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g factor of electrons in an InAs quantum well

T. P. Smith III and F. F. Fang
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598
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We have studied the spin splitting of Landau levels for a two-dimensional electron gas in an InAs/GaSb single quantum well. The effective g factor, g^*, is between 7.8 and 8.7 which is below the bulk value. The reduction in g^* is due to nonparabolicity effects resulting from confinement of free electrons to a narrow quantum well. Under these circumstances g^* enhancement due to many-body effects is smaller than the reduction due to nonparabolicity.

When free carriers are confined to a narrow quantum well the lowest energy level (subband) can lie well above the conduction-band edge. For free carriers in narrow-gap semiconductors such as InAs the nonparabolicity of the conduction band significantly increases the effective mass of the electrons. This is also manifested as a reduction in the effective g factor.[1] In a two-dimensional electronic system (2DES) many-body effects also play a role in determining the spin splitting of Landau levels. As first proposed by Janak,[2] g^* is enhanced due to exchange effects in a 2DES. Ando and Uemura[3] analyzed spin effects in the context of the screened Hartree-Fock approximation and derived an oscillatory g^* for electrons in a 2DES. This oscillatory behavior is related to the relative occupancy of spin levels in the 2DES. If, for example, most of the electrons are in a spin-up state then the exchange energy for spin-up electrons will be larger than that of spin-down electrons and there will be an increase in the splitting between the two spin levels. If, on the other hand, the occupancy of spin-up and spin-down levels is roughly the same, then the exchange energies of all electrons will be approximately the same and there will be no enhancement of g^*. Thus, g^* oscillates between its bare value (when the Fermi level is between Landau levels) and its maximum enhanced value (when the Fermi level is in the center of a Landau level). The amplitude of the oscillations, and hence the average value of g^*, increases with magnetic field. Because nonparabolicity and many-body effects drive g^* in opposite directions, quantum wells in narrow-gap semiconductors provide a unique opportunity to study the relative importance of these two effects.

Tilted-magnetic-field experiments, first performed by Fang and Stiles,[4] yield the most direct measurement of g^*. Landau-level separation is determined by the magnetic field strength normal to the 2DES, while the spin splitting is determined by the total field strength. Thus, the relative strengths of these two splittings can be varied by tilting the 2DES in a magnetic field. In a constant magnetic field, if the tilting angle θ passes through a critical condition where the Zeeman splitting is an odd integral multiple of one half the Landau-level splitting, there will be a phase reversal in the Shubnikov—de Haas oscillations. This technique does not require the Zeeman splitting to be explicitly resolved. The most easily identified phase reversal is usually the first (when $g^*\mu_B B=\frac{1}{2}\hbar\omega_c$), where μ_B is the Bohr magneton, B is the total magnetic field, $\omega_c=eB\cos\theta/mc$, m is the electron effective mass, and θ is the angle between the 2DES and the magnetic field. Then g^* is given by

$$g^*=\frac{\cos\theta}{m/m_0}\ , \qquad (1)$$

where m/m_0 is the ratio of the effective mass to the free-electron mass. This technique is the most widely used method for g^* determination. However, this method relies on an accurate value for the effective mass. In addition, in low-carrier-concentration samples, the paucity of oscillations significantly reduces the accuracy of this method. For this reason, modeling of Shubnikov—de Haas oscillations and fitting of the temperature dependence of the magnetoresistance[5] and comparison of inter-Landau-level minima with intra-Landau-level minima,[6] have been used to obtain g^*. However, these techniques rely on certain assumptions about level broadening and the form of the density of states in a 2DES which are open to question.

Here we report the results of g^* measurements for electrons in a narrow InAs/GaSb single quantum well (SQW) using the tilted-field technique, together with the mass determination at the Fermi surface from the temperature dependence of Shubnikov—de Haas oscillations. We find that the effective g factor is reduced below the bulk value at the band edge and that it does not exhibit any magnetic field dependence. We also find that the effective mass is markedly different than the band-edge value. Thus we believe that, in our samples, nonparabolicity effects are dominant.

