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Oscillatory Landé factor of two-dimensional electrons under high magnetic fields

E. E. Mendez and J. Nocera
IBM Research Division, Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598

W. I. Wang
Department of Electrical Engineering, Columbia University, New York, New York 10027
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Using resonant-tunneling spectroscopy in magnetic fields up to 30 T, we have shown that the Landé factor g of two-dimensional electrons oscillates with field between its three-dimensional value and a value strongly enhanced by many-body effects. The experiments were carried out at 1.4 K in GaSb-AlSb-InAs-AlSb-GaSb type-II heterolayers, in which holes tunnel resonantly between two GaSb electrodes through magnetic states in the conduction band of an InAs quantum well. The density of these two-dimensional electrons was controlled by the application of external hydrostatic pressure. For the largest electron density ($N_s = 1.2\times10^{12}$ cm^{-2}) the g factor oscillated with field between a minimum value of 8 and a maximum of 15. Variations of the same order were observed for lower densities, down to $N_s = 5.2\times10^{11}$ cm^{-2}. This large enhancement is explained by the exchange interaction between electrons with the same spin.

For two-dimensional (2D) electrons under a perpendicular magnetic field, the spin-Zeeman splitting of their Landau levels can be enhanced by the exchange interaction between them. This many-body effect has been invoked[1] to explain the observed value of the effective Landé factor g of 2D electrons at a Si-SiO_2 interface.[2] Detailed calculations[3] have predicted an oscillating g factor as the relative occupation of the two spin states is modified, be it by varying the electronic density at constant magnetic field or by changing the field and keeping the density constant. Physically, the variation of g can be seen as a consequence of Pauli's exclusion principle, by which electrons in the spin state with smaller population feel a stronger repulsive Coulomb force. The largest enhancement of the Landé factor happens for a maximum difference in the population of the two states, and is zero when both populations are equal.

Recent light-scattering experiments have shown spectroscopic evidence of exchange enhancement in a spin-polarized 2D system.[4] The prediction of an oscillating g factor has been indirectly confirmed by a theoretical fit to the high-field magnetoresistance[5] and by a study of its angular dependence, using the so-called coincidence technique.[6] Both methods have significant limitations; the former, for example, employs an *a priori* oscillating g factor with several fitting parameters, while the latter, to keep the perpendicular field constant, requires a comparison between measurements at different total fields. Moreover, the physical picture that emerges from those analyses remains incomplete since in both cases the determination of g is restricted to the Landau level sweeping through the Fermi energy, giving no information about levels deeper in the conduction band.

In this paper we show that a resonant-tunneling current perpendicular to a 2D electron system can resolve its spin-Zeeman states and therefore provide a much more direct way of determining the g factor for any occupation number. This concept is demonstrated experimentally in InAs-AlSb-GaSb heterostructures, in which we have observed g to oscillate between extreme values of 8 and 15.

The InAs-AlSb-GaSb polytype system was chosen because of its unique properties, which make it particularly suitable for magnetic spectroscopy by resonant tunneling.[7] The top of the valence band of GaSb lies above the bottom of the conduction band of InAs, so that in a GaSb-InAs heterostructure charge flows from the former to the latter, leading to an accumulation of electrons and holes on different sides of the interface. A thin AlSb layer between those two materials acts as a potential barrier controlling the amount of charge transferred. If the InAs-AlSb-GaSb unit is replicated, as in a GaSb-AlSb-InAs-AlSb-GaSb heterostructure, electrons are confined in the thin InAs quantum well formed by the conduction-band profile. In an ideally symmetric structure the number of electrons balances the total number of holes, equally accumulated at the valence band of each of the two GaSb interfaces. (See Fig. 1.) In real structures, additional, extrinsic electrons from residual impurities or interface states break that balance.

