InAs-AlSb quantum wells in tilted magnetic fields

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InAs-AlSb quantum wells are investigated by transport experiments in magnetic fields tilted with respect to the sample normal. Using the coincidence method, we find, for magnetic fields up to 28 T, that the spin splitting can be as large as five times the Landau splitting. We find a value of the g factor of $|g| \approx 13$. For small even-integer filling factors the corresponding minima in the Shubnikov–de Haas oscillations cannot be tuned into maxima for arbitrary tilt angles. This indicates the anticrossing of neighboring Landau and spin levels. Furthermore, for particular tilt angles we find a crossover from even-integer-dominated Shubnikov–de Haas minima to odd-integer minima as a function of magnetic field.

I. INTRODUCTION

The energy spectrum of two-dimensional electron gases (2DEG's) in magnetic fields of arbitrary orientation is fairly well understood.[1,2] Most considerations follow a single-particle approach which is powerful to explain several of the experimentally observed features. For magnetic fields tilted with respect to the sample normal, one finds that the Landau splitting, which is proportional to the component of the field perpendicular to the 2DEG's can be tuned with respect to the Zeeman splitting which is proportional to the total magnetic field. This is used in the so-called coincidence method,[3] where the appearance and disappearance of minima in Shubnikov–de Haas oscillations (SdH) as a function of tilt angle is observed in magnetotransport experiments. The analysis in terms of a picture of noninteracting electrons has proven very powerful for the analysis of energy spectra in Si metal-oxide-semicondector field-effect transistors,[3] InAs-GaSb superlattices,[4] InAs-GaSb quantum wells,[5] GaAs-$Al_xGa_{1-x}As$ heterostructures,[6] $Ga_yIn_{1-y}As$/InP heterostructures,[7] and Si/SiGe heterostructures.[8] In this paper we focus on InAs-AlSb quantum wells, and extend preliminary studies on this material system.[9] We present several features that are perfectly well explained in the existing single-particle picture, namely (1) the appearance and disappearance of even- and odd-integer SdH minima as a function of tilt angle; (2) a Zeeman splitting as large as five times the Landau splitting for tilt angles around 87°; and (3) a g factor for InAs of about 13, in agreement with considerations based on conduction-band nonparabolicity.[10] In contrast to straightforward expectations, we find (4) nonvanishing SdH minima for even-integer filling factors $\nu = 4, 6$, and 8 in the range of tilt angles and magnetic fields where these filling factors can be observed; and (5) a regime at low magnetic fields where even-integer filling-factor SdH minima persist for all tilt angles, while the usual coincidence features occur at higher magnetic fields. These observations are discussed in view of other experiments[7,8] and theoretical ideas based on exchange enhancement.[12,13]

II. LEVEL CROSSING IN THE SINGLE-PARTICLE REGIME

All samples contained 15-nm-wide InAs quantum wells, confined by AlSb or $Al_xGa_{1-x}Sb$ ($x \leqslant 0.8$) barriers. The sample details were summarized in Refs. 14 and 15. Our samples are of very high quality, and have mobilities up to 84 m^2/V s. In this paper we focus on a sample with a GaSb cap and a carrier density of $N_s = 6.2 \times 10^{11}$ cm^{-2} (UCSB No. 9503-18). The samples were patterned into geometries suitable for transport experiments, and equipped with Ohmic contacts to the 2DEG.

The samples were mounted on a revolving stage in several cryostat environments. The angle α is measured between the magnetic-field orientation and the sample normal. For the data taken at $T = 1.7$ K and magnetic fields up to 8 T the revolving stage was computer controlled. Consequently very dense data sets were obtained. We also measured the samples in a dilution refrigerator at sample temperatures down to 100 mK and magnetic fields up to 15 T, as well as in a ^{3}He system with a base temperature of about 400 mK and magnetic fields up to 28 T. Because of the Landau-level broadening the temperature dependence of the SdH oscillations basically levels off below 1.7 K. The difference in the experimental resolution of the three setups is mostly determined by the respective measurement electronics.

