relativistic Landau levels. Due to the extremely large Landau-level splitting $[4,5]$, completely resolved levels can be observed up to room temperature $[6]$. However, even at very high perpendicular magnetic fields the Zeeman splitting within one Landau-level is negligible smaller compared to the Landau-level splitting and, more importantly, the Landau-level width generally exceeds the spin-splitting. Exceptionally, the zeroth Landau level in SLG becomes extremely narrow at magnetic fields $B > 20 \text{T}$ [4], which allows an experimental observation of a spin-related gap opening at magnetic fields $B > 20 \text{T}$ [7]. Another observation of a spin degeneracy lifting with an effective $g$-factor $g^* = 2$ was reported for $\nu = \pm 4$, in SLG for magnetic fields $B > 30 \text{T}$, combined with lifting the valley-degeneracy at $\nu = \pm 1$ [8].

In this paper we determine the spin splitting of broadened Landau levels for SLG and BLG by measuring Shubnikov-de Haas oscillations in tilted magnetic fields. This technique allows adjusting the ratio between the spin splitting and the Landau level splitting, by controlling the ratio between a total magnetic field and a component perpendicular to a two-dimensional graphene flake. Using the well-established Lifshitz-Kosevich formula [9,10] we determine the product of effective $g$-factor and cyclotron mass, $m^*g^*$, from the angular dependence of the SdH amplitudes and we find that $g^*$ is enhanced compared to the free electron value.

We have fabricated field-effect transistors from SLG and BLG, by micromechanically exfoliating graphene flakes from graphite. The flakes were deposited on top of a Si/SiO$_2$ wafer, structured into a Hall-bar and covered with Au/Ti contacts [11]. Charge carriers are introduced by applying a gate voltage on the conducting Si substrate.

We present a detailed analysis on the spin splitting in a SLG sample made from Kish graphite with a mobility $\mu = 0.8 \text{ Vm}^{-2}\text{s}^{-1}$ and BLG sample originating from natural graphite with a mobility $\mu = 0.3 \text{ Vm}^{-2}\text{s}^{-1}$. Two other devices, one SLG and one BLG sample, showed qualitatively similar results.

To determine the spin-splitting we have measured the longitudinal resistances $R_{xx}$ as a function of charge carrier concentration $n$ at a constant perpendicular magnetic field. We adjusted the total magnetic field $B_{tot}$ for each tilt angle such that the normal component $B_n$ is the same (inset to Fig.1). The value of $B_n$ was verified by measuring the Hall resistance of the devices in the non-quantized regime.

In Fig.1 we show the experimental $R_{xx}(n)$ dependencies for SLG at $B_n = 6 \text{T}$ (a) and for BLG at $B_n = 8 \text{T}$ (b). $R_{xx}$ shows Shubnikov-de Haas oscillations with maxima whenever the Fermi energy is situated in the middle of a spin- and valley-degenerated Landau level $E_N$, $N = 0, 1, 2, \ldots$ being the Landau-level index. For the higher Landau levels ($N \geq 2$) the longitudinal resistances do not exhibit zero minima indicating that the level broadening is comparable to the cyclotron energy at these perpendicular magnetic fields.

When increasing $B_{tot}$ at a constant $B_n$ the oscillation amplitudes for both BLG and SLG are reduced. From this reduction we determined the spin-splitting. We use the Lifshitz-Kosevich formula for systems with a general dispersion and we specifically include spin-splitting [9,10] with an effective $g$-factor $g^*$ [12,13] and tilted magnetic fields [14]. The oscillatory contribution to the longitudinal resistance can be described as [2]:

$$
\hat{R}_{xx} = A \cos \left( \frac{\hbar}{eB_n} S(E)|_{E=E_F} + \pi + \varphi_B \right)
$$

(1)

where $S(E)|_{E=E_F}$ is a extremal cross section of the Landau orbits in the $k$-space, $A$ is the oscillation amplitude and $\varphi_B$ is Berry phase, $\varphi_B = \pi$ for SLG [1,2].
The amplitude $A$ contains a monotonic $n$-dependent part, a temperature dependence, a $B_n$-dependent contribution and a damping factor due to spin splitting depending on the total field $B_{\text{tot}}$. At a constant temperature and perpendicular magnetic field this $B_{\text{tot}}$-dependence of the SdH amplitude $A$ for charge carriers with cyclotron mass $m^*$ and effective $g$-factor $g^*$ is given by \cite{12, 14}:

$$A = A_0(N) \cos \left( \frac{\pi g^* m^* B_{\text{tot}}}{2 m_e B_n} \right)$$

with cyclotron mass \cite{1}:

$$m^* = \frac{\hbar^2}{2\pi} \frac{dS(E)}{dE} \bigg|_{E=E_F}$$

and $A_0(N)$ is constant for a given $N$.

