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Effects of nonequilibrium electron distribution and electron-electron interaction observed in spin-split cyclotron resonance of InAs/AlSb single quantum wells at high magnetic fields

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We have observed two remarkable phenomena in spin-split cyclotron resonance of InAs/AlSb single quantum wells under short-pulse high magnetic fields produced by the single-turn coil technique. The first phenomenon is a hysteretic phenomenon, which was observed with a rapid sweep of the magnetic field in increasing and decreasing directions ($\sim$100 T in a few microseconds). The sweep-rate dependence of the cyclotron resonance spectra revealed that the hysteretic phenomenon is attributable to the nonequilibrium electron distribution in the lowest Landau levels ($N=0$) with plus and minus spins induced by short-pulse high magnetic fields. At low temperatures of around 15 K, a disagreement in intensity between the two different spins is observed in such a way that the total intensity is conserved. The hysteresis is attributed to a slow spin-flip relaxation between the two spin states of the $N=0$ Landau level with a time constant of 1 μs comparable with the field pulse duration. At high temperatures of around 100 K, a different type of hysteresis is found, where the absorption intensity of the minus spin is smaller in the down sweep than in the up sweep. The sweep-rate dependence shows that the up sweep does not change significantly, but the minus spin decreases with increasing the sweep rate in the down sweep. This is attributed to a slow electron transfer from donor levels in AlSb to a Landau level in InAs. The second phenomenon is the electron-electron interaction effect on the spin-split cyclotron resonance, which displays an intriguing dependence on the filling factor ν and the temperature at around 45 T, where $0.3 \leqslant \nu \leqslant 1.2$. With increasing temperature, the absorption intensity of the down spin increases, exceeding the amount expected from the Boltzmann distribution, while that of the up spin shows the opposite behavior. For samples with different carrier concentrations, the spin splitting at $\nu=0.7$ is smaller than that at $\nu=0.4$ by 1 T at around 50 K. These features can be explained qualitatively by a recent theory by Asano and Ando that calculates the effect of the electron-electron interaction on cyclotron resonance spectra by numerical diagonalization for a finite-size system with a finite number of electrons.

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I. INTRODUCTION

In high magnetic fields, we can expect a variety of unique phenomena in the two-dimensional electron gas (2DEG), because the cyclotron energy and Zeeman energy become extremely large, exceeding several tens of meV, and the filling factor ν becomes around or smaller than 1. To study 2DEG in ultrahigh magnetic fields more than 100 T, cyclotron resonance (CR) has proven to be the most informative technique.[1]

Electronic dynamics in 2DEG in magnetic fields is currently being investigated extensively. One of the incentives is that the complete quantization of Landau levels mimics the discrete levels in a quantum dot.[2] For the study of electronic dynamics between Landau levels, several methods have been utilized to realize nonequilibrium states. Interband optical excitation generates electron-hole pairs, which relax towards the band edge or recombine during the relaxation. The relaxation time from excited states can be obtained from the photoluminescence decay profile.[3] Luminescence experiments under selective optical excitation by circularly polarized light give the spin-flip relaxation time of photoexcited carriers through an analysis of the ratio between luminescence intensities of the two components of the electron spin. Experimental results in GaAs/Al$_x$Ga$_{1-x}$As quantum wells in magnetic fields showed that the complete quantization of the two-dimensional structure makes spin-conservation processes much faster than spin-flip processes.[4] Intraband optical excitation between Landau levels can also generate a nonequilibrium electron distribution without creating holes. Recently, the progress of the free-electron laser system has enabled intraband relaxation measurements by its tunability, high intensity, and short pulse of the order of a picosecond. Far-infrared pump-probe measurements of CR in InAs/AlSb quantum well in magnetic fields determined the relaxation time between Landau levels and provided unambiguous evidence for the LO-phonon bottleneck effect.[5]

In the present work, we introduce another method to create nonequilibrium states, which has never been reported in the past to the best of our knowledge. If a relaxation process is longer than the sweep speed of a magnetic field, a nonequilibrium electron distribution should be realized. When the field is increased, the degeneracy of Landau levels increases and the electrons relax to levels at lower energies. When the field sweep rate is faster than the relaxation process, however, more electrons occupy the higher levels than in thermal equilibrium. This phenomenon is regarded as a kind of adiabatic heating.

Besides the relaxation phenomena, another interesting problem to be studied by high-field CR is the electron-

electron interaction effect. These effects have been extensively studied experimentally and theoretically in connection with spin-split CR of GaAs/$\mathrm{Al}_x\mathrm{Ga}_{1-x}$As heterojunctions. For a system that is translationally invariant, CR spectra are independent of any electron-electron interactions. This is known as Kohn's theorem.[6] In a system where translational invariance is broken or that has a number of distinct CR frequencies, however, Kohn's theorem is no longer valid and the effects of electron-electron interactions appear in CR spectra. CR is a spin-conserving transition and the g factor is dependent on the energy and the Landau index. Therefore, observation of two distinct transitions should be expected for different two spin states when electrons occupy the Landau levels of the both spins. Spin-split CR shows an intriguing dependence on the filling factor ν and the temperature in the extreme quantum limit.[7,8] Two peaks are observed and their positions are independent of temperature at $\nu<\frac{1}{10}$, while only a single peak is observed at $\nu>\frac{1}{6}$. A crossover between these types of behavior occurs at $\nu\sim\frac{1}{9}$, where two peaks merge into a single peak with decreasing temperature. These intriguing observations were explained theoretically by Cooper and Chalker.[9] They calculated effects of electron-electron interactions on spin-split CR assuming that electrons form a Wigner lattice. Their calculation is strictly applicable only for the absolute zero temperature and an extreme quantum limit of $\nu\leqslant 1$. Cole *et al.* measured cyclotron resonance in high-mobility two-dimensional (2D) hole systems in GaAs-$\mathrm{Al}_x\mathrm{Ga}_{1-x}$As heterostructures and found a large temperature dependence of the resonance field of a single peak.[10,11] They explained the phenomena by solving the classical kinetic equations for a two-component system.