The results obtained on different samples depend on the carrier concentration. The filling factor is definded by $\nu = N_s h/eB$, where N_s is the electron density of the 2DEG. For perpendicular fields, i.e., $\alpha = 0$, all observed features at magnetic fields $B \leqslant 1.5$ T, where the Zeeman splitting is not yet resolved, can be analyzed with one single SdH period with very high accuracy.[15] Effects of inversion asymmetry induced zero-field spin splitting[16] are therefore not consid-

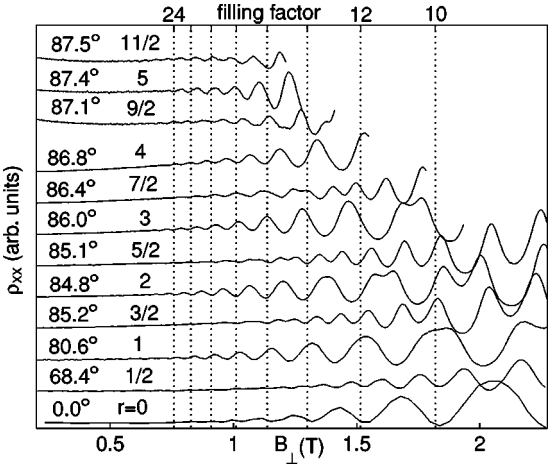

FIG. 1. ρ_{xx} traces for various tilt angles where different coincidence situations are met. The topmost three curves are scaled up to $\times 5$, and a parabolic background has been subtracted for clarity.

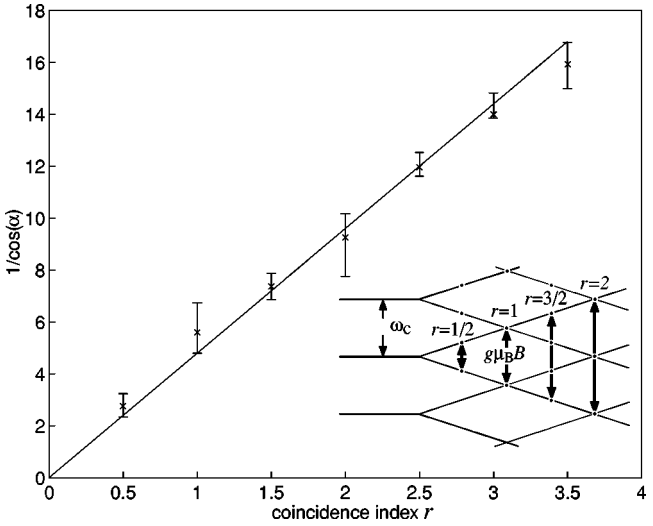

FIG. 2. Coincidence plot gathered from the angles in Fig. 1. The straight line has a slope of 4.8, yielding $g=2/(\text{slope}\times 0.032)=13$, where the effective mass $m^*/m_e=0.032$ has been unsed.

ered. From the largest filling factors that we can observe, we estimate the Landau-level width to about 0.4 meV.

We can follow the disappearance and reappearance of minima at even- and odd-integer filling factors as a function of increasing tilt angle. This interplay between pronounced even- and odd-integer filling factor minima occurs for a series of angles. It also shows up in the respective quantum Hall plateaus.[9]

Figure 1 shows magnetoresistance traces at specific tilt angles where either SdH minima occur only at even-integer filling factors, at even and odd, or only at odd-integer filling factors. The amplitude of the SdH oscillations at large tilt angles is magnified with respect to the other traces. The angles are determined by measuring ρ_{xy} with high accuracy. The absolute error in the angle becomes larger with increasing tilt angle because of the $\cos(\alpha)$ dependence.

We find that the carrier density decreases by up to 5% if parallel magnetic fields larger than 20 T are applied. This also shows up in a nonlinear Hall effect for large parallel fields. We attribute this behavior to magnetic freeze-out of carriers due to a redistribution of the electrons from the well into some localized states. The reason for this could be a strong diamagnetic shift of the quantum-well state. This effect has no consequences for the results presented in this paper, but explains why the SdH minima in Fig. 2 for large tilt angles α do not exactly fall onto the dashed lines.

