Anomalous spin-splitting of two-dimensional electrons in an AlAs Quantum Well

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We measure the effective Landé g-factor of high-mobility two-dimensional electrons in a modulation-doped AlAs quantum well by tilting the sample in a magnetic field and monitoring the evolution of the magnetoresistance oscillations. The data reveal that $|g| = 9.0$, which is much enhanced with respect to the reported bulk value of 1.9. Surprisingly, in a large range of magnetic field and Landau level fillings, the value of the enhanced g-factor appears to be constant.

73.40.Kp, 73.40.-c, 72.15.Gd, 73.40.Hm

The effective Landé g-factor and effective mass $m^*$ are two fundamental parameters that characterize the energy levels of two-dimensional electron systems (2DESs) in semiconductors in the presence of a magnetic field ($B$). In a simple, non-interacting picture, the cyclotron energy ($\hbar \omega_c = \hbar e B_{\perp} / m^*$) associated with the electron's orbital motion determines the separation between the quantized energy levels (Landau levels), while the Zeeman energy ($g \mu_B B$) gives the "spin-splitting" of the Landau levels ($B_{\perp}$ is the component of $B$ perpendicular to the 2DES plane).

For 2DESs in a high $B_{\perp}$ it is well known that when there are unequal populations of electrons with opposite spin, electron-electron interaction can lead to a substantial enhancement of the spin-splitting energy which can in turn be expressed as an enhancement of the effective g-factor $g^\ast$. In GaAs 2DESs, for example, the exchange enhancement of the g-factor leads to the energy gaps for the quantum Hall effect states at odd Landau level fillings ($\nu$) being much larger than the bare Zeeman energy $g \mu_B$. Moreover, the magnitude of the g-factor enhancement oscillates with $\nu$ as the spin population difference does $g^\ast$.

We report here an experimental determination of the spin-splitting energy for electrons confined to a modulation-doped AlAs quantum well (QW). In contrast to GaAs, where electrons occupy the conduction band minimum at the Brillouin zone center (Γ-point) and form a spherical Fermi surface, in AlAs they occupy conduction band ellipsoids near the zone edge (X-point). This is somewhat similar to the case of 2D electrons at the Si/SiO$_2$ (100) interface except that in the AlAs QW that we have studied, an ellipsoid with its major axis parallel (as opposed to perpendicular) to the 2D plane is occupied. In our measurements we utilize the "coincidence" method, a technique which has been used to study the g-factor enhancement in other 2DESs such as those in Si/SiO$_2$, SiGe, and GaAs. The results are surprisingly simple yet puzzling: in a large range of $\nu$, we find a significant enhancement of the g-factor with respect to the reported bulk value but, remarkably, the enhancement appears to be independent of $\nu$. The 2DES behaves like a non-interacting system of electrons but with a much-enhanced g-factor.

The experiment was done on samples from two wafers that were grown by molecular beam epitaxy on undoped GaAs (100) substrates. In both wafers the 2DES is confined to a 150 Å-wide AlAs QW which is separated from the Si dopants by AlGaAs barriers. Three samples (A, B, and C) from wafer 1 and one sample (D) from wafer 2 were used in the tilt experiment. Sample A was photolithographically patterned with an L-shaped Hall bar whose two perpendicular arms lay on the [100] and [010] directions. Samples B, C, and D had a van der Pauw geometry. Samples A and B had evaporated metal front gates to control the density. The experiments were performed in a pumped $^3$He system at a temperature of 0.3 K, in magnetic fields up to 16 T. The samples were mounted on a platform which could be rotated in situ. The ungated carrier density of sample A $n = 2.08 \times 10^{11}$ cm$^{-2}$ and the mobilities along the two arms of the L-shaped Hall bar were 6.1 m$^2$/Vs for the high-mobility direction and 4.2 m$^2$/Vs for the low-mobility direction.

