Observation of spin-splitting crossing between subbands in the optically detected cyclotron-resonance spectra of $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ heterojunctions

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We present an investigation of the properties of a two-dimensional electron gas confined at an $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ interface by optically detected cyclotron resonance (ODCR). ODCR spectra structured by quantum oscillations and subharmonic cyclotron resonances have been observed. Quite unexpectedly, the ODCR spectra also reveal a very strong and sharp peak with several fine structures. It is shown that this observation is due to the energy-level crossing of the spin splitting between the first and second subbands of the two-dimensional electron gas. The strong and sharp absorption is made possible only under conditions such that the energy separation of Landau levels is equal to the incident far-infrared photon energy, the Fermi energy lies in the center of a Landau level, and the uppermost occupied states of the two subbands have the same energy and spin. This behavior provides a precise determination of the effective mass and g factor.

Recently, the technique of optically detected cyclotron resonance (ODCR) has opened up more possibilities in studying cyclotron resonance (CR) because some of the disadvantages connected with the conventional CR technique can be avoided.¹⁻⁵ In the ODCR measurement, CR is detected by observing changes in photoluminescence (PL) caused by cyclotron heating or cyclotron-induced impact ionization of the bound excitons and impurity-bound carriers. Thus, CR detection can have the advantages of using highly sensitive optical detectors and CR can be studied in a thin undoped layer sample. In this paper we report a study of the properties of the two-dimensional electron gas confined at a single $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ interface by the ODCR technique. In addition to the observation of quantum oscillations and subharmonic cyclotron resonances, we also observe a very sharp and strong signal with several fine structures in the ODCR spectra. We find this result extremely surprising, because in a ternary alloy the CR is usually very broad due to alloy scattering. This remarkable behavior is attributed to the energy-level crossing of the spin splitting between the first and second subbands. From this analysis, the effective g factor and the effective mass of the two-dimensional electron gas can be determined precisely.

The PL measurements were performed using an Ar ion laser. The sample was placed in a 7-T superconductor magnet (Oxford). The PL signal was dispersed by a SPEX 0.5-m monochromator and detected by a liquid-nitrogen-cooled Ge detector (North-Coast). In the ODCR measurements the sample was simultaneously irradiated by a CO_2 -pumped far-infrared (FIR) laser (Edinburgh Instruments) working at $118.8\text{ }\mu\text{m}$. The FIR radiation was guided by mirrors to the sample and was modulated by a mechanical chopper. Two types of ODCR data were collected. One is the so-called ODCR spectrum, which measures the changes in PL signal induced by FIR radiation as a function of the applied magnetic field with the spectrometer fixed to correspond to an emission peak. The

other is the FIR-modulated PL signal (FMPL), which involves measuring the ODCR signal as a function of PL wavelength with the magnetic field fixed to the CR position.

The $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ heterostructure studied in this work was grown by a VG V-80H MK II molecular-beam epitaxy system. The structure consisted of $1\text{ }\mu\text{m}$ of $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ on (100)-oriented Fe-doped InP substrate, followed by a 20-nm undoped $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ spacer, a Si-doped (10^{18} cm^{-3}) n -type $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ layer of 80 nm, and finally a Si-doped (10^{18} cm^{-3}) $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ cap layer of 5 nm thickness.

A typical PL spectrum of the $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ sample obtained at 3.995 T is shown in Fig. 1(a). The reason for presenting the spectrum at 3.995 T is

FIG. 1. (a) Photoluminescence spectrum of $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ heterostructure at a magnetic field $B = 3.995\text{ T}$. (b) FIR ($\lambda = 118.8\text{ }\mu\text{m}$)-modulated photoluminescence spectrum (FMPL) of the same sample obtained at $B = 3.995\text{ T}$. $T = 5\text{ K}$.

FIG. 2. The FIR ODCR spectrum of $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ heterostructure. The spectrum was monitored at 0.805 eV. The arrows mark the field where E_F lies in the center of the n th Landau level. The broken arrows mark a subharmonic sequence and correspond to $\Delta n = 3, 4, 5$, and 6 transitions among the Landau levels. $T = 2$ K.

to be able to compare it with the ODCR spectrum presented below, but no principal differences from the zero-field spectrum are observed. This broad spectrum with the peak position at 0.805 eV may originate in unresolved contributions from free excitons, bound excitons, and donor-to-free-hole recombinations. The change in the PL signal induced by CR at 3.995 T as a function of photon energy is shown in Fig. 1(b). In the ODCR spectrum, we observe a positive increase at the highest energy followed by a steep decrease. It was recently shown that the mechanism on which the detection of ODCR is based is cyclotron-resonance-induced impact ionization of the bound excitons and donor-bound electrons.⁶ This mechanism causes the negative peak at 0.805 eV, and thus the positive signal is then attributed to the increased free-exciton recombination.