The inset in Fig. 2 describes the various coincidence situations which are characterized by the parameter r, the ratio of Zeeman and cyclotron energies:

$$r=\frac{g\mu_B B_{tot}}{\hbar\omega_c}.$$

Here $\omega_c=eB_\perp/m^*$, m^* is the effective electron mass, μ_B is the Bohr magneton and $B_\perp=\cos(\alpha)B_{tot}$. We thus arrive at

$$r\cos(\alpha)=\frac{gm^*}{2m_e},$$

where m_e is the free-electron mass. The data in Fig. 1 show the resistance traces at r values always close to the indicated numbers of 1/2, 1, 3/2, ... The larger the tilt angle, the more difficult it is to realize a given coincidence situation accurately, since the span of angles at which it takes place decreases with $\cos\alpha$. Nevertheless we demonstrate that SdH oscillations can be measured in a situation where the Zeeman splitting is five times larger than the Landau splitting.

Figure 2 shows the coincidence situations plotted as $1/\cos(\alpha)$ versus r. The slope of this curve is proportional to the product gm^*. We determined the effective mass for this sample by temperature-dependent SdH measurements, and found a value for the effective mass of $m^*=(0.032\pm 0.002)m_e$, which is in agreement with values reported in the literature.[17] Using this value for m^* we computed $|g|\approx 13$.

Such experiments have been performed on a series of samples. In a first approximation the obtained data can be described by using Landau levels and spin levels behaving and crossing as expected in a single-particle model. Because the g factor is so large, effects of electron-electron interactions, the so-called exchange enhancement,[18] are expected to be relatively small. Furthermore these effects should increase for decreasing filling factors. In our case the experimental data can best be described with a product gm^* which is constant over the investigated range of magnetic fields and angles.

The effects of nonparabolicity can be estimated using a $\mathbf{k}\cdot\mathbf{p}$ formalism,[19] which in its simplest case reduces to the two-band model

$$m^*(E)=m^*(E=0)\left(1+2\frac{E}{E_g}\right)$$

Here $E_g=400$ meV is the band gap of InAs, and E is the electron energy relative to the conduction-band edge. Because of the huge conduction-band offset between InAs and AlSb (1.35 eV), we use the model of a quantum well with infintely high walls. The total energy E can, to a good approximation, be written as the sum of an approximate Fermi energy $E_F=N_s\pi\hbar^2/m^*$ and an approximate confinement energy $E_c=\hbar^2/2m^*\pi^2/a^2$, where a is the quantum-well width.

With this we obtain for the density dependence of the effective mass in the two-band model:

$$m^*(N_s)=\frac{m_0^*}{2}+\frac{m_0^*}{2}\sqrt{1+\frac{8}{E_g}\left(\frac{\hbar^2}{2m_0^*}\frac{\pi^2}{a^2}+\frac{\pi\hbar^2}{m_0^*}N_s\right)}$$

Here $m_0^*=m^*(E=0)$, i.e., the effective mass at the conduction-band edge, which for InAs is $m_0^*/m_e=0.023$. We find $m^*(N_s=4.4\times10^{11}\ \mathrm{cm}^{-2})/m_e=0.032$, in agreement with our experimentally determined value. The values for the energies are $E_F=52$ meV and $E_c=51.6$ meV.

At the same time the g factor is reduced,[10] in agreement with our experimental findings. For the g factor the two-band model results in

$$g(E)=g(E=0)(1-\alpha E).$$

The parameter α is estimated in Ref. 20 to be $\alpha=0.0025\times1/\mathrm{meV}$ for a quantum well system very similar to ours. This results in a g factor of $|g|=12$ very close to our experimental result. Using the expressions for the g factor and the effective mass, one finds that the total effect of nonparabolicity on the product gm^* almost cancels out.

Several additional aspects should be considered in this discussion. For large tilt angles the in-plane magnetic field component can be as large as 10 T. In this case it is well known that the Fermi surface is no longer a circle but an ellipse. The effective mass thus depends on B^2. We measured the temperature dependence of the SdH oscillations in tilted magnetic fields in order to extract the effective mass as a function of field and tilt angle. Within the experimental accuracy we found that the effective mass is constant to 5% in the investigated parameter regime. On the same footing, one also expects that the g factor becomes a magnetic-field-dependent quantity. With these complications in mind one has to take the analysis of the product gm^* from the plot in Fig. 2 with a grain of salt.

