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Spin-resolved cyclotron resonance in InAs quantum wells: A study of the energy-dependent g factor

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We report the observation of the spin-doublet splitting of cyclotron resonance (CR) in a two-dimensional electron gas (2DEG). Two discernible CR peaks, originating from spin-conserved transitions between adjacent sets of spin-split Landau states, are observed at a magnetic field as low as 4.4 T. The observed doublet features in the vicinity of even and odd integer filling factors are attributed to the linear dependence of the g factor and effective mass on the electron energy, respectively. In addition, our data show that the g factor of a 2DEG has a smaller energy dependence than that of bulk electrons.

Cyclotron resonance (CR) has been used to study the effective mass and the dynamic transport properties of a two-dimensional electron gas (2DEG) for two decades.[1-7] However, up to now, the spin-doublet splitting (also called Δg splitting) in a 2DEG has not been observed in GaAs/$Al_xGa_{1-x}As$ heterojunctions,[7] where numbers of low-dimensional properties have been extensively studied. This is partially because the criterion of observing the spin-doublet CR is much more stringent than, e.g., the spin-resolved Shubnikov–de Haas (SdH) oscillations.[8] In dc transport, when spin Zeeman splitting is larger than a few kT, and there are sufficient localized states between two spin-split extend states, a minimum in SdH oscillations would occur when the Fermi level lies at the middle of N^+ and N^- levels (N is the Landau level index, and $+$ and $-$ represent spin up and down). In contrast, in order to obtain spin-resolved CR, it is not the total energy of the Zeeman splitting which matters. Instead, it is the energy *difference* of two adjacent Zeeman splittings which should be larger than the broadening of Landau levels. The Zeeman splitting is determined by $g^*\mu_B B$, where g^*, μ_B, and B are the effective g factor, Bohr magneton, and magnetic field, respectively. The g^* values at the conduction-band edge in III-V semiconductors are smaller than the free-electron value, $+2$, due to the spin-orbit interaction between the s-like (the lowest conduction band) and p-like (both the valence bands and the next higher conduction bands) states. When the electron energy is increased, the g factor approaches the free-electron value. As a result, if the band-edge g factor is negative (positive), the Zeeman splitting is smaller (larger) for Landau levels with a higher index. Within a small energy range, it has been found that the g factor can be approximated[9] by $g^*=g_0+\beta E$ from experiments performed in three-dimensional (3D) systems.[10-13] Here β and E are in units of eV^{-1} and eV, respectively. It is this energy dependence of the g factor which makes the spin-doublet CR observable, regardless of how large the absolute g_0 is. However, on the other hand, the more the g_0 deviates from the free-electron value, the stronger the energy dependence will be (a larger β), which can be seen in Table I.

To observe this Δg splitting, a high-mobility sample is required due to the small difference between adjacent Zeeman splittings. In addition, a high carrier density n_s is also preferred because the higher n_s is, the higher B will be for $\nu=2$, where the Landau filling factor ν is defined by $\nu=hn_s/eB$. More specifically, for $n_s=1.21\times10^{11}$ cm^{-2} (2.42×10^{11} cm^{-2}), $\nu=2$ occurs at $B=5$ T (10 T), and the Zeeman splitting for the lowest Landau level is 0.11 meV (0.22 meV) for GaAs, while the Δg splitting, depending on B^2, is only 0.016 meV (0.063 meV). To have Δg splitting discernible, the Landau-level broadening should be smaller than the Δg splitting, which implies a minimum mobility of 1.1×10^6 cm^2/V s (3.0×10^5 cm^2/V s). However, as the mobility and the carrier density become higher, the energy obtained from the CR linewidth is larger than the Landau-level width due to saturation effects.[5] As a result, this makes the observation of Δg splitting of a 2DEG in GaAs extremely difficult, if not impossible, using the conventional CR spectroscopy. Recently, Watts *et al.*[7] used an impedance matching technique to overcome the saturation effect, but the search of spin-split CR still failed. The absence of Δg splitting of a 2DEG in GaAs/$Al_xGa_{1-x}As$ was attributed to the suppressed splitting due to the electron-electron interactions. To resolve this puzzle, i.e., the lack of Δg splitting in 2DEG's, we perform CR experiments on a narrow band-gap material, i.e., InAs quantum well sandwiched by AlSb barriers. When the band gap is smaller, the interaction force between the conduction and valence bands is stronger, and indirectly, results in a larger β. As shown in Table I, the β of bulk InAs is 13

TABLE I. The energy-dependent g factor $g^*=g_0+\beta E$ of the conduction electrons for several III-V semiconductors (Ref. 9), where β and E are in units of eV^{-1} and eV, respectively.