The effective masses for the conduction band ellipsoids in bulk AlAs are $m_l = 1.1 m_e$ for the longitudinal mass and $m_t = 0.19 m_e$ for the transverse mass. For QWs of width greater than ~60 Å, the 2D electrons will be forced to occupy the two ellipsoids whose major axes lie in the plane of the 2DES. In our samples, measurements have shown that only one of the two in-plane ellipsoids is occupied. In particular, cyclotron resonance measurements reveal a cyclotron resonance effective mass of $m_{CR} = 0.46 m_e$, in excellent agreement with the mass, $\sqrt{m_l m_t}$, expected for in-plane ellipsoids. This observation is consistent with the work of Smith et al., who also conclude that in multiple AlAs QW samples with a QW width of 150 Å only a single in-plane ellipsoid with similar $m_{CR}$ is occupied.

We used the coincidence method to determine the product of the Landé g-factor and the effective mass ($g m^*$) of the electrons in the AlAs QW. Note that this method cannot determine the sign of $g$. When a 2DES is tilted in a magnetic field, the Zeeman energy $g \mu_B B$ changes relative to the cyclotron energy $\hbar \omega_c$ because the Zeeman energy is proportional to the total $B$ while the
Landau level separation depends on $B_\perp$. At the coincidence angles, spin-up and spin-down levels of different Landau levels become degenerate. This degeneracy can be seen in magnetoresponse data. At a coincidence angle, in an ideal non-interacting system, half of the Landau levels (LLs) for a tilt experiment of an ideal, non-interacting 2DES with $|gm^*| = 4.1$ cm$^{-1}$ are shown in Fig. 1. The spin-down (-up) levels are shown as solid (dotted) lines. The coincidences are marked with vertical lines and labelled in order. When the Fermi energy lies halfway between two of the LLs on the plot, the system is at an integer $\nu$ and an $R_{xx}$ minimum is observed. At a given angle, the energy gap ($\Delta_\nu$) between the LLs is the vertical distance between the LLs on the plot. Larger $\Delta_\nu$ are manifest as stronger $R_{xx}$ minima at that $\nu$. Qualitatively, all of the $R_{xx}$ minima in Fig. 2 have the behavior described in Fig. 2a. For example, Fig. 2a predicts that $\Delta_4$ (shaded for clarity) will be large at $\theta = 0$, disappear completely at $\theta_1$, reach a maximum again at $\theta_2$, and remain constant through all higher angles. The $\nu = 4$ $R_{xx}$ minimum reflects this behavior.

We also have similar tilt measurements of sample B gated to a density of $3.9 \times 10^{11}$ cm$^{-2}$, sample C at a density of $2.4 \times 10^{11}$ cm$^{-2}$, and sample D at a density of $3.6 \times 10^{11}$ cm$^{-2}$. The data from all of the samples look similar, with all of the coincidences happening at the same angles. Since the quality is better at the higher densities, more minima are observed at higher $\nu$, and they, too, follow the behavior predicted by Fig. 2a in the manner described above. The quality of the highest density data (from sample B) allows us make a more precise measurement of the coincidence angles and therefore $|gm^*|$ than would be possible with the data of Fig. 1 alone. Data from sample B are shown in Fig. 2b: the strengths of various $R_{xx}$ minima as they evolve with $\theta$ are plotted. This plot was made by subtracting a linear background from the $R_{xx}$ vs. $B_\perp$ data, and plotting the new $\Delta R_{xx}$ value for each integer $\nu$. Since a particular $R_{xx}$ minimum is strongest when its corresponding $\Delta_\nu$ is largest, it is the minima in Fig. 2b that correspond to maxima in $\Delta_\nu$. At $\theta_1$ and $\theta_2$, the odd-$\nu$ curves in Fig. 2b show minima, and at $\theta_3$ the even-$\nu$ curves show minima. It is the positions of the minima in Fig. 2b that we used to calculate accurately the angles of the coincidences, and therefore $|gm^*| = 4.1$, to within 4%.

The coincidence data provide a value for the ratio of the Zeeman and cyclotron energies, i.e., $|gm^*|$, but not for the magnitude of these energies individually. The magnitude of $\Delta_\nu$ can be determined from measurements of the activated behavior of the various $R_{xx}$ minima according to $R_{xx} \propto \exp(-\Delta_\nu/2k_BT)$. We have done such measurements on sample B for the smaller fillings ($\nu = 1-3$) at various densities and angles. These measurements are consistent with the Landau level diagram in Fig. 2a, which indicates that $\Delta_1$ and $\Delta_2$ should be $\hbar \omega_c$ at any

This $g$-factor is consistent with the data of Smith et al. [4], because observation of the first coincidence alone cannot determine $|gm^*|$ to better than the integer multiple $l$.

