PHYSICAL REVIEW B VOLUME 59, NUMBER 20 15 MAY 1999-II

Anomalous spin splitting of two-dimensional electrons in an AlAs quantum well

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(Received 11 January 1999)

We measure the effective Landé g-factor of 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. [S0163-1829(99)50120-3]

The effective Landé g-factor and effective mass m^* are two fundamental parameters that characterize the energy levels of two-dimensional electron systems (2DES's) in semiconductors in the presence of a magnetic field (B). In a simple, noninteracting picture, the cyclotron energy ($\hbar\omega_c \equiv \hbar e B_\perp/m^*$) 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 2DES's 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.[1–3] In GaAs 2DES's, 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 (ν) being much larger than the bare Zeeman energy.[4] Moreover, the magnitude of the g-factor enhancement oscillates with ν as the spin population difference does.[3–8]

We report here an experimental determination of the spin-splitting energy for 2DES's confined to a modulation-doped AlAs quantum well (QW). In our measurements we utilize the "coincidence" method, a technique used to study the g-factor enhancement in other 2DES's such as those in Si/SiO_2,[1] SiGe,[7] and GaAs.[4] The results are surprisingly simple yet puzzling: in a large range of ν, 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 ν. The 2DES behaves like a noninteracting system of electrons but with a much-enhanced g-factor.

The experiment was done on four 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 $Al_xGa_{1-x}As$ barriers. For details see Ref. 9. Some of the samples had evaporated metal front gates to control the density. The 2DES's we studied had carrier densities from 1.4 to 3.9×10^{11} cm^{-2} and typical low-temperature mobilities of around 6 m^2/Vs. 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* so that the magnetic field could make an angle θ with respect to the normal to the 2DES plane.

Before describing the experimental data, it is useful to summarize some characteristics of the 2DES in AlAs QW's. The constant-energy surfaces for the conduction band minima of *bulk* AlAs are six half ellipsoids (three full ellipsoids) at the X-points of the Brillouin zone. For these ellipsoids, the longitudinal mass (m_l) is $1.1m_e$ and the transverse mass (m_t) is $0.19m_e$.[10] Normally, the confinement potential created by the QW structure is expected to cause only the ellipsoid with the larger mass (in this case m_l) perpendicular to the plane to be occupied. However, experiments have shown that for AlAs QW's of width greater than $\sim$60 Å, the 2D electrons occupy the ellipsoids whose major axes lie in the plane of the 2DES.[9,11–15] In particular, for our samples, measurements reveal a cyclotron resonance effective mass of $m_{\mathrm{CR}}=0.46m_e$, in excellent agreement with the mass, $\sqrt{m_l m_t}$, expected for in-plane ellipsoids.[9] Smith *et al.* also observe a similar m_{CR}. Presumably, this reversed ellipsoid occupancy is caused by biaxial strain in the AlAs layer due to a lattice mismatch between the AlAs and the $Al_xGa_{1-x}As$ barriers. Additionally, several groups have observed that only one of the two in-plane ellipsoids are occupied.[9,12,14–16] Evidence for this includes magnetoresistance data that show minima at odd filling factors, an anisotropic mobility that is consistent with an anisotropic Fermi contour, and optical measurements that through symmetry arguments conclude a nondegenerate ground state. Also, Fourier transforms of magnetotransport oscillations reveal only one subband. We hypothesize that the lifting of the degeneracy between the two in-plane ellipsoids is caused by a slight anisotropy in the strain, which could be caused by a slight deviation of the substrate surface from the ideal (100) face.

We used the coincidence method[1] 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 (spin-splitting) $g\mu_B B$ changes relative to the cyclotron energy (Landau level separation) $\hbar\omega_c \equiv \hbar e B_\perp/m^*$ because the former is proportional to the total B while the latter depends on $B_\perp$. At the coincidence angles, spin-up and spin-down levels of different Landau levels become degenerate. In an ideal noninteracting system, this causes half of the longitudinal resistance (R_{xx}) minima, corresponding to either the even or the odd integer ν, to disap-