For the spherical Fermi surface in SLG and BLG with a Fermi wave-vector $k_F = \sqrt{\pi n}$, the extremal cross section of the Landau orbits is $S(E)|_{E=E_F} = \pi k_F^2 = n\pi^2$ and Eq. (1) yields the concentration-dependent resistance oscillations as we observe them in our experiments:

$$\tilde{R}_{xx} = A \cos \left( \frac{\hbar \pi^2}{e B_n} n + \pi + \varphi_B \right) = A \cos \left( \frac{\pi}{2} \nu + \pi + \varphi_B \right),$$

where $\nu = (h n) / (e B_n)$ is the filling factor. As expected, the oscillation period, $(2eB_n) / (\hbar \pi)$, is independent on the band structure of the 2D material and only depends on the filling factor.

To accurately determine the experimental oscillation amplitudes we have fitted our experimental data $R_{xx}(n)$ to Eq. (2) in two steps. First we determined the oscillation period and a smooth background using all oscillations measured for a wide range of the carrier concentrations. Second we fitted the oscillation amplitudes $A$ for each individual oscillation using the above determined period and background as fixed parameters. In Fig. 2 we show the final results of this fitting procedure for the SdH amplitudes as a function of the total magnetic field for different Landau levels $N$. For clarity all amplitudes are normalized to $A_0$.

The experimentally observed reduction of the SdH amplitudes can be qualitatively visualized in a simple density of states (DOS) picture of a Landau level as depicted in Fig. 3b). In a purely perpendicular magnetic field the Landau level width exceeds the spin splitting and the DOS of the spin-down state (orange, horizontally dashed in Fig. 3b) overlaps with the one of the spin-up states (red, vertically dashed) to one broad Landau level. When increasing $B_{\text{tot}}$ by leaving $B_n$ constant, these two states move apart yielding an additional broadening of the Landau level with a reduced DOS in the center (green, solid areas in Fig. 3b). Eventually, when the spin splitting exceeds the level width a minimum between two distinct levels starts to develop in the DOS. This scenario is indeed observed experimentally in SLG (Fig. 3b). The SdH maxima corresponding to the $N = 9$ and $N = 10$ Landau levels starts to develop in the DOS. This scenario is indeed observed experimentally in SLG (Fig. 3b). The SdH maxima corresponding to the $N = 9$ and $N = 10$ Landau levels starts to develop in the DOS. This scenario is indeed observed experimentally in SLG (Fig. 3b). The SdH maxima corresponding to the $N = 9$ and $N = 10$ Landau  

FIG. 1: (color online) Shubnikov de Haas oscillations in SLG (a) at $T = 1.3$ K and in BLG (b) at $T = 0.4$ K as a function of the carrier concentration for different total fields $B_{\text{tot}}$ or tilt angles $\theta$, respectively. When varying $\theta$ the total field $B_{\text{tot}}$ is adjusted such that the perpendicular field $B_n$ remains constant, i.e. $B_{\text{tot}} = B_n / \cos \theta$. The oscillation maxima are marked with the corresponding Landau level numbers $N$. The inset schematically shows this tilting configuration.

FIG. 2: (color online) Normalized oscillation amplitudes as a function of total field $B_{\text{tot}}$ at a constant perpendicular field $B_n$ in SLG (a) and BLG (b). Error bars represent standard least squares fitting errors in the determination of $A$. Solid lines are fits to Eq. (2) with $m^* g^*$ as a fit parameter.
landau levels at $B_{tot}=B_n=5$ T do not show any splitting. Increasing of the total field at a constant perpendicular component leads to a reduction of the oscillation amplitude and eventually appearance of spin-resolved peaks at the highest field of 28 T. However, this splitting is not yet enough to determine the energy difference by e.g. activation measurements.

A quantitative analysis of this decrease of the SdH amplitudes with increasing total magnetic field is done by fitting the data to Eq. 2 with $m^*g^*$ as a fitting parameter (solid lines in Fig. 2). The values for $m^*g^*$ obtained are plotted as a function of the charge carrier concentration in Fig. 3 for SLG (a) and BLG (b). For both SLG and BLG the product $m^*g^*$ increases with concentration, which can be mainly attributed to the concentration dependent cyclotron mass $m^*$ of particles with a linear [1] and hyperbolic dispersion [15] as predicted by Eq. 3.