Other features of Fig. 1 are also consistent with $|g| = 9.0$. Figure 2a is a plot of the energies of the Landau levels (LLs) for a tilt experiment of an ideal, non-interacting 2DES with $|gm^*| = 4.1$ cm$^{-1}$. The spin-down (-up) levels are shown as solid (dotted) lines. The coincidences are marked with vertical lines and labelled in order. When the Fermi energy lies halfway between two of the LLs on the plot, the system is at an integer $\nu$ and an $R_{xx}$ minimum is observed. At a given angle, the energy gap ($\Delta_\nu$) between the LLs is the vertical distance between the LLs on the plot. Larger $\Delta_\nu$ are manifest as stronger $R_{xx}$ minima at that $\nu$. Qualitatively, all of the $R_{xx}$ minima in Fig. 2 have the behavior described in Fig. 2a. For example, Fig. 2a predicts that $\Delta_4$ (shaded for clarity) will be large at $\theta = 0$, disappear completely at $\theta_1$, reach a maximum again at $\theta_2$, and remain constant through all higher angles. The $\nu = 4$ $R_{xx}$ minimum reflects this behavior.

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\( \theta \), and that \( \Delta_{\nu} \) should be \( \hbar \omega_c \) for angles \( \theta_1 \) and above. Shown in Fig. 2b are the measured \( \Delta_{\nu} \) at various densities for \( \nu = 1 \) and \( \nu = 2 \) at \( \theta = 0 \) and for \( \nu = 3 \) at \( \theta_1 \). The slope of the line fitted to the points in Fig. 2b is 3.4 K/T, in reasonable agreement with \( \hbar \omega_c \) which is expected to be 2.9 K/T. The \( \simeq 15\% \) discrepancy could come from the uncertainty in the mass measurement and also from the fact that the measured \( \Delta_{\nu} \) are reduced from the true \( \Delta_{\nu} \) by the disorder in the sample, which is expected to have a smaller effect as the sample density is increased. Therefore it is reasonable that the slope of the line should be somewhat greater than the expected slope for a system with no disorder. The negative y-intercept of the line in Fig. 2a gives one estimate of the disorder in the sample: 14 K. We get another estimate of roughly 9 K by examining the \( B_1 \)-dependence of the Shubnikov-de Haas oscillations [13]. The observation that the magnitude of the y-intercept (14 K) is larger than 9K is also consistent with the disorder becoming less important as the density is increased. Finally, Fig. 3b shows how some of the \( \Delta_{\nu}^1 \) change as the sample is tilted. The fact that \( \Delta_1 \) and \( \Delta_2 \) do not rapidly increase as the sample is tilted is strong evidence that neither \( \Delta_1 \) nor \( \Delta_2 \) are gaps of \( g_\mu_B B \). Together, all of these observations form a consistent picture that shows reasonable agreement with the predictions of Fig. 2a.

The data we have presented so far all support the idea that this AlAs 2DES behaves like the non-interacting Landau level diagram in Fig. 2a. There are some details, however, that are not explained by this picture. One is that at high densities, the \( R_{xx} \) minima for \( \nu \) up to 6 are visible, although very weak, at angles at which they are expected to disappear completely. As Fig. 2b shows, however, they are at their weakest at the expected angles. We do not understand this unexpected anticrossing-like behavior. The other is that, as the sample is tilted, \( \Delta_1 \) and \( \Delta_2 \) fall with increasing \( \theta \) (Fig. 3b) while Fig. 2a indicates that they are expected to stay constant at \( \hbar \omega_c \). However, the fact that both \( \Delta_1 \) and \( \Delta_2 \) have the same behavior with \( 1/\cos \theta \) suggests that the same effect is causing this deviation from the ideal behavior predicted by the Landau level diagram.