The FIR-induced CR spectrum monitored at 0.805 eV as a function of magnetic field is shown in Fig. 2. We typically find quantum oscillation in the resonance amplitude, as shown by the arrows. In addition, subharmonic structure appears at the low-field side of the resonance. With the same spirit as that accounting for the oscillations of conventional CR in Si inversion layers^{7,8} and $\text{GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ (Ref. 9) heterojunction, the oscillations are caused by a modulation of the resonance amplitude as the Landau levels move through the Fermi level. One can regard this oscillation as the Shubnikov-de Haas (SdH) oscillation of the CR. When the Fermi energy lies in the center of a Landau level, one gets minimum PL signal (maximum FIR absorption) for $\omega_c < \omega$, a maximum for $\omega_c > \omega$, where ω_c and ω are the cyclotron and FIR radiation frequencies, respectively. The oscillations are periodic in reciprocal field, and the period can be used to measure the electron density (n_s), i.e., $\Delta(1/B) = 2e/hn_s$, where e is the electron charge and h the Planck constant. The obtained $n_s = 7.0 \times 10^{11} \text{ cm}^{-2}$, which is in good agreement with the standard SdH measurement for the sample under the same experimental condition.

The subharmonic structure that appears on the low-

FIG. 3. The FIR ODCR spectrum of $\text{In}_{0.5}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ heterostructure. The spectrum was monitored at 0.809 eV, which corresponds to the emission of free-exciton recombination. $T = 2$ K.

field side of the resonance in Fig. 2 forms approximately a subharmonic sequence B_r/n and corresponds to $\Delta n = 3, 4, 5$, etc., transitions among the Landau levels, where B_r is the magnetic field of CR. According to Ando's calculation,⁷ the existence of subharmonics is the result of the mixing of Landau levels caused by short-range scattering. A similar behavior has also been observed in the conventional CR study of Si space-charge layers.⁸ From this result, the obtained effective mass is $0.044m_0$, which is consistent with the previous measurements for similar samples.¹⁰ The enhancement of this value from the bulk electron mass $0.041m_0$ at the band edge is mainly due to the nonparabolicity in this material. From the previous experiment and theoretical calculation,^{10,11} the structure at 2.95 T may also contain an interimpurity transition of the residual donor, the $1s$ -to- $2p^+$ transition. The corresponding binding energy of the donors is 3 meV.

The structure at 5.05 T that appears on the highest-field side of the resonance in Fig. 2 can be attributed to the CR of the two-dimensional electron gas in the second subband. To see this structure more clearly, we have performed FIR-induced CR spectrum monitored at 0.809 eV, which is the energy of the free-exciton recombination as shown in Fig. 3. We observe a large decrease of the free-exciton recombination occurring at 5.05 T. This large decrease is the result of the fact that after absorbing a FIR photon the electron in the second subband escapes from the triangular potential well and recombines with the hole accumulated at the other side of the interface. The deduced effective mass of the second subband is $0.055m_0$. A similar effective-mass value has also been obtained in the previous measurement,¹⁰ but the interpretation is ambiguous.

There exists a number of theoretical and experimental work on the study of the effective mass in a heterojunction. The results show that the effective mass depends on many factors, such as nonparabolicity-induced band-structure effects,¹² polaron effects,¹³ and electron-electron interaction,¹⁴ etc. For the two subband-occupied heterojunctions, most reports give the fact that the effective mass of the first subband is heavier than that of

the second subband.^{15,16} This result can be understood by considering the effect of conduction-band nonparabolicity in the light of the heterojunction potential profile. The electrons associated with the first subband are effectively at higher energy from the band edge than those with the second subband, and hence a more enhanced effective mass. However, our result shows a reversed behavior. This fact may be interpreted in term of the strong polaron coupling of the electrons in the second subband. It has been pointed out that the effective mass of the second subband can be greatly enhanced if the energy separation between the first and second subbands is near the LO-phonon energy.¹⁷ In our $\text{In}_x\text{Al}_{1-x}\text{As}/\text{In}_x\text{Ga}_{1-x}\text{As}$ heterostructure, the dominant LO phonon is GaAs-like and has an energy of about 34 meV.¹⁸ The energy separation between the first and second subbands can be obtained from the difference between the corresponding Fermi energies. The Fermi energies can be obtained by

$$E_{Fi} = \frac{\pi \hbar n_i}{m_i^*}, \quad (1)$$

where the electron concentration n_i and the effective mass m_i^* of the i th subband can be obtained from the above results and the standard SdH measurement. If we substitute $n_0 = 7.0 \times 10^{11} \text{ cm}^{-2}$, $n_1 = 1.2 \times 10^{11} \text{ cm}^{-2}$, $m_0^* = 0.044m_e$, and $m_1^* = 0.055m_e$, the obtained $E_{F0} = 38.2 \text{ meV}$, and $E_{F1} = 5.2 \text{ meV}$. Thus, the energy difference between the first and second subbands is 33.0 meV, which is approximately equal to the LO-phonon energy. The strong deviation of the enhanced mass of the first subband therefore can be attributed to the resonant polaron coupling in our structure.