	InSb	InAs	GaAs	InP
3D	$-51+144E$[a]	$-15+80E$[b]	$-0.44+6.3E$[c]	$1.26+2.2E$[d]
2DEG		g_0+60E[e]	$-0.377+4.5E$[f]	

[a]Reference 10.
[b]Reference 11.
[c]References 12 and 13.
[d]Reference 13.
[e]This work.
[f]References 14 and 15.

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times larger than that of GaAs. As a result of large β, we are able to observe the spin-resolved CR of a 2DEG in the range $4.4 \leq B \leq 13$ T, which covers a range of $5.5 \geq \nu \geq 1.8$. In the vicinity of even integer ν, the CR-doublet feature is attributed to the energy-dependent g factor. On the other hand, in the vicinity of odd integer ν, the nonparabolicity effect of InAs conduction band, i.e., the energy-dependent effective mass, $m^* = m_0^* + \alpha E$ (α in units of eV^{-1}), is responsible for the observed doublet feature. The β obtained from our data is smaller than that of bulk electrons, i.e., the Δg splitting is suppressed in 2D systems. This can be explained by the fact that the 2DEG has a total kinetic energy of ~ 110 meV higher than the bulk band-edge electrons. It is expected that β decreases as the electron energy is increased, according to band-structure considerations.

Two samples (samples 1 and 2) used in this work are from the same wafer grown by molecular-beam epitaxy on a (001) GaAs substrate at 430 °C. It consists of 1-μm GaSb and 1-μm AlSb buffer layer, 10 periods of 25-Å GaSb/25-Å AlSb for smoothing the surface, a 200-Å AlSb lower barrier, a 149-Å InAs quantum well, a 500-Å top AlSb barrier, and a final capping layer of 30-Å GaSb. The growth transition between AlSb and InAs was accomplished with InSb-like interface bonds (as opposed to AlAs bonds)[16] and all layers are not intentionally doped. The thickness of the InAs well is determined from the least-square fit to the far-infrared absorption due to transverse-optical phonons.[17] The dc mobility determined by van der Pauw measurement at 4.2 K is 175 000 $cm^2/V\,s$. The carrier densities for samples 1 and 2 are 6.5×10^{11} and 5.7×10^{11} cm^{-2}, respectively. The CR experiments were carried out at 4.2 K on wedged samples at a fixed magnetic field of up to 13 T with a rapid scan Fourier transform spectrometer.

Figure 1(a) shows normalized transmission spectra, $T(B)/T(0)$, for sample 1 in steps of 0.2 T, where arrows mark the filling factors. We found the spectra exhibit ν-dependent line shapes. The spectra for $B \leq 4.6$ T have symmetric CR line shape, and their full linewidth at half maximum increases from 11 cm^{-1} at 3.2 T (corresponding to $\nu = 8.4$) to 15 cm^{-1} at 3.8 T ($\nu = 7.1$), and then decreases back to 11 cm^{-1} at 4.4 T ($\nu = 6.1$). At $B = 5.0$ T, an extra signal at the high-energy shoulder can be clearly observed. The strength of this high-energy peak increases to be comparable to the lower-energy peak at 5.4 T ($\nu = 5$). This double-peak feature is even more pronounced at $B \geq 7.8$ T ($\nu < 3.5$), where their separation is larger than the individual linewidth, as shown in Fig. 1(b). At 13 T, the low-energy peak has a full width of 8.3 cm^{-1}, and the high-energy one is 10.9 cm^{-1}, smaller than the double-peak separation of 16.5 cm^{-1}. To discuss this double-peak feature, we plotted the resonance position (ω_c) as well as their corresponding effective masses, $m_{CR} = eB/\omega_c$, against the magnetic field in Fig. 2 for sample 1. The corresponding filling factors are also marked by arrows. In addition, lattice absorptions due to different materials are indicated. Owing to the distorted CR line in the vicinity of the lattice absorption band,[18] as shown in Fig. 1(a) at $B = 7.8$ T, an accurate determination of resonance position in those regions is difficult,