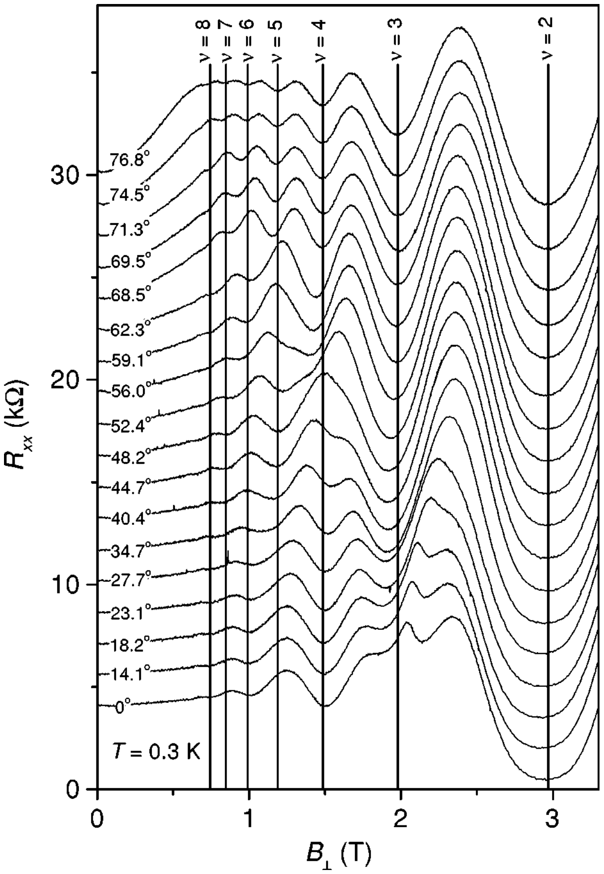

FIG. 1. Magnetoresistance traces from a 2DES (density $=1.4\times10^{11}$ cm^{-2}) in an AlAs QW at various tilt angles.

pear. The other half reach a maximum strength. Once the angle at which a coincidence occurs is found, $|g|m^*$ can be determined from the equation

$$l\hbar\omega_c=|g|\mu_B B \quad , \tag{1}$$

where l is an integer index determined by both the relative values of $|g|\mu_B B$ and $\hbar\omega_c$ at $\theta=0$ and the order of the coincidence observed. For example, if $|g|\mu_B B=0.3\hbar\omega_c$ at $\theta=0$, then at the first coincidence angle (θ_1) $l=1$, at the second coincidence angle (θ_2) $l=2$, etc. However, if $|g|\mu_B B=1.3\hbar\omega_c$ at $\theta=0$, then for θ_1, $l=2$; for θ_2, $l=3$; and so on. For all of the coincidence measurements in other materials that we cite, $l=1$ for θ_1; i.e., the Zeeman energy is *smaller* than the cyclotron energy at $\theta=0$.[3–8] Our data show that this is not the case in the AlAs QW we have studied.

In our experiments, the sample was mounted on the tilting stage with the (011) axis parallel to the tilt axis. We determined the $\theta=0$ position of the sample by fixing B at a small value and maximizing the Hall resistance as a function of θ. We made magnetoresistance measurements at various θ, determining θ by comparing the Hall resistances and the positions of the R_{xx} minima to those of the $\theta=0$ trace. Figure 1 shows R_{xx} vs. $B_\perp$ data, at a density of 1.4×10^{11} cm^{-2}, for various angles, offset vertically for clarity. Concentrating on ν from 3 to 8, we see that in the $\theta=0$ trace, there are no R_{xx} minima corresponding to the odd ν, while there are strong even-ν minima. As the sample is tilted, the situation slowly reverses itself, so that at $\theta=48.2°$, there are no minima corresponding to the even ν, but strong minima exist for the odd ν. This indicates that θ_1 is near 48°, in agreement with the data of Smith *et al.*[14] However, Smith *et al.* reached the conclusion that $|g|m^*=1.52$ using Eq. (1) with $l=1$. This conclusion is inconsistent with the remainder of our data. If l is taken to be 1 for the first coincidence, then at $\theta=0$,