To develop quantum-mechanical theory for finite temperatures, Asano and Ando calculated CR spectra by means of numerical diagonalization of the Hamiltonian for a finite-size system with a finite number of electrons.[12,13] The CR is determined by the real part of a dynamical conductivity, which is calculated using the Kubo formula. As for the spin-split CR, the situation is that there are up-spin and down-spin electrons in the $N=0$ Landau level and the cyclotron energy for the up-spin is slightly larger than that for the down-spin by $\hbar\Delta$. The calculated spectra depend on four parameters, ν, $\nu_\uparrow/\nu_\downarrow$, $E_c/\hbar\Delta$, and kT/E_c. ν is the total filling factor. $\nu_\uparrow$ and $\nu_\downarrow$ are the filling factors of two kinds of electrons. $E_c/\hbar\Delta$ is the coupling constant defined by $E_c=e^2/\epsilon l$ with $l=\sqrt{\hbar/eB}$. ϵ is the static dielectric constant. T is the temperature.

According to their calculation, CR spectra are categorized into three types of behavior when the coupling constant increases depending on the properties. The first type is a positive-mode repulsion, which is defined when the higher-frequency peak is pushed away toward the higher-frequency side and its intensity is transferred to the lower-frequency peak. The second type is a negative-mode repulsion, which behaves contrary to the positive-mode repulsion. The third type is a motional narrowing, which is defined when the two peaks merge into a single peak. These features are mapped on a $(\nu_\uparrow,\nu_\downarrow)$ plane in the range of $0\leqslant\nu_\uparrow,\ \nu_\downarrow\leqslant 1$ at $T=0$ in Fig. 4 of Ref. 13. For $0\leqslant\nu\leqslant 1$, only the positive mode repulsion is found, but for higher ν, complicated behavior appears, showing mixing of the negative-mode repulsion and the motional narrowing. An increase of temperature is regarded qualitatively as an increase of ν with a fixed $\nu_\uparrow/\nu_\downarrow$ at $T=0$ in the map on the $(\nu_\uparrow,\nu_\downarrow)$ plane. This is because an overlapping of the wave functions of up- and down-spin electrons becomes appreciable with increasing temperature.

Figure 1 shows the dependence of CR on the relative concentration of the two kinds of electrons at $kT/E_c=1$ and $\nu=1$.[16] In the weak-coupling regime of $E_c/\hbar\Delta=0.1$, the spectrum consists of two independent peaks, the intensity of which is proportional to $\nu_\uparrow$ and $\nu_\downarrow$. In contrast, in the strong-coupling regime of $E_c/\hbar\Delta=10$, only a single peak is observed, the position of which provides a weighted average of two resonances. In the intermediate-coupling regime of $E_c/\hbar\Delta=1.0$, with increasing $\nu_\downarrow$, the absorption intensity of the down-spin electron increases, but the shape and the intensity are not as simple as those found for $E_c/\hbar\Delta=0.1$.

A simplified three-level model is employed to calculate the Landau levels of the InAs/AlSb quantum well in magnetic fields parallel to the growth direction. At first, following a paper by Zawadzki,[17] the three-dimensional energy structure is calculated for bulk InAs in magnetic fields using the three-level model, which takes account of the Γ_6, Γ_7, and Γ_8 levels. Next, to consider the effects of the electrical potential in the z axis, we set $k_z=\sqrt{2m_0^*E_l^{\mathrm{EMA}}}/\hbar$, where m_0^* is the band-edge effective mass and E_l^{EMA} is the lth subband energy calculated by the effective-mass approximation (EMA).

For CR in InAs-based 2D systems, there have been only few reports in the past. Yang *et al.* observed a spin-split and mass-split CR in InAs/AlSb single quantum wells for $1.8\leqslant\nu\leqslant 5.5$ and found no effects of electron-electron interactions on their peak positions.[14] Nicholas *et al.* observed spin-split CR in InAs/GaSb superlattices in high magnetic fields of 50 T and found a minimum in the spin splitting at a temperature in the vicinity of 100 K.[15] They attributed this minimum to the electron-electron interaction on the basis of the Cooper-Chalker theory.

In this paper, we report features of the above-mentioned two problems in spin-split cyclotron resonance of an InAs/AlSb single quantum well under short-pulse high magnetic fields produced by the single-turn coil technique. The first feature is a hysteretic phenomena that can be interpreted by a relaxation process. We investigated the field sweep-rate dependence in two samples with different carrier concentration and mobility. Pulsed high magnetic fields induce a nonequilibrium state and the subsequent relaxation process can be observed in CR spectra as a hysteresis between the up-sweep trace and the down-sweep trace. Hysteretic phenomena in the spin-split CR spectra are interpreted on the basis of a slow spin-flip relaxation and a slow electron transfer from donor states in AlSb. The second one is the electron-electron interaction (*e-e* interaction) effect observed in CR spectra. We study the temperature dependence of spin-split CR of 2DEG in InAs/AlSb single quantum wells in high magnetic fields of around 45 T. ν ranges from 0.3 to 1.2. The temperature is varied from 10 to 300 K. These experimental results are explained qualitatively by the calculation of the numerical