The most interesting features of this 2DES are its apparent non-interacting behavior and its unexpectedly large \( g \)-factor. A constant \( g \)-factor in this system is surprising given the results of previous experiments which all show variations in \( g \) that are well explained by electron-electron interaction. Ando and Uemura proposed that this enhancement depends on the spin-population difference in the 2DES. They conclude that the enhancement in \( g \) for a given Landau level \( N \) goes as

\[
\sum_{N'} J_{NN'}^g g(n_{N'\uparrow} - n_{N'\downarrow}),
\]

where \( n_{N'\uparrow} (n_{N'\downarrow}) \) is the number of spin-up (down) electrons in the \( N' \) Landau level [3]. In the case of the Si metal-oxide-semiconductor structure, \( J_{NN'} \) became negligible for \( N' \neq N \). Qualitatively, this is true for all of the previously studied systems [1, 3], because of the common feature they share: for angles less than the first coincidence angle there is only a spin-population difference when the Fermi energy lies within one Landau level (between the two spin-split levels). This is due to the fact that \( |g| \mu_B B \) is smaller than \( \hbar \omega_c \) at \( \theta = 0 \). These experiments were all performed at angles near the first coincidence angle because with a smaller \( g \), the coincidences are at much higher angles, and features at the second coincidence angle and beyond are not resolved. In our AlAs QW sample, we have a system in which \( g \mu_B B \) (with \( |g| = 9.0 \)) is significantly larger than \( \hbar \omega_c \) even at \( \theta = 0 \). This not only leads to larger spin-population differences, but also to a situation in which the Fermi energy can never lie within one single Landau level. Therefore it is some different, and unknown, values of \( J_{NN'} \) that are relevant to this system. Under this picture, one hypothesis is that the enhancements due to spin-population difference are not significant. This would lead to the data matching what would be expected of a non-interacting system of electrons. However, this would not explain the magnitude of the \( g \)-factor. The expected bulk value from theoretical calculations is 1.9 [19], and the \( g \)-factor of electrons in bulk Al\(_{0.8}\)Ga\(_{0.2}\)As has been measured by electron-paramagnetic-resonance to be 1.96 [20]. Also, van Kesteren et al. have reported a value of \( \simeq 1.9 \) for electrons in AlAs QWs based on optically detected magnetic resonance experiments on AlAs-GaAs superlattices [12]. It could be that there is some other, still unknown, electron interaction-driven mechanism that is causing the enhancement seen here. It is also possible that the QW structure or some band structure effect is somehow causing the enhancement over the bare value of 1.9. If this is the case, it is a very interesting development that warrants further study, because a better understanding of the mechanism might allow one to use it to control the \( g \)-factor independently of the other system parameters.

In summary, we have magnetoresistance and temperature dependence data revealing that 2D electrons in a 150 Å QW behave as a non-interacting 2DES with a \( g \)-factor of 9.0. The coincidences observed in the magnetoresistance data accurately determine \( |g m^*| = 4.1 \), and the activation energies agree with this \( |g m^*| \). The magnitude of the \( g \)-factor is surprising because it remains constant with \( \nu \), and therefore appears to be enhanced by some unknown mechanism other than the one that is observed in other 2DESs.

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FIG. 1. Magnetoresistance traces from a 2DES (density = $1.4 \times 10^{11}$ cm$^{-2}$) in a 150 Å-wide QW (sample A) at various angles of tilt.

FIG. 2. a: Diagram of the Landau level energies for a tilt experiment in a non-interacting 2DES with $|gm^*| = 4.1$. The solid (dashed) lines correspond to spin-up (-down) Landau levels. b: $\Delta R_{xx}$ points as a measure of the relative strengths of the $R_{xx}$ minima. The $\Delta R_{xx}$ were calculated by subtracting a linear background from the $R_{xx}$ vs. $B_\perp$ data.

FIG. 3. a: Activation energies from sample B. The activation energy for $\nu = 2$ was measured at various densities. b: Activation energies at various $\theta$ measured in sample B.
$T = 0.3 \text{ K}$
\( \nu = 1 \quad n = 2.4 \times 10^{11} \text{ cm}^{-2} \)

\( \nu = 2 \quad n = 3.9 \times 10^{11} \text{ cm}^{-2} \)

\( \nu = 3 \quad n = 3.9 \times 10^{11} \text{ cm}^{-2} \)

**Diagram (a):**
- \( \Delta_1 \)
- \( \Delta_2 \)
- \( \Delta_3 \)

**Diagram (b):**
- Slope = 3.4 K/T
- \( \nu = 1 \)
- \( \nu = 2 \)
- \( \nu = 3 \)