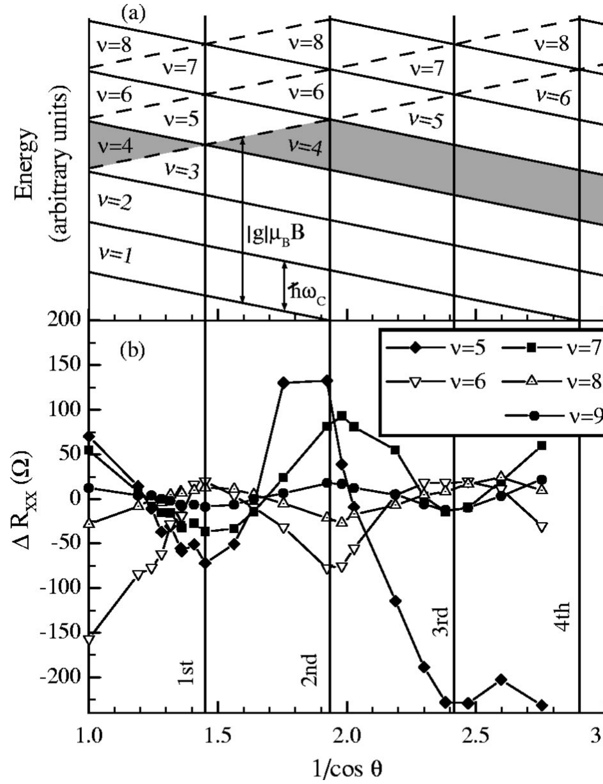

FIG. 2. (a) Diagram of the Landau level energies for a tilt experiment in a noninteracting 2DES with $|g|m^*=4.1$. The solid (dashed) lines correspond to spin-up (-down) energy levels. (b) ΔR_{xx} data as a measure of the relative strengths of the R_{xx} minima. The ΔR_{xx} were calculated by subracting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

$$\frac{|g|\mu_B B}{\hbar\omega_c}=l\cos\theta_1=0.7. \tag{2}$$

With this ratio, one would expect that at $\theta=0$ the odd-ν R_{xx} minima would be stronger than the even-ν minima. Figure 1 shows that the opposite is true. Moreover, the angles of subsequent coincidences are inconsistent with $l=1$. On the other hand, *all* of the coincidences that we observe are consistent with $l=3$ for θ_1, $l=4$ for θ_2, etc. (see below). This yields $|g|m^*=4.1$. This value is consistent with the data of Smith *et al.*[14] because observation of the first coincidence alone cannot determine $|g|m^*$ to better than the integer multiple l.

We now elaborate on several features of our data which are all consistent with a large $|g|m^*$. Figure 2(a) is a plot of the energies of the spin-split Landau levels for a tilt experiment of an ideal, noninteracting 2DES with $|g|m^*=4.1$.[17] The spin-up (-down) levels are shown as solid (dashed) lines. The coincidences are marked with vertical lines and labeled in order. When the Fermi energy lies halfway between two of the energy levels on the plot, the system is at an integer ν and an R_{xx} minimum is observed. At a given angle and filling ν, the vertical distance between the energy levels on the plot corresponds to the energy gap (Δ_ν). Larger Δ_ν are manifested as stronger R_{xx} minima. Qualitatively, all of the R_{xx} minima in Fig. 1 have the behavior described in Fig. 2(a). For example, Fig. 2(a) predicts that Δ_4 (shaded for clarity) will be large at $\theta=0$, disappear completely at θ_1, reach a maximum again at θ_2, and remain constant through all higher angles. The $\nu=4$ R_{xx} minimum in Fig. 1 indeed shows this behavior.

We repeated the measurements at densities of 2.4, 3.6, and 3.9×10^{11} cm^{-2}, and with the tilt axis parallel to the (001) direction at a density of 1.4×10^{11} cm^{-2}. In all cases, the coincidences happen at the same angles. Since the quality is better at the higher densities, more minima are observed at higher ν, and they, too, follow the behavior predicted by Fig. 2(a) in the manner described above. Data from the highest density are summarized in Fig. 2(b), which shows the strengths of various R_{xx} minima as they evolve with θ. This plot was made by subtracting a linear background from the R_{xx} vs. $B_\perp$ data, and plotting the new ΔR_{xx} value for each integer ν. Since a particular R_{xx} minimum is strongest when its corresponding Δ_ν is largest, it is the *minima* in Fig. 2(b) that correspond to maxima in Δ_ν. At θ_1 and θ_3, the odd-ν curves in Fig. 2(b) show minima, and at θ_2 the even-ν curves show minima.[18] The positions of the minima in Fig. 2(b) allow us to calculate accurately the coincidence angles, and lead us to conclude that $|g|m^*=4.1$, to within 4%.