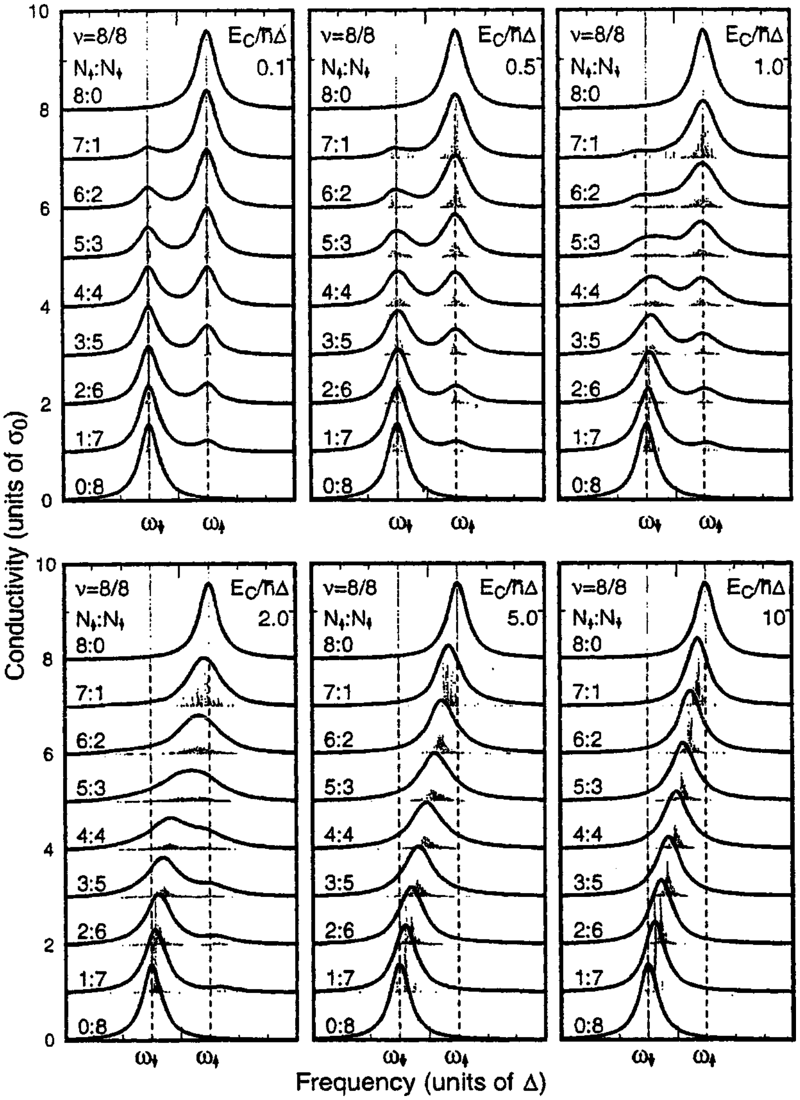

FIG. 1. The dependence of CR on the relative concentration of the two kinds of electrons at $kT/E_c = 1$ and $\nu = 1$ (Ref. 16). The coupling constants are 0.1, 0.5, 1.0, 2.0, 5.0, and 10.0. The thin dotted lines are the calculated absorption lines. The solid lines are obtained by replacing each thin dotted line with a Lorentzian characterized by half-width of Δ/5.

diagonalization for a finite-size system by Asano and Ando.

After this Introduction, Sec. III describes the experimental setup and sample structure. Experimental results and their comparison with theoretical calculation of the two phenomena are discussed in Sec. IV. Finally, we conclude in Sec. V.

II. EXPERIMENTAL PROCEDURE

Infrared transmission experiments were performed on two InAs/AlSb single quantum wells grown on an undoped GaAs substrate by molecular beam epitaxy at Imperial College. Thick strain-relaxing layers of 0.8-μm GaSb and 0.8-μm AlSb followed by a 10-period superlattice of 2.5-nm AlSb and 2.5-nm GaSb were grown on the substrate. The well/barrier interfaces were InSb-like. Sample IC558 has a 12-nm GaSb cap, 15-nm AlSb barrier, 15-nm InAs well, and 20-nm AlSb barrier layer, and sample IC563 has the same structure except for the cap layer width of 42 nm. The carrier concentration of IC558 found from dc transport measurement is 5×10^{11} cm^{-2} at 4 K and 12×10^{11} cm^{-2} at 300 K. That of sample IC563 is estimated to be smaller by 3×10^{11} cm^{-2} than that of IC558 from the total CR absorption intensity. The mobility of IC558 (IC563) is 26 (10) m^2/V s. Figure 2 shows the temperature dependence of ν in samples IC558 and IC563 at 44 T, where CR absorptions occur for a wavelength of 10.6 μm. In the InAs/AlSb system, it is known that electrons are supplied to the InAs layer, not from an intentional doping, but from surface donor levels, deep donor levels in AlSb, and the interface between InAs and AlSb.[18]

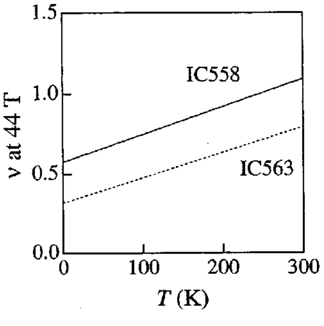

FIG. 2. Temperature dependence of filling factors in sample IC558 and IC563 at 44 T, where CR absorptions occur at a wavelength of 10.6 μm.

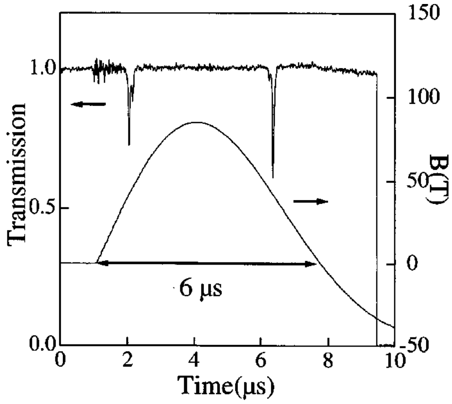

FIG. 3. Waveforms of a transmission signal and a magnetic field signal for a maximum field of 80 T. Note the change in intensity.

The single-turn coil technique can generate high magnetic fields with a very short duration of 6 μs.[19] Figure 3 shows waveforms of a transmission signal and a magnetic field signal. CR peaks can be observed twice during one pulse, first on the up sweep and again on the down sweep, allowing any hysteresis to be observed. For a maximum field of 140 T, a CR peak at about 40 T is observed 0.5 μs after the start of the pulse and then again 4.5 μs later. If the field is pulsed only to 45 T, these times become 2.2 and 1.5 μs, respectively. Thus, by changing the maximum field, changes in occupation can be probed with a time resolution of less than 0.1 μs.