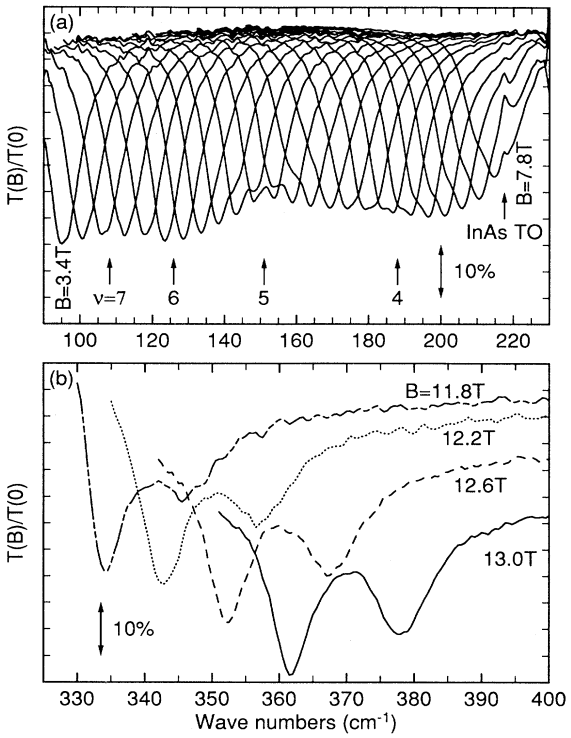

FIG. 1. Normalized transmission spectra for sample 1 (a) in steps of 0.2 T within the designated magnetic fields and (b) in steps of 0.4 T at higher B. Arrows indicate the position for the integer filling factors. The distortion of the line shape due to InAs transverse-optical phonons can be observed at $B = 7.8$ T. Temperature is 4.2 K, and spectral resolution is 1 cm^{-1}.

e.g., at $B \sim 8.4$ T of Fig. 2. As we can see, although this double-peak feature remains in wide range of B, the difference of the corresponding masses of the double peaks is larger at odd integer ν than at even integer ν. This is because at even integer ν, both transitions occur between the same pairs of Landau levels, and the energy difference of two involved transitions is determined by the energy-dependent Zeeman splitting, as shown in the inset of Fig. 2(a). On the other hand, at odd integer ν, one transition occurs between $(N-1)^-$ and N^-, while the other occurs between N^+ and $(N+1)^+$. In this case, the CR splitting is dominated by the nonparabolicity effect, i.e., the energy difference of two adjacent Landau separations.

To qualitatively explain the data, we first calculated the in-plane dispersion relation at $B = 0$ by following the procedure outlined by Bastard,[19] where not only the nonparabolicity effect, but also the effect due to the penetration of electron wave function into AlSb barriers are included. The energy-dependent effective mass, $m^*(E)$, and the 2D density of states (DOS) $= m^*(E)/(\pi\hbar^2)$ are obtained subsequently by taking the first derivative of the dispersion. We obtained[20] the lowest subband energy E_0 to be 61.1 meV for a 149-Å well and $m^*(E) \simeq 0.02655 m_0 + 0.130(E - E_0)$. In the presence of a magnetic field, the in-plane kinetic energy is further quantized into a series of Landau levels with a degeneracy of

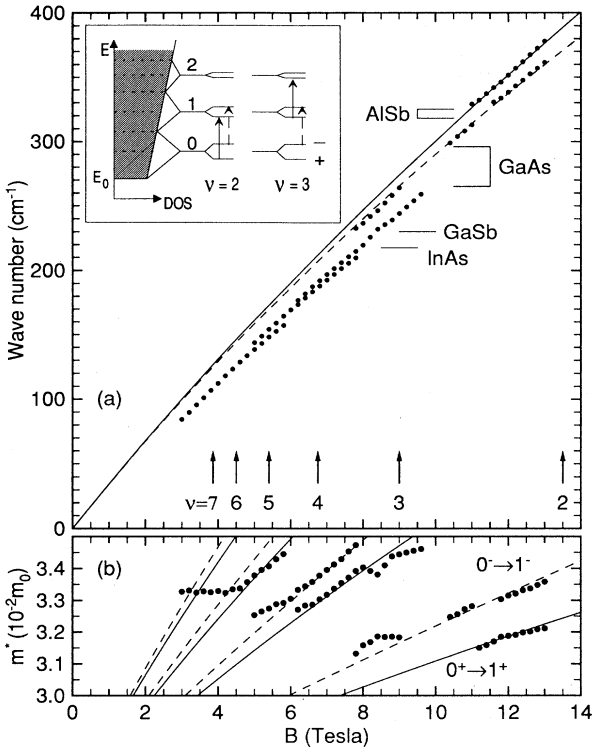

FIG. 2. (a) Dots: the measured resonance positions for sample 1; solid (dashed) line: the calculated transition positions for the lowest spin-up (-down) Landau level. The arrows mark the corresponding filling factor. Several lattice absorptions are also indicated. (b) Dots: the corresponding effective masses; solid (dashed) lines: the calculated effective masses for spin-up (-down) transitions. Inset: the schematic energy diagram depicting the determination of Landau levels. The allowed spin-up (spin-down) CR transition at even and odd integer ν is indicated by solid (dashed) arrow.