The amount of transferred charge depends on the thickness of AlSb, L_{AlSb}, the width of the InAs well, L_{InAs}, and the overlap energy Δ between the valence and conduction bands of GaSb and InAs, respectively. When a voltage is applied between the two GaSb end layers acting as electrodes, current flows from the emitter to the collector by resonant interband tunneling through the 2D quantum state, E_1, in the InAs well.[8] The current is abruptly interrupted when the energy of the holes at the emitter is lower than E_1 since then there no longer are states available for tunneling. The details of the line shape of the current-voltage (I-V) characteristics have been recently elucidated.[9]

Under a magnetic field H, the 2D density of states of electrons in the InAs well is quantized into Landau levels, as sketched in Fig. 1. Because of the large cyclotron energy of electrons in InAs ($\simeq 5$ meV/T) and the small Fermi energy of the holes at the GaSb emitter ($\simeq 4$ meV), at

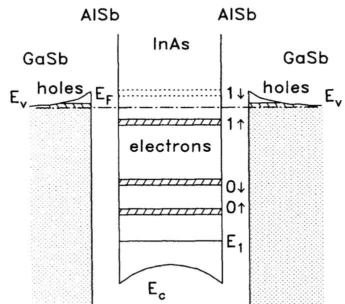

FIG. 1. Sketch of the energy bands, in the proximity of the Fermi level, of a GaSb-AlSb-InAs-AlSb-GaSb heterostructure under a magnetic field perpendicular to the interfaces. The field is assumed to be high enough for the spin splitting of the Landau levels of the electrons in the InAs quantum well to be larger than the Fermi energy of the holes in the GaSb electrodes. The small Landau-level quantization of the heavy holes has been ignored.

moderate fields, say 6 T, the Landau-level separation is already much larger than the energy distribution of holes so that on this scale the latter constitutes a quasimonoenergetic beam. When, at a fixed field, an external voltage between the GaSb electrodes aligns the hole distribution with an electron Landau level, resonant tunneling occurs and the current increases sharply. With a further increase of the voltage the holes are aligned with a gap between two Landau levels, tunneling is then inhibited, and the current drops abruptly. The same process is repeated for subsequent Landau levels and, thus, the current-voltage (I-V) characteristic shows a sawtooth behavior, with each current peak corresponding to a Landau level of InAs. As the number of occupied levels decreases with increasing field so does the number of peaks; at a given field this number is determined by the electronic density under equilibrium conditions.

In the heterostructure discussed in detail here (grown by molecular-beam epitaxy on a p^+-type GaSb substrate[7]), L_{InAs} is 150 Å and L_{AlSb} is 40 Å. By applying hydrostatic pressure, which reduces the overlap energy Δ from its $p=0$ value of $\simeq 0.15-0.20$ eV, the electron density was decreased from 1.2×10^{12} cm^{-2} (case C) at atmospheric pressure to 7.3×10^{11} cm^{-2} (case B) at $p=8$ kbar, and then to 5.2×10^{11} cm^{-2} (case A) at 13 kbar.

The I-V characteristics at $H=0$ for the cases of extreme density are shown at the bottom of Figs. 2(a) and 2(b). Since the peak voltage (voltage for maximum current) occurs when the quantum state E_1 is aligned in energy with the ground state of the accumulation layer of the GaSb emitter and since the current peak (maximum current) is proportional to the number of holes in the emitter, it is not surprising that experimentally the higher the pressure the lower the peak voltage and the peak current. Although details of these pressure-dependent characteristics will be discussed elsewhere, it is worth mentioning here that while the peak current decreases by a factor of about 4 at $p=13$ kbar, the total number of electrons drops only by a factor of 2. This difference is explained by the presence of extrinsic electrons in the InAs well,[10] as mentioned above.

When a magnetic field is applied parallel to the tunneling current, the I-V characteristics of Fig. 2 show the sawtooth shapes anticipated above. For instance, when $N_s=5.2\times10^{11}$ cm^{-2}, at 8 T there are two negative-resistance features, for an occupation of the two lowest Landau levels ($N=1$ and 0). The quantum limit (only $N=0$ occupied) is reached at $\simeq 11$ T. In contrast, when $N_s=1.2\times10^{12}$ cm^{-2} to reach the quantum limit requires $\simeq 24$ T.

Since the tunneling current shows a maximum at the voltage V_i at which a resonant-energy condition is achieved, it is possible to correlate that voltage with the energy E_i of the corresponding quantum state in the well. If we assume that the voltage between the two GaSb electrodes drops exclusively and uniformly in the two AlSb barriers,[11] then the energy of a quantum state relative to the Fermi level is given by the simple equation $E_i=eV_i/2$.