Infrared radiation of wavelengths λ from 10.6 μm ($\hbar\omega = 117$ meV) to 9.25 μm ($\hbar\omega = 134$ meV) was supplied by a CO_2 laser. Infrared radiation of $\lambda = 5.53$ ($\hbar\omega = 224$ meV) was supplied by a CO laser. The sample temperature was varied from room temperature down to approximately 10 K by flowing liquid helium around the sample.

III. RESULTS AND DISCUSSION

A. Nonequilibrium electron distribution

Figure 4 shows the temperature dependence of the CR spectra at $\lambda = 10.6$ μm in sample IC558 for similar maximum fields (~90 T). The two peaks are the spin-conserving CR transitions of the two distinct spins from the $N=0$ to $N=1$ Landau level. The peak at lower fields is of the plus spin and that at higher fields is of the minus spin. At all temperatures we observe hysteretic phenomena, whose properties differ between 15 K and temperatures higher than 100 K. At first, we discuss only the low-temperature case.

Figure 5 shows the dependence on the maximum-field of the CR spectra at $\lambda = 10.6$ μm and 16 K in sample IC558. As the maximum field is increased, the field sweep rate is increased, so that we can see the sweep-rate dependence. The spectra taken on the down sweep were almost independent of the maximum field. We observe only a single peak of the plus spin, whose linewidth increases consistently as the maximum field is increased because of the inhomogeneity of the magnetic field and the limitation of the response time of the detector system. On the up sweep, on the other hand, we found a significant dependence on the maximum field. When the maximum field is limited to 55 T, only a single peak was observed in the same way as in the down sweep. As the maximum field of the pulse is increased up to 85 T, however, the minus-spin component appears and the plus-spin component decreases. This tendency becomes more and more prominent with increasing maximum field up to 141 T. The total absorption intensity is conserved for all the spectra and between the up and down sweep.

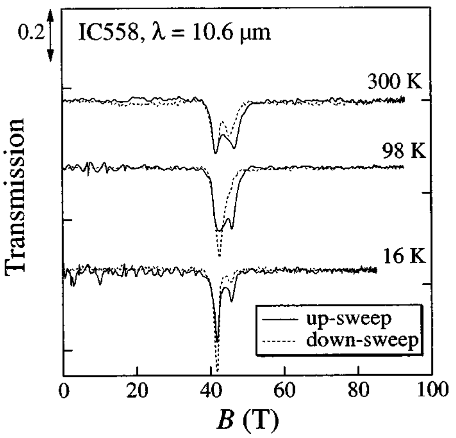

FIG. 4. Temperature dependence of CR spectra of the CR doublet on the up- and down traces at $\lambda = 10.6$ μm in sample IC558. The solid lines are spectra for up sweep of the fields and the dashed lines are spectra for down sweep.

At 45 T and 16 K, the filling factor ν is estimated to be 0.6 for sample IC558 and the Zeeman splitting of the $N=0$ Landau level is calculated to be 23 meV by the simplified three-level model. Electrons are expected to exist only in the plus-spin state of the $N=0$ Landau level in equilibrium condition. The Boltzmann factor is $\sim 10^{-9}$ at 16 K for the upper spin state. Therefore, only the spectra in the down sweep and those in the up sweep with the lowest maximum field approximate to equilibrium conditions. The higher spin state in the up sweep with high maximum field, on the other hand, should not be observed for equilibrium electrons. The lack of equilibrium is not due to the effect of Joule heating in the system of electrons and lattice by eddy current, because the

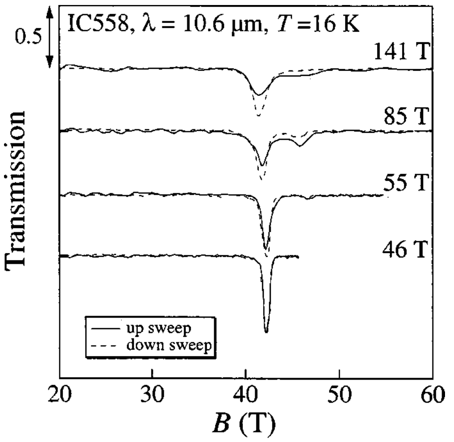

FIG. 5. CR spectra for maximum fields of 46, 55, 85, and 141 T at $\lambda = 10.6$ μm and 16 K in sample IC558.

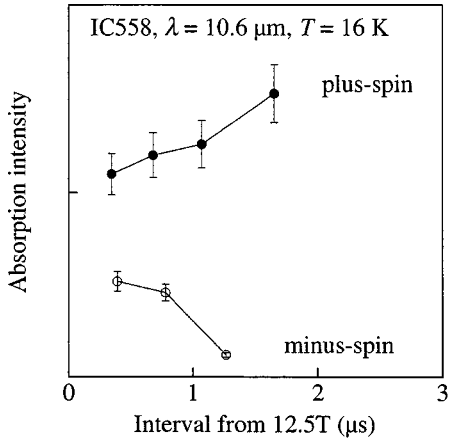

FIG. 6. Absorption intensity of the CR in the up sweep as a function of time. The abscissa is an interval from the instant of 12.5 T to the resonant field for each spin. The solid circles are for the plus spin and the open circles are for the minus spin.

heating effect is not visible for another InAs/AlSb system (IC563) and $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}/\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}$ system in which the amount of generated heat is expected to be of the same order of magnitude as in Sample IC558.

We suppose that the lack of equilibrium is caused by a slow spin-flip relaxation compared with the 6-μs duration time of the magnetic field. In the up sweep, the magnetic field increases at a rate of $dB/dt \sim 50$ T/μs, which depends on the maximum field. With $n = 5 \times 10^{11}$ cm^{-2}, the plus and minus-spin states of the $N=0$ Landau level are expected to be completely occupied in thermal equilibrium by electrons at 12.5 T, because a short inter-Landau-level relaxation time of 0.1 ns has been measured with the same sample at this field.[5] As the field is increased, the degeneracy of the plus-spin increases and the increased levels should be filled by electrons relaxing from the minus-spin states. However, when the field increases faster than the relaxation time, some electrons will remain in the minus-spin states. Thus the minus-spin states should be occupied by more electrons than expected for the Boltzmann distribution, resulting in a non-equilibrium population.