$2eB/h$ (including spin) for each level. As a result, the energy of the Nth Landau level, E^N, can be determined by integrating the DOS from E_0 up to an energy so that the total density is equal to $(2N+1)eB/h$, as shown in the inset of Fig. 2(a).[21] Furthermore, the spin-split level, $E^{N,\pm}$, is then obtained by introducing the Zeeman term, i.e., $E^{N,\pm}=E^N\pm(g_0+\beta E^N)\mu_B B/2$. The cyclotron mass for spin-conserved transition can be calculated by

$$m_{\rm CR}^{N,\pm}=\hbar eB/(E^{N+1,\pm}-E^{N,\pm}) . \quad (1)$$

Note that in the whole calculation processes, β is the only adjustable parameter. The fit is focused on the data in the range $11\le B\le 13$ T, where the splitting is larger than the CR linewidth for both samples. This is necessary because the cyclotron mass at low B contains a larger error bar due to the fact that Δg splitting is smaller than the CR linewidth, and to the presence of InAs, GaSb, GaAs, and AlSb lattice absorptions. The calculated masses are shown as lines in Fig. 2(b), assuming a constant β of 60. The fitting is excellent for both samples. However, the β is smaller than the calculated value for the InAs conduction-band edge.[11] This suppression of Δg splitting in a 2DEG is not due to the many-body interaction in a lower-dimensional system.[7] Instead, it is a result of a higher electron energy due to the quantization effect and the large Fermi energy. More specifically, the Fermi energies for samples 1 and 2 are 53 and 47 meV, resulting in a total electron energy of 114 and 108 meV, respectively. As has been calculated for GaAs/$Al_xGa_{1-x}As$ heterojunction,[15] when the electron energy is increased, not only does g_0 decrease, β is also smaller (see Table I). From our experiment, g_0 is not obtainable, however, β is 25% smaller than the bulk band-edge value. We attribute this smaller β to the band-structure effect, i.e., the 2D electrons have a total energy of $\sim$110 meV above the bulk conduction-band edge.

As discussed above, our data can be well explained by the linear-dependent g factor on the electron energy, i.e., a ν-independent constant β, which originates from the interaction between bands. However, it has been shown that for a 2DEG subject to a strong magnetic field, the g factor oscillates versus $1/B$ due to the electron exchange interaction.[8] More specifically, the g factor is enhanced more than 10 times at odd integer filling factor over the value at even integer filling factor, which is the same as the value at $B=0$. Stein, von Klitzing, and Weimann[14] measured the Zeeman splitting by studying the electron spin resonance on a high-mobility 2DEG in GaAs/$Al_xGa_{1-x}As$ heterostructures. They observed neither an oscillatory nor an enhanced g factor. According to Kohn's theorem,[22] in the absence of electron-impurity interactions, the center-of-mass Hamiltonian and the Hamiltonian for relative degrees of freedom are completely uncoupled. As a result, the elastic optical transition remains unaffected by exchange interactions. For a modulation-doped GaAs/$Al_xGa_{1-x}As$ system of high mobility, Kohn's theorem is relevant. However, the electron lifetime in our samples, limited by the residual impurities, is only 3.3×10^{-12} s, corresponding to a modest mobility of 83 000 cm^2/V s for the GaAs system. It is known that both the electron-impurity scattering and the nonparabolicity existing in our system can break the translational invariance, and make the many-body effect observable in CR experiments. We carefully search for the change of the g factor due to the electron exchange effect. In the range $11\le B\le 13$ T, the ν varies from 2.44 to 2.07 for sample 1, and from 2.15 to 1.82 for sample 2. Within this wide range of ν ($1.82\le\nu\le2.44$), the data do not show any ν-dependent feature. It becomes an interesting question whether it is possible to obtain an inhomogeneous 2DEG to break the translational symmetry, and still maintain a high mobility so that the Landau-level broadening is smaller than the Δg splitting.

In conclusion, we have observed spin-resolved CR of a 2DEG in InAs single quantum wells under a wide range of magnetic fields, $4.4\le B\le13$ T, corresponding to the filling factor, $5.5\ge\nu\ge1.8$. The observed CR splitting is larger at odd integer filling factors than at even ones. This is explained by the fact that the energy difference of two adjacent Landau separations due to the nonparabolicity effect is larger than that of two adjacent Zeeman

splitting due to the energy-dependent g factor. Our data also show that the spin splitting is smaller in two than in three dimensions. The suppression of the splitting is attributed to a higher electron energy in a 2D system.

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