A rather surprising result occurs when the carrier density of the two-dimensional electron gas is changed by illumination. Figure 4 shows the FIR-induced CR spectrum monitored at 0.805 eV. In addition to the observation of quantum oscillations and subharmonics, we observe a very strong and sharp peak at the field of CR and several fine structures. The first information that can be obtained from this measurement is a precise determina-

FIG. 4. The FIR ODCR spectrum of an $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ heterostructure. The spectrum was monitored at 0.805 eV. $T = 2 \text{ K}$. It shows the sharp and strong peak with fine structures occurring at CR of the first subband.

FIG. 5. The relative energy positions of the spin splitting of the Landau levels of the first and second subbands. (a)–(e) corresponds to the peak positions of the magnetic fields a – e indicated in Fig. 4, respectively. E_0 and E_1 represent the first and second subbands, respectively. The numbers are the corresponding Landau-level indices. Each Landau level is split into spin-up and spin-down states.

tion of the effective mass because of its narrow linewidth. The interpretation of this observation is demonstrated in Fig. 5. The very strong and sharp peak arises because of the following facts, as shown in Fig. 5(b). First, the energy separation of the Landau levels of the first subband is equal to the FIR photon energy, which is the basic requirement for CR to occur. Second, the Fermi energy lies in the center of a Landau level, which causes a maximum FIR absorption, as pointed out by Ando.⁷ Third, the uppermost occupied states of the two subbands have the same energy and spin quantum number. The last condition accounts easily for the transfer of electrons between the two subbands. Thus, after electrons being excited to a higher Landau level, the unoccupied states in the first subband can immediately be refilled since electrons can easily transfer from the second subband, and hence the CR amplitude is greatly enhanced. Since the above three conditions can be fulfilled only at a particular magnetic field, the enhanced CR amplitude is thus restricted to a very narrow region. The other fine structures labeled as a , c , d , and e in Fig. 4 can also be explained by the conditions as shown in Figs. 5(a), 5(c), 5(d), and 5(e), respectively. As the magnetic field is increased from the condition of Fig. 5(b), the energy of the Landau level of the

first subband with a larger Landau-level index will increase faster than that of the second subband with a smaller Landau-level index. Thus, the conditions shown in Figs. 5(a), 5(c), 5(d), and 5(e) can be adjusted by tuning the applied magnetic field. The transfer of electrons between states having the same energy and different spins as shown in Figs. 5(a), 5(c), and 5(e) can be attributed to the effects of various scattering processes. By comparing Eqs. 5(c) and 5(d), we will expect that the enhancement should be larger in the case of Fig. 5(d), since the process of Fig. 5(d) involves the transfer of electrons between the energy states with the same spin quantum number. This expectation is just what has been observed in Fig. 4.

From the above analysis, we should be able to obtain the effective g factor. For example, when the relative position of the Landau levels of the first and second subbands moves from Fig. 5(c) to Fig. 5(d), the difference in the energy change of the Landau levels of the two subbands caused by increasing the applied magnetic field is equal to the spin splitting. This behavior can be expressed as

$$(N_0 + \frac{1}{2}) \frac{\hbar e(B_d - B_c)}{m_0^*} - (N_1 + \frac{1}{2}) \frac{\hbar e(B_d - B_c)}{m_1^*} = g^* \mu_B B_d, \quad (2)$$

where $N_0=3$ and $N_1=0$ are the Landau-level indices of the energy levels of the first and second subbands involved in this process, respectively. m_0^* and m_1^* are the effective mass of the first and second subbands, respectively. B_d and B_c are the magnetic field of the structures d and c shown in Fig. 4, respectively. g^* is the effective g

factor, and μ_B is the Bohr magneton. Using our experimental values of m_0^* and m_1^* , the obtained absolute value of g^* is 3.2, which confirms the values obtained in the previous reports,^{19,20} and disagrees with the measurements in Refs. 21 and 22.

The above striking behavior of the very strong and sharp absorption and fine structures occurring at the field of the CR of the first subband can be adjusted by changing the carrier concentration such that it occurs at the field of the CR (5.05 T) of the second subband (not shown here). This observation can also be interpreted by using the same analysis, and the obtained information is thus similar.

We have thus demonstrated that the spin-splitting crossing of the Landau levels between the first and second subbands of a two-dimensional electron gas can cause a very strong and sharp transition at the field of CR with several fine structures. This behavior can serve as a precise determination of the effective mass and g factor. In addition, strong ODCR spectra structured by quantum oscillations, subharmonic cyclotron resonances, and interimpurity transition have been observed, from which fruitful information concerning the electronic properties of the two-dimensional electron gas can be obtained. Therefore, our study also provides a further evidence to show that the ODCR technique is a powerful and convenient tool for the investigation of semiconductor heterostructures.

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