The InAs/GaSb SQW samples studied were grown by molecular-beam epitaxy, as previously described.[7] They have a well width of 100 Å, a carrier concentration of 5.7×10^{11} cm^{-2}, and a mobility of 60 000 cm^2/V s at 4.2 K. The well is assumed to be symmetric. Detailed analysis of the low-field magnetoresistance and Hall voltage indicates that the contribution of holes in GaSb accumulation layers to the conductivity is negligible. In an ideal sample the number of electrons would be equal to the number of holes but interface states between the GaSb and InAs create an imbalance of free carriers.[8] This simplifies our analysis since no competing Shubnikov—de

Haas oscillations are present to obscure the interference between the spin and Landau-level splitting of the electrons. The samples were fabricated into Hall bars and tilted-field experiments were performed by rotating them about their long axis.

Previously, Chang *et al.*[9] studied the magnetoresistance of InAs/GaSb superlattices with well widths of 500 and 1000 Å, considerably wider than our sample. They found that g^* was between 19 and 23 for the wide well and approximately 17 for the 500-Å well superlattice. These values are enhanced above the bulk band-edge value [~ -15 (Refs. 10 and 11)] and are most likely due to many-body effects in the absence of nonparabolicity. Our results are quite different.

Figure 1 shows three traces of ρ_{xx} versus $(1/\cos\theta)$, where θ is the angle between the applied field and the 2DES, as shown in the inset. The point at which the phase reversal occurs is indicated by an arrow. The error in the determination is conservatively taken to be the difference between the two closest extrema. The position of the phase reversal can be identified by examining the amplitude of the Shubnikov–de Haas oscillations (the first phase reversal results in a reduction in the oscillation amplitude) or by plotting the index of the maxima and minima as a function of $1/\cos\theta$ and looking for the phase reversal directly (as in the upper plot in Fig. 1). Both methods are used here.

We also determined the effective mass for electrons in our samples from the temperature dependence of the Shubnikov–de Haas oscillations. The effective mass was found to be $(0.050\pm0.005)m_0$ for normal magnetic field strengths between 2.3 and 3.6 T, a value which is considerably higher than the commonly accepted value of $0.023m_0$ at the conduction-band edge. Since this is the range in which g^* was determined, we feel this is the appropriate mass to be used in (1). The parallel component of the magnetic field has little effect through the diamagnetic shift in energy ($\Delta E = \langle z^2\rangle H_{\parallel}$) (Ref. 12), where $\langle z^2\rangle$ is the mean-square distance of the wave function from the well interfaces. Below 2.3 T the oscillations are too weak for accurate analysis and above 3.6 T the oscillations are no longer sinusoidal. Recently, Heitman *et al.*[13] studied the cyclotron resonance of electrons in a 200-Å InAs quantum well and obtained a mass of $0.0374m_0$. Our result is consistent with, though considerably larger than, this value since the lowest subband is approximately 50 meV higher for our 100-Å well. From tunneling into InAs surface accumulation layers, Tsui[14] measured an effective mass of 0.05 at an energy of 300 meV above the conduction-band edge. However, calculation of the lowest subband energy for a 100-Å square well of InAs bounded by GaSb and inclusion of band-bending effects,[15] assuming the band offset between the conduction-band edge of InAs and the valence-band edge of GaSb is 150 meV, place the Fermi energy between 125 and 150 meV above the conduction-band edge, indicating that the effective mass should be 20% smaller. This discrepancy may be due to the difference between confinement of electrons to a surface accumulation layer versus a quantum well bounded by GaSb. The large number of valence states in the GaSb may tend to increase the effective mass due to penetration of the *s*-like InAs electron wave function into the *p*-like GaSb states.