The dashed lines in Fig. 3a show the calculated dependence of $m^*g^*$ for $g^*=2$ and $g^*=2.7$ using $m^*(n)=(\hbar/e\sqrt{\pi n})$ [1]. The shadowed areas represent a 10% uncertainty of this calculation mainly due to the experimental errors and some uncertainty in the Fermi velocity [10].

For SLG (Fig. 3a), the increase of $m^*g^*$ with $n$ is symmetric for electrons and holes (i.e. negative and positive $n$ in the figure). A best fit using $m^*(n)$ for SLG yields $g^*=2.7\pm 0.2$ (the error is the standard deviation). This finding is shown directly in the inset of Fig. 3a, where we plot the value of $g^*$ determined in the middle of each Landau level $N$ for different perpendicular fields $B_n$. Within an experimental error $g^*$ does not show any dependence on $N$ or $B_n$.

For BLG (Fig. 3b) the experimental situation is more complex as the observed increase of $m^*g^*$ with $n$ is not symmetric for holes and electrons. Such a behavior is caused by an asymmetry of $m^*$ resulting from an asymmetric band structure of biased BLG, which was already observed experimentally in transport experiments [17], cyclotron resonance [18] and activation-gap measurements [5]. Applying the experimental cyclotron mass from Ref. 17 (depicted as blue crosses in Fig. 4) allows us to estimate $g^*$ to be about 2.5 for both electrons and holes which is, within experimental accuracy, reasonably consistent with the $g$-factor enhancement observed in SLG.

The observed enhancement of the effective spin-splitting compared to its free electron value can be explained by electron-electron interaction [19] yielding an interaction-enhanced splitting between two spin levels within one Landau level [20, 21].
\[g^* \mu_B B_{tot} = g \mu_B B_{tot} + E_{ex}^0 (n_\downarrow - n_\uparrow). \tag{5}\]

Here \(g = 2\) is a free-electron \(g\)-factor, \(E_{ex}^0\) is an exchange parameter, and \(n_\downarrow\) and \(n_\uparrow\) are the relative occupations of the two spin states of a given Landau level.

For Gaussian shaped Landau levels with broadening \(\Gamma > g^* \mu_B B_{tot}\), i.e. where the spin splitting is not yet resolved, this relative occupation difference can be approximated using the Taylor expansion of the Gauss error function \(\text{erf}(g^* \mu_B B_{tot}/\Gamma)\):

\[n_\downarrow - n_\uparrow \approx \sqrt{\frac{1}{2\pi}} \frac{g^* \mu_B B_{tot}}{\Gamma} \tag{6}\]

and Eq. (5) yields:

\[\frac{g^*}{g} = \left(1 - \sqrt{\frac{2\pi}{1 \text{ erf}(E_{ex}^0/\Gamma)}}\right)^{-1}. \tag{7}\]

\(E_{ex}^0\) is of the order of Coulomb interaction, \(E_{ex}^0 \propto \sqrt{\frac{1}{\tau}}\) [21], and \(\Gamma \propto \sqrt{\frac{1}{\tau}}\) [22]. Therefore, the ratio \(E_{ex}^0/\Gamma\) remains constant and the \(g\)-factor enhancement is indeed predicted to be constant as we observe experimentally. Using the experimentally found \(g^* = 2.7\) in Eq. (7) yields \(E_{ex}^0 = 130\) K at 10 T when assuming \(\Gamma = 200\) K [11].

For a completely spin-polarized system, i.e. \(n_\downarrow - n_\uparrow = 1\), one might then speculate that the exchange enhancement in the Eq. (5) would be an order of magnitude larger than a single particle Zeeman energy at this particular field.

Finally, we note that the experimentally found enhanced values of \(g^*\) in graphene are close to those observed in transport experiments in graphite [23]. This may suggest that an exchange-induced enhancement of \(g^*\) is quite common for graphitic materials. In contrast, no interaction-induced \(g\)-factor enhancement is observed using electron-spin resonance in graphene [24] and graphite [25] since these measurements are not sensitive to many body corrections [26]. Interestingly, measuring the Zeeman splitting of single-electron states in quantum dots, where no exchange enhancement of the \(g\)-factor is expected, also yields \(g \approx 2\) [27], albeit with a considerable experimental uncertainty.

To conclude, we have experimentally measured and analyzed spin-splitting in SLG and BLG. We have shown that the product between the cyclotron mass \(m^*\) and the effective \(g\)-factor \(g^*\) increases with charge carrier concentration, as expected for a linear dispersion in SLG and a hyperbolic dispersion in BLG. Using the known concentration dependence of \(m^*\) we found that \(g^*\) in graphene is enhanced compared to the free-electron value and we attribute this to electron-electron interaction effects.

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