III. LEVEL ANTICROSSINGS AT SMALL FILLING FACTORS

Figure 3 shows magnetoresistance traces down to even-integer filling factors of $\nu=6$. We only present the range of angles where the situation corresponding to $r=1$ occurs. The tilt angle is changed in rather small increments, which are monitored by the change in the Hall resistance ρ_{xy}. Similar but less pronounced features also occur in a sample that has a lower carrier density of $N_s=4.4\times10^{11}\ \mathrm{cm}^{-2}$. The highest perpendicular magnetic fields correspond to total magnetic fields of 28 T. For $\alpha=73.5°$, minima occur for even- and odd-integer filling factors. As the tilt angle increases, even-integer minima weaken until about 78.8°, and then increase again in strength. They never completely disappear even up to filling factors of $\nu=16$. This means that there always remains a minimum of the density of states at the Fermi energy when the single-particle model predicts a crossing of spin and Landau levels.

An anticrossing of single-particle levels has been predicted for filling factor $\nu=2$ (Refs. 12 and 13) based on the transition from a spin-unpolarized state at small tilt angles to a spin-polarized state at large tilt angles. Experimental data

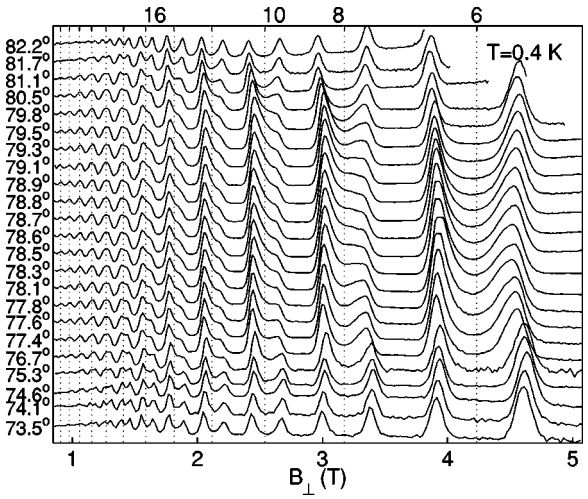

FIG. 3. Magnetoresistance ρ_{xx} vs the perpendicular component of magnetic fields for various tilt angles in the regime of coincidence $r=1$, and $g\mu_B B=\hbar\omega_c$. Nonvanishing minima at even-integer filling factors are observed.

obtained on $Ga_yIn_{1-y}As/InP$ heterostructures[7] showed the expected single-particle behavior for low-mobility samples while a non-suppression of the SdH minimum at $\nu=2$ for high-mobility samples was observed. This was interpreted in the framework of the formation of a spin-polarized ground state[12] induced by the strong parallel magnetic field. In the case of Ref. 7 the SdH minimum corresponding to filling factor $\nu=4$ and higher even-integer filling factors were perfectly well suppressed at the same tilt angle, as expected in a single-particle model. The authors[7] argued that for low-mobility samples and higher-integer filling factors neighboring levels overlap due to their broadening, and the exchange interaction cannot help to further open the gap.

The experimental situation in our case is different in the following aspects. The SdH minima at even-integer filling factors weaken but do not disappear. Furthermore their weakening goes hand in hand with their overall appearance, i.e., the sudden importance of an exchange driven opening of a gap cannot be observed. Unfortunately the carrier density in our samples is too high to observe the behavior of SdH minima corresponding to filling factors $\nu=2$ and 4 at large tilt angles and experimentally accessible magnetic fields.

In order to obtain an understanding of the energy structure in tilted magnetic fields, we calculated the magnetoresistance following Gerhardts.[21] We included a constant background density of states in order to model the broad minima in the magnetoresistance. Based on the single-particle energies

$$E_{s,n}=\hbar\omega_c\left(n+\frac{1}{2}\right)+sg\mu_B B,\quad n=0,1,2,\ldots,s=\pm\frac{1}{2},$$

an anticrossing between neighboring levels of $\Delta E=0.29\hbar\omega_c$ was inserted into the model. At $B_\perp=4.2\ T$ ($\nu=6$) and $m^*=0.032m_e$, this corresponds to $\Delta E=4.4$ meV. We assumed a Gaussian Landau-level broadening $\Gamma=\hbar/\tau_q=1.5$ meV, with $\tau_q=0.45$ ps. The magnetic field dependence of the anti-crossing was approximated with a smooth parabolic curvature.