Figure 2 shows the results of g^* measurements for total magnetic field strengths from 5–10 T. The measured g^* is smaller than the measured value of 15 for bulk InAs[10,11] for all magnetic fields studied. In addition, there is little or no change in g^* as magnetic field

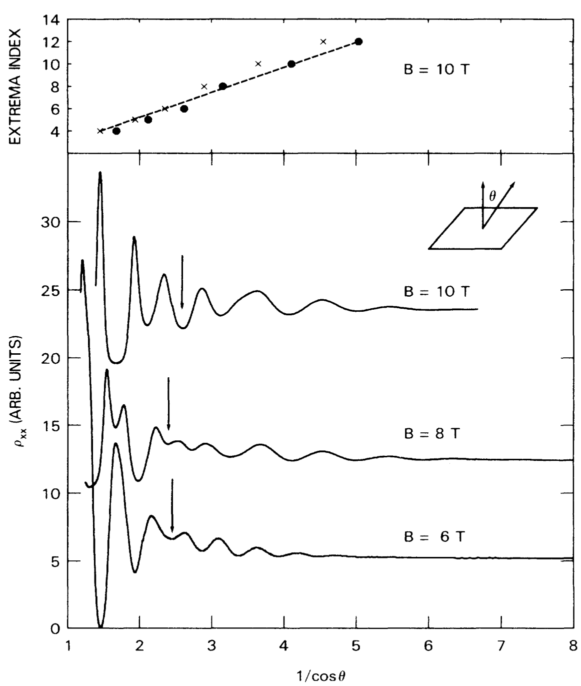

FIG. 1. ρ_{xx} vs $1/\cos\theta$ at different magnetic fields. The arrows indicate the point where a phase reversal occurs. The scale of the three curves has been adjusted so that the Shubnikov–de Haas oscillations are roughly the same amplitude. The data at 10 T were taken at 2.2 K to reduce the spin splitting, while the data at 6 and 8 T were taken at 1.4 K. The upper portion of the figure is a plot of the maxima and minimum in ρ_{xx} vs $1/\cos\theta$.

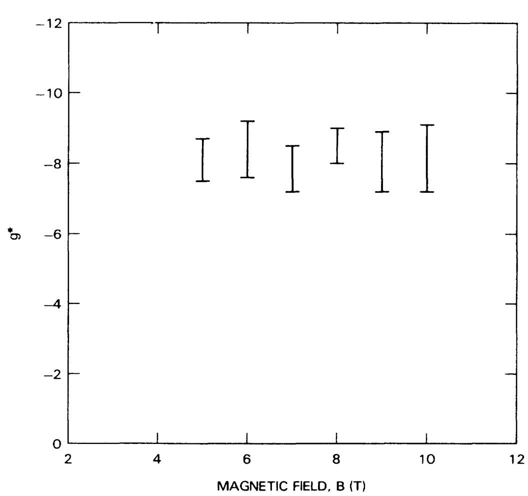

FIG. 2. The effective g factor g^* vs magnetic field.

strength increases. As noted above, this is in contrast to the results obtained in wider wells by Chang *et al.*[9]

A reduction in g^* was observed in bulk InAs by Pidgeon *et al.*[10] in magnetoabsorption measurements. Their results showed that g^* could vary from its band-edge value of -15 to $+2$ as transitions occurred higher in the conduction band. The theory of Roth *et al.*[16] relates the effective g factor to the effective mass through the following:

$$g^*=2\left[1+\left(1-\frac{m_0}{m}\right)\frac{\Delta}{3E_g+2\Delta}\right], \qquad (2)$$

where E_g is the energy gap and Δ is the spin-orbit splitting. If we take $\Delta=0.44$ and $E_g=0.41$ eV and use the measured value of m_0/m, then $g^*=-5.9\pm1.0$. This is in fairly good agreement with our experimental results. The discrepancy may be due to many-body effects which would increase the absolute value of g^*, but nonparabolicity is clearly more important.

In conclusion, we have measured g^* of electrons in a narrow InAs/GaSb quantum well. The g^* is between -7.8 and -8.7. This absolute value of g^* is reduced below the bulk band-edge value of -15 due to nonparabolicity effects. Although the measured value is larger than the predicted value, indicating that many-body effects are also present, we observe little or no change in g^* as a function of magnetic field.

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