Figure 6 shows the time dependence of the absorption intensity in the up sweep. The abscissa is an interval from the instant of 12.5 T ($\nu=2$) to the resonant field for each spin. In order to estimate the spin-flip relaxation time from Fig. 6, we need to solve the rate equation concerning the plus- and minus-spin states of the $N=0$ Landau level,

$$\frac{df_-}{dt} = -\frac{f_-(1-f_+)}{\tau_1},$$

where τ_1 is the relaxation time from the minus- to the plus-spin states and f_+ (f_-) is the filling factor of the plus-(minus-) spin states. To obtain the spin-flip relaxation time exactly, we should take account of the following two points. First, the absorption intensity is not proportional to the carrier distribution due to an effect of the e-e interaction,[8,13] which will be discussed in the next section. This effect can be estimated from comparison with CR spectra obtained in the field with a maximum of 50 T, which can be interpreted as a signal of the equilibrium states. The electron temperature in the field with the maximum of 85 T (141 T) is estimated to be 70 K (120 K). Figure 7 shows the time dependence of the carrier concentration in the up sweep, taking into account e-e interaction effects. Second, the relaxation time will be strongly dependent, and this dependence has yet to be established. The nonequilibrium electron distribution found in CR spectra is the sum of all the deviations from equilibrium that have built up in the fields between 12.5 T ($\nu=2$) and the resonance. For these reasons, it is difficult to estimate the exact value of the relaxation time. However, as can be seen in Fig. 7, we found a relatively good agreement between the experiment and the calculation assuming the constant τ_1 of 1 μs. This result indicates that a relaxation time longer than 1 μs is required for the observation of the nonequilibrium distribution in CR spectra measured in the single-turn coil technique.

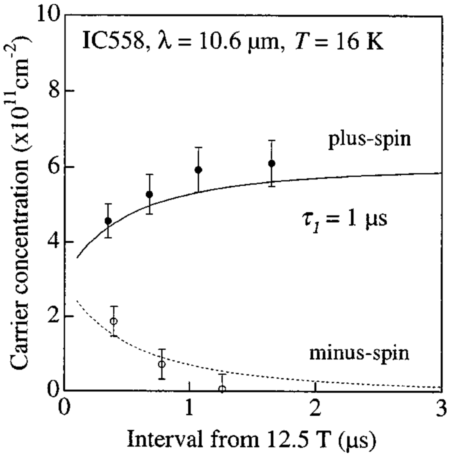

FIG. 7. Carrier cincentrations of each spin in the up sweep as a function of time. The abscissa is an interval from the instant of 12.5 T to the resonant field for each spin. The solid (dashed) line is the calculated value of the carrier concentration of the plus spin (minus spin), assuming that the spin-flip relaxation time is the constant value of 1 μs.

In InAs, the Landau-level wave functions consist of an admixture of the up- and down-spin states by the strong spin-orbit interaction, which allows the relaxation from the minus- to the plus-spin state by an electric-type perturbation.[21] Owing to the discreteness of the density of states, the spin-flip relaxation (τ_1) is an energy loss process and can happen through an inelastic emission of phonons. Figure 8 shows the Landau levels in the 15-nm InAs/AlSb quantum well calculated by the simplified three-level model. The LO-phonon energy in InAs is 29.5 meV.[22] In fields between 12.5 and 46 T (the resonant field of the minus spin), where the Zeeman energy is smaller than the LO-phonon energy, the LO-phonon scattering is ineffective. Scattering by acoustic phonons is also unlikely, because it is difficult to satisfy the energy conservation and the momentum conservation at the same time due to the discreteness of the density of states and the large Zeeman splitting. Multiphonon scattering may bypass the above single-phonon processes.[23] However, we believe that the experimentally determined re-

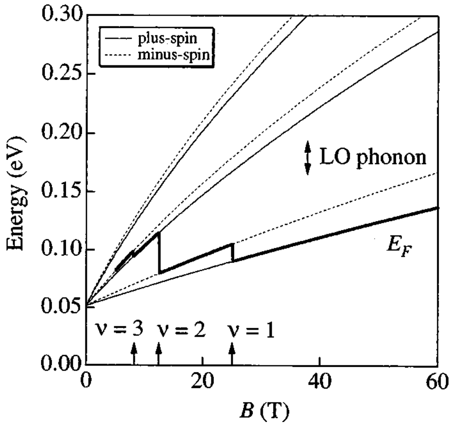

FIG. 8. Calculated Landau levels of the ground subband in the 15-nm InAs/AlSb quantum well as a function of magnetic fields by the simplified three-level model. The solid (dashed) lines are for the plus (minus) spin. The thick line is the Fermi energy. The LO-phonon energy in InAs is 29.5 meV (Ref. 22).

laxation time of about 1 μs, which is relatively large as a process in a two-dimensional electron system, is reasonable.

The simplified three-level model predicts that the Zeeman energy of the $N=0$ Landau level becomes equal to the LO-phonon energy at about 60 T. At this field, spin-flip magnetophonon resonance (MPR) should occur, and the spin-flip relaxation time becomes considerably small. As a result, the nonequilibrium is released and an equilibrium is realized rapidly. Experimentally, the population of the upper component of the doublet was not observed in the CR spectra at 5.53 μm and 24 K. At 5.53 μm, the CR occurs at 108 T higher that the MPR field.

In sample IC563, which has smaller carrier concentration and lower mobility than sample IC558, no hysteresis was observed even at the same condition. In other words, no indication of nonequilibrium distribution was observed. We deduce two possible reasons for this. The first one is the smaller carrier concentration in sample IC563. With sample IC563 $\nu=2$ is at 8 T, which is lower than the IC558 case, as a result the spin-flip relaxation starts from lower fields. The spin-flip relaxation is expected to be faster in lower fields due to the smaller Zeeman splitting. In sample IC563, therefore, nonequilibrium distribution might not be realized at the resonant field. The second is the lower mobility. At the resonant field, the Zeeman splitting is just a little smaller than the LO-phonon energy. In the system with a lower mobility, the scattering by LO phonons or multiphonons could be mediated by the broader density of states.