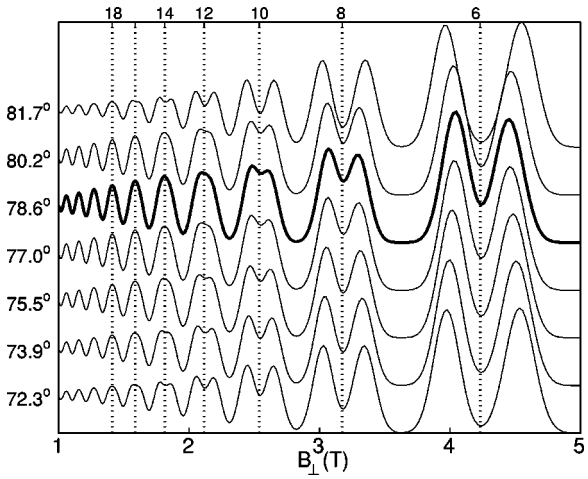

FIG. 4. Model calculation of the magnetoresistance for various tilt angles. The parameters have been chosen to match the experimental data presented in Fig. 4. The bold curve is at the angle where the coincidence $\hbar\omega_c = g\mu_B B$ is met

Figure 4 shows calculated resistance traces. There is at least qualitative agreement between the calculated (Fig. 4) and experimental (Fig. 3) data sets. From the simulation it is obvious that the situation where even-integer minima in the SdH oscillations are weakened or even suppressed extends over a significantly larger range of angles compared to the experiment. This could arise from our rough modeling but also hints at the importance of interaction effects for the details of SdH oscillations.

What could be the reason for the persistent appearance of even-integer SdH minima in the regime where the underlying single-particle energy levels are expected to cross? For small filling factors the effects of exchange enhancement[18] have been demonstrated in various experiments (for a recent example, see Ref. 11 and references therein). From our experimental data at small filling factors we do not see an indication that eletron-electron interactions in terms of exchange enhancement play a significant role. For the case of perpendicular magnetic fields, $\alpha = 0$, the energy levels are described by three quantum numbers, namely, subband, Landau, and spin quantum numbers. This is based on the fact that the Hamiltonian can be separated into a part describing the electron motion in the plane of the 2DEG and another part responsible for the quantization in growth direction. For tilted magnetic fields mixed levels arise whose degeneracy is still completely controlled by the perpendicular magnetic-field component.[2] For the InAs-AlSb system this approach has to be extended in order to incorporate the strong conduction-band nonparabolicity of InAs, as well as the possible strain in the well due to the different lattice constants of barrier, well, and GaAs substrate. One can envision that such effects already lead to possible level couplings and anticrossings, as observed in the experiment.

IV. EVEN-INTEGER SDH MINIMA AT LOW MAGNETIC FIELDS

Figure 5 presents a gray-scale plot composed of magnetoresistance traces taken at very closly spaced tilt angles around the regime of $r = 1$ and $r = 2$. Here we focus on the

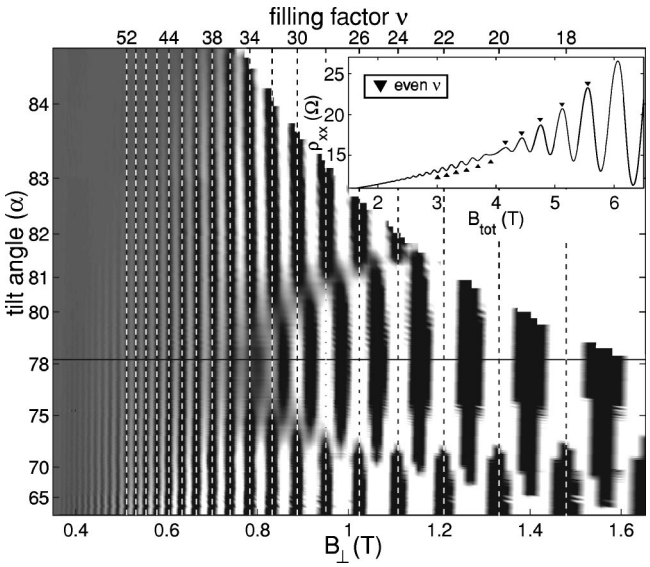

FIG. 5. Gray-scale plot of ρ_{xx} data. A slowly varying background has been removed, and the oscillation amplitude has been raised at low magnetic fields to make the effect visible. The vertical axis is linear in $1/\cos(\alpha)$. Black (white) areas indicate small (large) values of the resistance. The inset shows one (unprocessed) ρ_{xx} curve at $\alpha = 78.2°$ (Horizantal line in the gray-scale plot). The triangles mark the positions of even-integer filling factors.