The coincidence data provide a value for the ratio of the Zeeman and cyclotron energies, i.e., $|g|m^*$, but not for the magnitude of these energies individually. For ν from 1 to 3, at various densities and angles, we determine the magnitude of the Δ_ν from measurements of the activated behavior of the relevant R_{xx} minima according to $R_{xx}\propto\exp(-\Delta_\nu/2k_BT)$. These measurements, too, are consistent with the Landau level diagram in Fig. 2(a), which indicates that Δ_1 and Δ_2 should be $\hbar\omega_c$ at any θ, and that Δ_3 should be $\hbar\omega_c$ for angles θ_1 and above. Shown in Fig. 3(a) are the measured Δ_ν at various densities for $\nu=1$ and $\nu=2$ at $\theta=0$ and for $\nu=3$ at θ_1. The slope of the line fitted to the points in Fig. 3(a) is 3.4 K/T, in reasonable agreement with $\hbar\omega_c$ which is expected to be 2.9 K/T. The approximately 15% discrepancy could come from the uncertainty in the mass measurement and also from the fact that the measured Δ_ν are reduced from the true Δ_ν 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. 3(a) gives one estimate of the disorder in the sample: 14 K. We get another estimate of roughly 9 K by examining the $B_\perp$ dependence of the Shubnikov–de Haas oscillations.[19] The observation that the magnitude of the y-intercept (14 K) is larger than 9 K is also consistent with the disorder becoming less important at higher density. Finally, Fig. 3(b) shows how some of the Δ_ν change as a function of θ. The fact that Δ_1 and Δ_2 do not rapidly increase as the sample is tilted is strong evidence that neither Δ_1 *nor* Δ_2 are gaps of $g\mu_BB$. Together, all of these observations form a consistent picture that shows reasonable agreement with the predictions of Fig. 2(a), for $|g|m^*=4.1$.

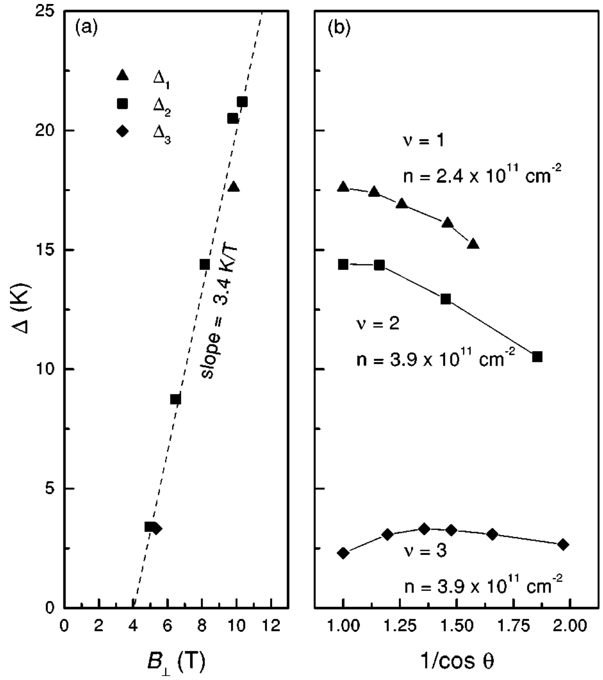

FIG. 3. (a) Activation energies (Δ_ν). Δ_2 was measured at various densities. (b) Activation energies at various θ.

Using $m^*=0.46m_e$,[9] we conclude that the Landé g-factor of electrons confined to this AlAs QW is ±9.0. This assumes that m^* does not change appreciably as we tilt the sample, an assumption we feel is reasonable since previous tilt experiments in Si/SiO_2,[20] and $Al_xGa_{1-x}As$/GaAs (Ref. 21) structures using both electron tunneling and cyclotron resonance methods have shown that the change in m^* is less than 5% as the sample is tilted. This change is on the order of the error in our measurement of $|g|m^*$.