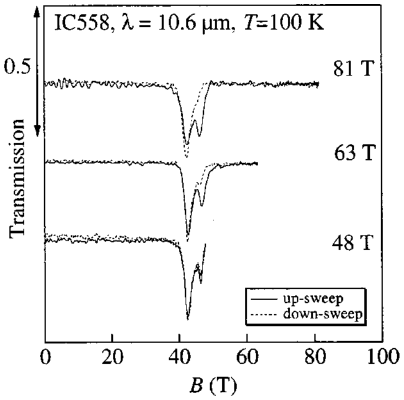

FIG. 9. CR spectra for maximum fields of 48, 63, and 81 T at $\lambda=10.6$ μm and 100 K in sample IC558.

At higher temperatures, we observed a different type of hysteretic phenomenon. Figure 9 shows the maximum-field dependence of CR spectra at $\lambda=10.6$ μm and 100 K in sample IC558. ν at 44 T is 0.85 with $n=9\times10^{11}$ cm^{-2}. When the magnetic field is limited to 48 T, no hysteresis was observed and the absorption intensity for the plus- and minus-spin states can be interpreted to reflect the equilibrium carrier distribution at 100 K. Contrary to the case at low temperatures, there is almost no dependence on the maximum field in the up sweep. In the down sweep, however, the absorption intensity of the minus-spin state decreases with increasing maximum field. Thus the hysteresis becomes clearer on increasing the maximum field, while there is almost no hysteresis for the plus-spin component. Some kind of an escape of electrons from the minus-spin states during the period when the magnetic field is exceeding the resonant field may explain the reduction of the absorption intensity of the minus-spin state in the down sweep. One possible mechanism for the escape is electron transfer and freeze out of remotely located residual donor states in the AlSb layer or the GaSb surface donors. The calculation by the simplified three-level model predicts that a crossover takes place between the minus-spin state of the $N=0$ Landau level and the remotely located donor states in AlSb at around 50 T, although the field dependence of the donor level is not known and expected to be at least smaller than that of the Landau level. Consequently, the electrons in the minus-spin state can be transferred to the donor state in AlSb in fields higher than the crossover field. When the field is swept lower faster than the transfer from the donor level to the Landau level in the InAs well, electrons cannot return to the InAs layer and would stay in the donor level. Thus in the down sweep, with increasing sweep rate, the electron concentration of the minus-spin state decreases. Hence, the nonequilibrium electron distribution is realized in fields that sweep faster than the transfer time. The transfer time is difficult to determine exactly, but it must be longer than 1 μs for observing the hysteretic phenomenon in this field sweep rate.

When we see the spectra strictly, we can find a little hysteresis of the plus-spin component. This can be attributed to the slow spin-flip relaxation found in the low-temperature case but it is difficult to divide the effects of the slow spin-flip relaxation and the slow carrier transfer.

These observations show that fast magnetic-field sweeps create nonequilibrium populations of electron spins. This technique can be used to probe spin dynamics in many other systems of current interest if the characteristic time is between 0.1 μs and a few microseconds. InSb-related 2DEG will be the most potential candidate for this measurement, because InSb has a large *g* factor, which results in large Zeeman splitting and the long spin-flip relaxation time. A light source of continuous wavelength will be strong support for more detailed measurement of this method.

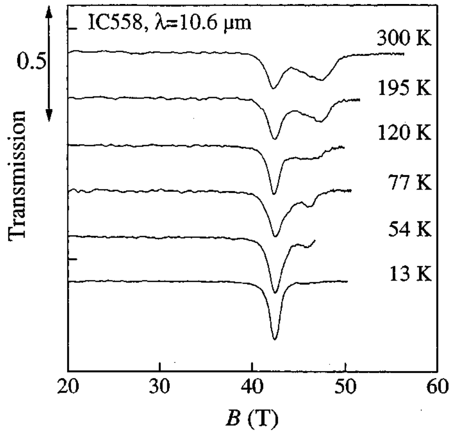

FIG. 10. CR traces of sample IC558 at a wavelength of 10.6 μm.

B. Electron-electron interaction

Figure 10 shows CR traces of sample IC558 as a function of temperature at a wavelength of 10.6 μm. We depicted only the traces for up sweep of the field because we did not find any difference in the traces for up and down sweep with a maximum field of 50 T. In the following discussion we are assuming that the electrons occupying the Landau levels are in thermal equilibrium. It should be emphasized that the hysteresis does not play an important role in this section, because the maximum field is limited to 50 T, and in this spectrum we did not find any evidence of nonequilibrium. This fact is evident in the 55-T spectrum of Fig. 5. In Figs. 10 and 13, it can be seen that the maximum field attained in the pulse is only 2 to 3 T greater than the resonance field of the upper of the two spin-split peaks. Two peaks are observed at 42 and 47 T corresponding to effective masses $m^* = 0.042m_0$ and $0.045m_0$ of the two spin states at $\hbar\omega = 117$ meV. They are much larger than the band-edge mass $m_0^* = 0.023m_0$ due to the nonparabolicity. As shown in Fig. 2, ν at 44 T is 0.6 at 13 K. The Zeeman splitting is evaluated to be 23 meV at 44 T from a calculation using the simplified three-level model. It is much larger in energy than kT at 13 K. Therefore, the electrons occupy only the up-spin states of the $N=0$ Landau level, which results in a single peak at 13 K. With increasing temperature, the electrons are excited to the down-spin states of the $N=0$ Landau level by thermal excitation, which causes appearance of the peak at around 47 T at higher temperatures. The peak position at lower fields is almost independent of temperature, but that at higher fields increases in field by 1.8 T with increasing temperature from 54 to 300 K. As shown in Fig. 11, the peak positions at 300 K are in good agreement with the calculation of the transition energy using the simplified three-level model.