regime of small magnetic fields. For $\alpha = 65°$ SdH minima occur at even-integer filling factors. As the tilt angle is increased, odd-integer minima take over at magnetic fields $B_\perp \geqslant 0.8$ T, and gradually disappear again in favor of even-integer minima. At magnetic fields below 0.8 T minima occur only at even-integer filling factors over the whole range of tilt angles. The inset of Fig. 5 shows a representative resistance trace at an intermediate tilt angle where the SdH oscillations are dominated by even-integer minima at low magnetic fields, a crossover regime, and odd integer filling factors at higher magnetic fields. A beating pattern would not display such a phase shift in the pattern of the oscillations.

Starting from the Landau and spin levels in tilted magnetic fields, such a behavior can occur in two ways: either the Landau energy is not exactly proportional to the perpendicular component of the magnetic field, or the Zeeman splitting is angle dependent. Both effects have been discussed to some extent before. Nonparabolicity effects are most likely a minor contribution for such small magnetic-fields. The large in-plane magnetic-field component, which can lead to an anisotropic effective-mass dispersion, should become more important for larger magnetic fields. However, the unusual behavior as presented in Fig. 5 occurs in the low-magnetic-field regime.

Leadley *et al.* showed that there is a critical collapse of the exchange-enhanced spin splitting in two-dimensional systems.[11] The authors found that the total spin splitting is a sum of the bare Zeeman splitting proportional to the total magnetic field and a contribution due to exchange enhancement which is proportional to the perpendicular component of the magnetic field:

$$\Delta_{spin} = g_0\mu_B B_{tot} + \beta\hbar e B_\perp / m^*$$

For the case of GaAs heterostructures, Leadley *et al.*

found $\beta = 0.2$, independent of magnetic field. In their case g_0 is the bare g factor because nonparabolicity effects are negligible in GaAs. In our case g_0 has to be identified with $g(E)$, where the nonparabolicity contribution stems from the position of the Fermi energy above the conduction-band edge and does not depend on magnetic field in the investigated range of parameters.

In the regime of large magnetic fields discussed above, where spin splitting is well resolved, we found that the exchange enhancement is a minor contribution. However, for small magnetic fields and large tilt angles the exchange contribution could play an important role. If the bare spin splitting is smaller than the Landau-level broadening, the exchange enhancement is not expected to play a role. In this case even-integer SdH minima will dominate the magnetoresistance for all tilt angles. Once the bare Zeeman splitting approaches and exceeds the Landau-level broadening, the exchange enhancement will further increase the spin gap and the usual coincidences between Landau and spin levels will take over.

For any functional dependence of g on B, which is smooth, one would not expect a sudden crossover from even-integer to odd-integer minima as depicted in the inset of Fig. 5. The sudden change in periodicity over a small magnetic-field range requires a mechanism which leads to an abrupt opening of the spin gap similar, as observed in Ref. 11 for the cititcal collapse of the exchange enhanced spin splitting.

V. SUMMARY

We have presented a series of SdH measurements on InAs-AlSb quantum wells in tilted magnetic fields. In a reasonable range of parameters the experimental results can be understood in a straightforward single-particle model. The coincidence method is based on independent Landau and spin levels. This way we obtain reasonable numbers for the effective mass and g factor that agree with results of a two-band model and experimental results of others. For large magnetic fields we find an anticrossing of neighboring Landau and spin levels. Most likely this is not a consequence of electron-electron interactions. We speculate that this effect arises from the pronounced nonparabolicity of the InAs conduction band as well as from the built-in strain in such samples. For very small magnetic fields SdH minima exist only at even-integer filling factors, independent of tilt angle. This is attributed to a critical filling factor necessary for the observation of spin-splitting

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