The data we have presented so far all support the idea that this AlAs 2DES behaves like the *noninteracting* Landau level diagram of Fig. 2(a). There are some features, however, that are not explained by this picture. One is that at high densities, the R_{xx} minima for ν from 3 to 6 are visible, although very weak, at angles at which they are expected to disappear completely. In the same vein, Fig. 3(b) shows that at $\theta=0$, Δ_3 is larger than expected. As Fig. 2(b) shows, however, the R_{xx} minima *are* at their weakest at the coincidence angles. The other is that, as the sample is tilted, Δ_1 and Δ_2 fall with increasing θ, and Δ_3 falls with increasing θ after the first coincidence [Fig. 3(b)]. Figure 2(a) indicates that they are expected to stay constant at $\hbar\omega_c$. However, the fact that both Δ_1 and Δ_2, and Δ_3 after the first coincidence, have qualitatively the same behavior with $1/\cos\theta$ suggests that the same mechanism is causing their decrease with θ.

The most interesting features of this 2DES are its unexpectedly large g-factor and its apparent noninteracting behavior. The value of the g-factor for electrons in bulk AlAs expected from theoretical calculations is 1.9,[22] 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.[23] Also, van Kesteren *et al.* have reported a value of $\simeq1.9$ for electrons in AlAs QW's based on optically detected magnetic resonance experiments on AlAs–GaAs superlattices.[12] So clearly, $|g|=9.0$ is much enhanced compared to the value of approximately 2, determined from zero-B or small-B measurements. What is the cause of such enhancement? It is known that in the presence of a large B and a spin-population difference, electron interaction can lead to a substantial enhancement of the spin-splitting energy, which is manifested as an enhanced g-factor. However, this interaction mechanism leads to an enhacement of the g-factor that oscillates with filling factor ν,[3–8] so a constant g-factor in our system is surprising. Ando and Uemura proposed that the oscillatory 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 $\Sigma_{N'} J^2_{NN'}(q)(n_{N'\uparrow} - n_{N'\downarrow})$, 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, $J_{NN'}$ is negligible for $N' \neq N$. Qualitatively, this is true for all of the previously studied systems that we cited, 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). In our AlAs QW sample, we have a system in which the Fermi energy can *never* lie within one single Landau level [Fig 2(a)]. Therefore, it is some different, and unknown, values of $J_{NN'}$ that are relevant to our system. It is possible that the enhancements due to spin-population difference are not significant, so the 2DES can behave like a noninteracting system. In this picture, however, the large magnitude of the g-factor remains unexplained.

It could be that the enhancement over the bare value of 1.9 is caused by some other, still unknown, electron interaction-driven mechanism, or that the QW structure or some band structure effect is somehow responsible. If this is the case, a better understanding of the mechanism might allow one to use it to control the g-factor independently of the other system parameters. In either case, the origin of this unexpected behavior deserves further investigation. Finally, we would like to point out that in this system, the electrons are completely spin polarized for fillings up to $\nu = 3$ at $\theta = 0$ (and up to even higher ν at finite θ). Therefore it provides a unique system in which one can study phenomena such as transitions between quantum Hall states, or quantum Hall and insulating states.[24]

In summary, we have magnetoresistance and activation data revealing that 2D electrons in a 150-Å AlAs QW behave as a noninteracting 2DES with $|g|m^* = 4.1$. This yields a g-factor of 9.0, whose magnitude is surprising because it remains constant with ν, and therefore appears to be enhanced by some unknown mechanism other than the one that is observed in other 2DES's.

We would like to thank J. P. Lu, S. A. Lyon, and D. C. Tsui for useful discussions and insights. This work was funded by the NSF.

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[17] It should be noted that only the product $|g|m^*$ has significance in this diagram. Any system with a given $|g|m^*$ will have the same Landau level vs tilt diagram for the ideal, noninteracting case, regardless of what the individual values of g and m^* happen to be.
[18] We note that about halfway between $\theta = 0$ and θ_1, Fig. 2(a) shows all ν greater than 2 to have a gap of $0.5\hbar\omega_c$. Therefore, all ν for which $0.5\hbar\omega_c$ is larger than the disorder and temperature should show minima. Indeed, in Fig. 1 at 34.7° and 40.4°, all ν up to 5 show minima, and in the high density data near those angles, all ν up to 8 show minima. As the angle is increased, the gaps of increasingly larger ν become fixed at $\hbar\omega_c$. For example, Fig. 2(a) shows that Δ_5 should remain $\hbar\omega_c$ after θ_3, consistent with the data of Fig. 1 and Fig. 2(b). Furthermore, in the 76.8° trace in Fig. 1, all of the minima are strong because at this angle, all gaps up to Δ_9 are $\hbar\omega_c$.
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