We can see several anomalous properties about the peak in higher fields. The linewidth is about twice as large as that in lower fields. The peak shape does not consist of a simple Lorentzian. The calculation by the simplified three-level model shows that the (0,1) level crosses the (1,0) level at about 25 T and so that interactions between these levels will be absent in the 40–50 T field range. As shown in Fig. 12, the total absorption intensity increases 2 times with rising temperature from 13 to 300 K, which is consistent with the increase of the carrier concentration deduced from the transport measurement. However, the absorption intensity of the down-spin peak at around 47 T exceeds the value expected from electron distribution in the down-spin states, and that of the up-spin states decreases more than theoretically expected. At 300 K, the down-spin peak exceeds the up-spin peak in intensity. We cannot attribute the stronger absorption of the down spin to the other transitions from the excited states, as can be seen in Fig. 11.

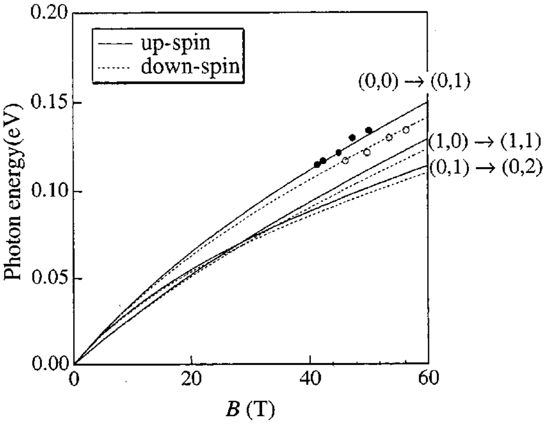

FIG. 11. Transition energies from the ground Landau level, together with the excited Landau level and the excited subband, calculated by the simplified three-level model. In (l,N), l represents the subband index and N represents the Landau level index. The solid line is for the up spin, and the dotted line is for the down spin. The parameters are $E_g = 0.42$ eV, $\Delta = 0.38$ eV, $m_0^* = 0.023m_e$, $g_0^* = -15$, the ground subband energy $E_0 = 60$ meV, and the first excited subband energy $E_1 = 200$ meV. Solid and open circles are measured resonance positions at 300 K at wavelengths of 10.6, 10.2, 9.55, and 9.25 μm.

To solve these questions, we compared the experimental results with the spectra calculated by means of the numerical

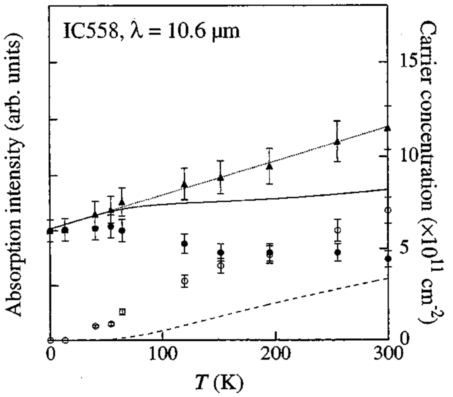

FIG. 12. Temperature dependence of the absorption intensity of the up spin (solid circle), the down spin (open circle), and the sum of them (triangle). The dotted line is a fitted line to the total absorption intensity. The solid (dashed) line shows the expected Boltzmann distribution of the up-spin (down-spin) electrons with the Zeeman splitting of 23 meV, assuming that the total intensity is proportional to the carrier concentration.

diagonalization in a finite-size system. At first, we summarize all the parameters in experimental conditions. ν at 44 T is 0.6 at 13 K and 1.2 at 300 K, E_c at 44 T is 25 meV, and $\hbar\Delta$ at 44 T is 6 meV calculated by the simplified three-level model. Therefore, $E_c/\hbar\Delta$ at 44 T is approximately 4 and kT/E_c is 0.05 at 13 K, 1 at 300 K. $(\nu_\uparrow : \nu_\downarrow)$ is expected to be (8:0) at 0 K, (7:1) at 150 K, and (6:2) at 300 K for the Zeeman splitting of 23 meV.

Now, let us examine the calculated results of $kT/E_c = 1.0$ and $E_c/\hbar\Delta = 1.0$ in Fig. 1. The calculated spectra reproduce the experimental results qualitatively as follows. (a) The peak position of the up-spin state has almost no dependence on the ratio of $(N_\uparrow : N_\downarrow)$. (b) The peak shape of the up-spin state is a single Lorentzian curve, but that of the down-spin state does not look like a single Lorentzian curve, and the width of the down-spin state is larger than that of the up-spin state. (c) The absorption intensity of the down-spin state is larger than expected from the carrier distribution, although there is no inversion of the absorption intensity between the up- and down-spin states, which was actually observed experimentally at temperatures higher than 200 K.

There are a few difficulties in comparing the experiment directly with the calculated results. The carrier concentration of sample IC558 depends on temperature, and ν is not equal to 1 exactly. In the calculation, the carrier distribution is changed without changing the temperature, but the carrier distribution is changed with temperature in the experiment. However, we believe that the agreement between the experiment and the calculation is reasonably good in a qualitative sense.

The value of $E_c/\hbar\Delta$ assumed in the calculation is one-fourth that in the experiment. We found good agreement with the calculated spectra at $E_c/\hbar\Delta = 1.0$ in Fig. 1. The calculated spectra of $E_c/\hbar\Delta = 2.0$ in Fig. 1 have a single-peak structure, which is entirely different from experiment. The smaller value of the interaction strength in the experiment is attributed to the finite thickness of 2DEG. In GaAs/Al$_x$Ga$_{1-x}$As heterojunctions, a reduction factor of 0.65 was found on comparison of CR experiments in a quantum limit condition of ultralow filling factor with the Cooper-Chalker calculation.[8] In the InAs/AlSb single quantum well of this paper, we found a factor of around 0.25, which is smaller than that in the GaAs/Al$_x$Ga$_{1-x}$As heterojunction. The large well width of 15 nm can reduce the effective e-e interaction significantly.