We will focus for a moment on case A. In Fig. 3(a) we summarize the energies of the various current peaks of Fig. 2(a) as a function of field, together with their Landau indices. The former are obtained from the above relation between voltage and energy. The 2D electron density, as well as the Landau indices, are readily deduced from a plot of the zero-bias tunneling conductance versus field, shown on Fig. 3(b). Starting at about 0.5 T, the

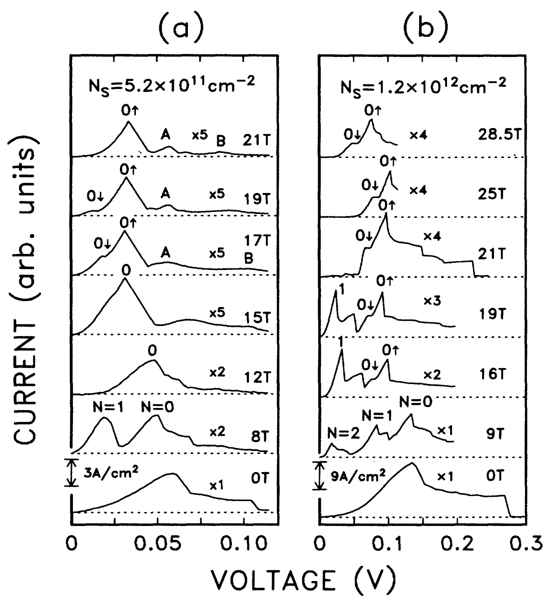

FIG. 2. Low-temperature ($T=1.4$ K) tunneling current-voltage (I-V) characteristics at representative magnetic fields of a heterostructure like the one described in Fig. 1. The thicknesses for the InAs and AlSb layers were 150 and 40 Å, respectively. The field was parallel to the current. (a) I-V characteristics taken with the sample subject to a hydrostatic pressure of 13 kbar, which reduced the overlap between the valence band of GaSb and the conduction band of InAs and resulted in a small transfer of electrons from the former to the latter. (b) Measurements taken with the sample under vacuum, so that the overlap energy, and correspondingly the charge transfer, is much larger than in (a).

conductance exhibits Shubnikov–de Haas oscillations, periodic with the inverse of the field, from which a 5.2×10^{11}-cm^{-2} electron density is obtained. At high fields the deep minima approach zero, resembling the vanishing conductance (in a Corbino geometry) of the quantum Hall effect (QHE) in parallel magnetotransport.

The behavior of the tunneling conductance is in fact intimately related to the physics of that well-known effect and, as in it, the Landau-level indices can be derived from the relation between the 2D density, the magnetic field, and the spin-resolved filling factor ν. At zero bias, the conductance vanishes whenever the Fermi level lies between two well-separated Landau levels and becomes maximum when it is in the center of a level. The main difference is that here we are probing the 2D density of states with a current perpendicular to it whereas the zero-conductance regions of the QHE are obtained for an in-plane current.