Figure 13 shows CR traces of sample IC563 as a function of temperature at a wavelength of 10.6 μm sample IC563 has a carrier concentration that is 3×10^{11} cm^{-2} smaller than sample IC558 at all temperatures. At 50 K, the spin splitting of sample IC563 ($\nu = 0.4$) was measured to be larger by 1 T than sample IC558 ($\nu = 0.7$). This can be interpreted by a weaker effective interaction in sample IC563 due to the smaller carrier concentration. The calculation by Asano and Ando predicts that the CR spectra at low temperatures and $\nu < 1$ should show basically the same behavior as that at low temperatures and $\nu = 1$ except that the interaction strength becomes weaker with decreasing ν.[12] Besides, as can be seen in Fig. 2 of Ref. 12, the spin splitting becomes smaller with increasing interaction $E_c/\hbar\Delta$. At higher temperatures, however, we found no clear difference in the relative absorption intensity of the up-spin and the down-spin states and the absorption shape from sample IC558. A qualitative explanation for this is difficult to find at the moment, because the calculation shows that at around $\nu = 1$ and higher temperatures, the CR spectra is expected to behave in a complicated manner.[13]

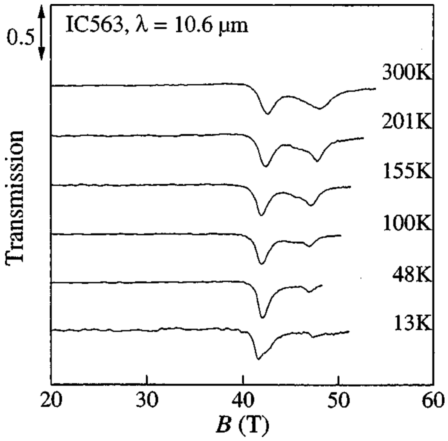

FIG. 13. CR traces of sample IC563 at a wavelength of 10.6 μm.

The temperature dependence at 5.53 μm in sample IC558 was measured and two peaks were observed at 109 and 130 T at temperatures higher than 200 K. The absorption intensity of the down-spin state was slightly larger than expected for the Boltzmann distribution. The shape of the CR absorption consisted of a single Lorentzian. To summarize, we found only a small anomaly at 5.53 μm. In these fields, $\hbar\Delta$ is large (~25 meV); therefore the effect of e-e interaction is expected to be small. Practically, $E_c/\hbar\Delta = 1.65$ at 120 T, which is the center of the spin-split CR at 5.53 μm. This value is about one-third of the value at 44 T.

Finally, we compare our experimental results with previous papers. CR spectra of GaAs/Al$_x$Ga$_{1-x}$As heterojunctions were very accurately measured,[7,8] and a unique ν dependence was found. For $\nu < \frac{1}{6}$, a spin splitting was found in the CR spectra, but only a single peak was observed for $\nu > \frac{1}{6}$, which is attributed to a single-mode behavior dominated by e-e interactions. In the InAs/AlSb system, $\hbar\Delta$ of the conduction band is about 13 times larger than that in the GaAs/Al$_x$Ga$_{1-x}$As system due to a strong spin-orbit interaction.[14] $E_c/\hbar\Delta$ in GaAs/Al$_x$Ga$_{1-x}$As is estimated to be around 70 at 10 T and that in InAs/AlSb is around 5. We succeeded in the observation of a spin splitting in CR at $0.3 \leqslant \nu \leqslant 1.2$ where only a single peak was observed in GaAs/Al$_x$Ga$_{1-x}$As, which is due to the weaker interaction strength in InAs/AlSb. We could observe spin splitting and related anomalies due to the e-e interaction even at the high temperature of 300 K in spite of the line broadening. This observation is due to the large $\hbar\Delta$ overcoming a large linewidth at 300 K. Yang *et al.* observed a spin-split and mass-split CR in an InAs/AlSb single quantum well at $1.8 \leqslant \nu \leqslant 5.5$.[14] The peak position was found to be in good agreement with the calculation of the transition energy outlined by Bastard,[20] which takes into account band effects without e-e

interaction. Higher magnetic fields in our experiment made it possible to observe spin-split CR at lower ν than Yang *et al.*, and this is the reason why we found an anomalous behavior in temperature dependence. The calculation by Asano and Ando shows that the e-e interaction pushes the up-spin and down-spin modes to lower energy at $\nu=1.75$ and $T=0$, which we can find at $E_c/\hbar\Delta$ higher than 2.0 in Fig. 9(a) of Ref. 13. The parameters estimated from their experiments are $\nu=1.8$, $E_c=13$ meV, and $\hbar\Delta=2$ meV; therefore $E_c/\hbar\Delta=6.5$ at 13 T. Considering the reduced interaction from the effect of a finite thickness of 2DEG, $E_c/\hbar\Delta$ should be around 1.5. It is a subtle question whether any visible shift of the absorption peak in CR spectra should be observed.

IV. CONCLUSION

We have measured spin-split CR spectra of InAs/AlSb single quantum wells over a wide range of temperature from 10 to 300 K at around 45 T, corresponding to $0.3\leqslant\nu\leqslant1.2$. Hysteretic phenomena and anomalous CR spectra were observed. The maximum field dependence reveals that the hysteresis is due to a nonequilibrium electron distribution. The deviation firm the equilibrium is induced by the fast sweep of the magnetic fields by the single-turn coil technique for slow relaxations of the order of microseconds. The spin-flip relaxation is found to be longer than 1 μs. The slow relaxation is attributed to the discreteness of the Landau level and the large Zeeman splitting due to the large g value of InAs and high magnetic fields. The transfer from the donor levels in AlSb to Landau levels in InAs is also found to be longer than 1 μs. The transfer is due to the crossover effect between these levels in high magnetic fields. By qualitative comparison of our results with the calculation of Asano and Ando by means of numerical diagonalization in a finite-size system, an intriguing dependence on ν and the temperature can be ascribed to the e-e interaction. It is found that the e-e interaction is significant in CR spectra even at 300 K. A qualitative comparison has shown that the finite thickness of 2DEG reduces the interaction strength by a factor of around 0.25.

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