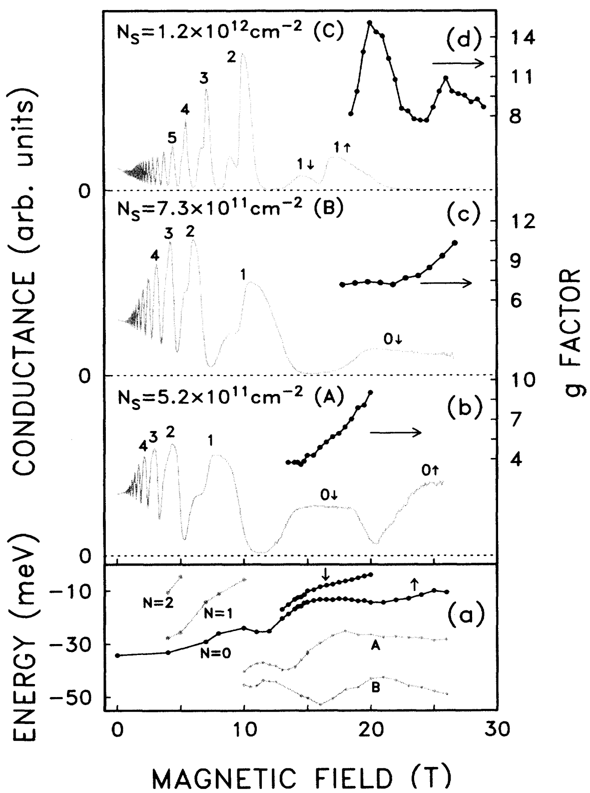

FIG. 3. (a) Plots of the peak voltages (converted to energies by dividing them by two) of the negative-differential-resistance (NDR) features of Fig. 2(a) vs magnetic field. The labels $N=2,1,0$ refer to the Landau levels that are the source of the peaks in the I-V characteristics. The origin of the structures labeled A and B is unknown. Since no true NDR was resolved for the $0\downarrow$ structure below 16 T, in this case the readings were taken at the minima in the dI/dV characteristics. (b)–(d) Zero-bias magnetoconductance (gray curves; left-hand scales) and Landé g factor (black dots connected by lines; right-hand scale) for three different carrier densities, determined, as well as the Landau indices (shown next to the conductance maxima), from the period of the low-field Shubnikov–de Haas oscillations. The values of the g factors are averages for both voltage polarities in the I-V characteristics.

More subtle may be the origin of the finite width of the zero-conductance regions, which in the QHE are caused by localization. Such an interpretation is questionable for magnetotunneling since the presence of localized states in two dimensions should not necessarily inhibit perpendicular transport. The explanation may be on the intrinsic nature of the 2D gases in InAs-AlSb-GaSb, whose densities readjust self-consistently with varying field, thus allowing the Fermi level to lie between Landau levels for certain field intervals. A definitive answer undoubtedly requires further work. In any event, the correlation of our magnetotunneling results with the QHE opens the possibility of studying 2D systems with a contactless probe that does not interfere directly with the system.

Returning to Fig. 3, frames (c) and (d) show the oscillatory conductance for cases B and C, respectively. As in case A, the spin splitting is fully resolved above 15 T, and signs of it are already evident at lower fields. However, our determination of the g factor is based not on these conductance measurements but on the complementary splitting of the $N=0$ current peak in the I-V characteristics of Fig. 2, where, for simplicity, we have shown only the two extreme densities.

A weak shoulder is visible on the current peak of case A at 15 T [see Fig. 2(a)], which at 17 T is resolved as a separate structure, then shifts to lower voltage with increasing field, and finally disappears through the origin at 20 T. [The motion of the $N=0$ doublet is best followed in the summary of Fig. 3(a).] This doublet is interpreted as due to spin-polarized tunneling, based on the fact that the low-voltage peak ($0\downarrow$) passes through $V=0$ precisely at the field (20 T) at which the conductance shows the minimum corresponding to the emptying of the $0\downarrow$ state ($\nu=1$). Although for cases B and C the extreme quantum limit ($\nu<1$) was not reached even at 30 T, based on a similar behavior with field, we ascribe the same origin to their respective $N=0$ doublets.

After converting the voltage separation of the two $N=0$ structures into energy, the g factor is derived simply by dividing that energy by the magnetic field and the Bohr magneton. The dependence of g with field for the three configurations is superimposed on Fig. 3(b) through Fig. 3(d). For cases A and B the behavior of g is similar: a monotonic increase with field, which in A ranges from a minimum value of 4 to a maximum of 9, whereas for B it is from 7 to 10.5.

This enhancement of g with field can be understood from the nature of the exchange interaction. Let us take case A as an example. At 11 T, the minimum in the zero-voltage conductance indicates that both the $0\downarrow$ and the $0\uparrow$ states are below the Fermi level. At 13 T (the lowest field at which the Landé factor was determined) both states are still almost equally populated and g is barely enhanced. But as the field increases, the $0\downarrow$ state becomes depopulated, and the exchange interaction, which is proportional to the population difference between $0\downarrow$ and $0\uparrow$, increases. The maximum is reached at 20 T, when $0\downarrow$ is very close to the Fermi level. The same can be said of case B, except that now, because of its higher density, the $0\downarrow$ state is not completely depopulated even at 26 T, the highest magnetic field compatible with our pressure-cell apparatus.

For case C, the splitting of $N=0$ is observable even when $N=1$ is partially occupied, as Fig. 3(d) illustrates. In this case, the g factor has a value of 8 at 18.5 T, a field at which, in equilibrium, $1\uparrow$ is still below the Fermi level. When the field increases so does g, reaching a maximum value of 15 at 20 T. From then on, g decreases to 8 at 23 T and finally it recovers to values between 9 and 10 beyond 26 T. This oscillatory behavior is in qualitative agreement with the results obtained for the other two configurations: g is minimum when the Fermi level is between two different Landau levels ($N=1$ and 0) and is maximum when one of them is partially empty ($N=0$ for A and B, and $N=1$ for C).

A closer look, however, reveals a more complicated picture. According to current theories,[3,12,13] the maximum g, $g_{\max}$, should occur for a field at which the Fermi level is midway between two spin states within the same Landau level (or, equivalently, when the filling factor is odd), and g should be minimum when the Fermi level is between spin states of different Landau levels (that is, for even filling factors). Then, assuming that the plot of the conductance versus field reflects the 2D density of states, $g_{\max}$ should happen at 15 T, not at 20 T. Equally surprising is the observed enhancement of g at fields above 23 T, where the broad zero-conductance region suggests a Fermi level between Landau levels.

Although we have no answer to these discrepancies, the explanation may lie on the details of the density of states, especially in view of the presence of residual donor impurities in InAs that contribute to the imbalance between electrons and holes, as briefly mentioned above. It is known that impurities can lead to asymmetric density of states that shift the resistance minima of the QHE away from the expected magnetic fields.[13] For example, for a donor-induced attractive potential, calculations using the self-consistent T-matrix approximation predict an asymmetric density of states with an impurity band on the low-energy side of the Landau levels.[14] Such a low-energy asymmetry would be consistent with the observed shift of $g_{\max}$ to higher fields.

How do the observed enhancements compare with theoretical estimations? In the Hartree-Fock approximation, the exchange-energy term for a magnetic level of Landau index n and spin σ can be expressed as[13] $\Sigma_{n\sigma} = -(e^2/\varepsilon\lambda)\sqrt{\pi/2}\sum_{n'} X_{nn'}\nu_{n'\sigma}$, where ε is the dielectric constant of InAs, λ is the magnetic length ($\lambda^2 = c\hbar/eH$), $\nu_{n'\sigma}$ is the filling factor for Landau level with index n' and spin state σ, and $X_{nn'}$ is a constant that depends on the level indices n and n'. (For example, $X_{00}=1$, $X_{01}=X_{10}=\frac{1}{2}$, $X_{11}=\frac{3}{4}$, etc.) Then, the maximum energy difference for case A is $\Sigma_{0\downarrow}-\Sigma_{0\uparrow} = (e^2/\varepsilon\lambda)\sqrt{\pi/2}X_{00}$, and similarly for case C, substituting X_{01} for X_{00}. At 20 T, these differences translate into Δg of 18 and 9, respectively, to be compared with the experimental enhancements of 5 and 7. Not surprisingly, the values of the latter set are smaller than the theoretical prediction, which assumes an ideal and simpler system. On the other hand, the fact that the discrepancy for case A is much larger than for case C suggests that, in the former, $g_{\max}$ is not reached even at the highest fields at which the spin splitting is observable—a likely possibility especially when an asymmetric density of states is considered.

A theoretical estimation for $g_{\min}$ using band parameters of bulk InAs yields for case C a value of 9, which is not very different from that determined in this work. In case A, the experimental value of 4 compares favorably with 4.5, estimated from a similar calculation that included the change with pressure of the various band parameters.

Further experiments should aim at reducing the background impurities in InAs on one hand, and at varying the thickness of AlSb on the other. A combination of the two would allow a better balance between electrons and holes and a wide range of carrier densities with different electron-hole separations. The interaction between the two kinds of carriers is something we have ignored here but that could well be at the core of some of the unexplained results.

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