Photoluminescence from a modulation-doped $Al_{0.33}Ga_{0.67}As/GaAs$ heterointerface under cyclotron resonance

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Magnetophotoluminescence and change in photoluminescence (PL) intensities, due to far-infrared irradiation at the cyclotron resonance (CR) magnetic fields, in modulation-doped $Al_{0.33}Ga_{0.67}As/GaAs$ single heterostructures are measured. The changes in PL intensities due to CR absorption strongly depend on the Landau-level filling factor (ν) and CR energy; i.e., the Landau-level separation. When $\nu<2$ and CR energy is more than intersubband energy separation, luminescence from the ground subband is almost quenched and that from the second subband is greatly enhanced by CR absorption. [S0163-1829(98)04148-4]

I. INTRODUCTION

Photoluminescence (PL) measurements are useful for investigating not only the band structures in undoped semiconductors but also the carrier properties in modulation-doped heterostructures.[1–10] For two-dimensional electron gas (2DEG) systems, magneto-PL spectra reflect many striking phenomena, such as the integer and fractional quantum Hall effects, which are generally studied in transport experiments.[6–8] Furthermore, the magneto-PL spectra themselves have unveiled interesting features, such as the Fermi-edge-singularity (FES).[9] In a magnetic field, electrons are distributed to Landau levels (LL's) and the filling factor ν is determined by the density of the 2DEG and the magnetic field. On the other hand, holes exist only in the lowest LL because the density of photogenerated holes is much less than that of the 2DEG in a weak excitation condition. In modulation-doped single heterostructures, electrons are confined at the heterointerface, however, photoexcited holes are not confined, and the separation of the wave functions is rather large. The measured PL spectra are, therefore, largely affected by the spatial separation between electrons and holes.

Under the irradiation of far-infrared (FIR) light at the cyclotron resonance (CR) magnetic field, electrons are excited to the higher LL's. Measuring the PL spectra in this nonequilibrium condition is effective for studying the interaction between electron-hole radiative recombination and electron excitation by CR absorption. In addition, changes in PL spectra due to CR absorption are also important from the viewpoint of the CR measurement method, which is called optically detected cyclotron resonance (ODCR).[11–18] This method has a super sensitivity for bulk materials. The principle of ODCR for bulk materials has been explained as a decrease of the bound-exciton luminescence due to an electron heating by the FIR absorption.[11,12] However, for heterostructures, the ODCR signal is complicated and the mechanism of ODCR has not been clarified. Regarding quantum well structures, changes in PL spectra under the CR condition are extremely small and only a few percent, though ODCR has been used for studying donor transitions[13] and exciton intratransitions.[17] On the other hand, rather large changes have been reported for single heterostructures,[15,18] although the signal changes are complicated; that is, some peaks are enhanced and other peaks are suppressed under the CR condition. Their principle has not been understood because of the complicated magneto-PL spectra in single heterostructures, especially in quantum Hall effect regions.

In this paper, we report the experimental results of the changes in the PL spectra due to CR absorption in the modulation-doped $Al_{0.33}Ga_{0.67}As/GaAs$ single heterostructures. In these structures the wave-function overlap between ground subband electrons and photogenerated holes is small, and that is different from quantum well structures. The overlap is rather large between the wave function of electrons in the second subband and that of holes. We discuss the recombination mechanism between electrons and photogenerated holes for magneto-PL spectra and also discuss how these spectra are modified by the FIR irradiation as a function of the LL filling factor (ν) and the CR energy, i.e., the FIR energy. For the sample with extremely low-electron density, the complicated feature of the magneto-PL disappears and a monotonically change of the PL intensity and emission energy is observed as a function of the magnetic field like as a bulk exciton emission.[8] Although the low-electron density region is important, we restrict our discussion to the high-electron density region where the rich features are observed in the magneto-PL spectra.

II. EXPERIMENTAL TECHNIQUE

The samples used in this experiment are conventional Si modulation-doped $Al_{0.33}Ga_{0.67}As/GaAs$ single heterostructures grown by molecular beam epitaxy. The layer structure is consist of a semi-insulated GaAs substrate, a 50-period 2-nm AlAs/2-nm GaAs superlattice buffer, 1-μm undoped GaAs, a 60-nm $Al_{0.33}Ga_{0.67}As$ spacer, 10-nm Si-doped $Al_{0.33}Ga_{0.67}As$, 80-nm undoped $Al_{0.33}Ga_{0.67}As$, 10-nm Si-doped $Al_{0.33}Ga_{0.67}As$, 15-nm undoped $Al_{0.33}Ga_{0.67}As$, and a 10-nm GaAs capping layer. The electron density and the mobility are $2.4\times10^{15}\ m^{-2}$ and $140\ m^2\ V^{-1}\ s^{-1}$ after illumination at 1.5 K. We control the electron density at the heterointerface by slightly etching the surface GaAs and $Al_{0.33}Ga_{0.67}As/GaAs$ layers in this experiment.

The multichannel ODCR setup is used for the optical

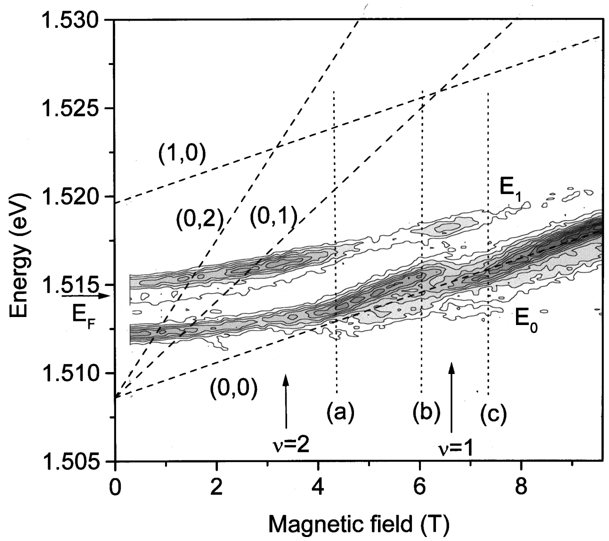

FIG. 1. Magneto-PL spectrum in the single heterostructure. (Sample *A*: Electron density is $1.6\times10^{15}\ \mathrm{m}^{-2}$.)

measurement. The details of the setup are shown in Ref. 18. It features charge-coupled devices (CCD) with an image intensifier synchronized with a pulsed FIR laser. With this setup, PL intensities are obtained as a function of both wavelength and magnetic field. A 514.5-nm cw Ar laser via a 1-mm-diameter optical fiber was used to excite the sample. The excitation power is weak enough not to modulate the electron density. The PL signal is collected by the same fiber and detected by the CCD through a 0.50-m single-grating spectrometer. For the FIR irradiation, the sample is mounted in the Faraday geometry in an FIR light pipe at the center of a superconducting magnet cooled down to 2 K. We used three FIR lines, 96.5, 118.8, and 163.0 μm, from a methanol-gas laser pumped by a CO_2 laser. The system also enables us to measure FIR transmission, and the CR magnetic fields were determined from the FIR transmission spectra.

III. RESULTS AND DISCUSSION

Figure 1 shows a typical magneto-PL spectrum for the sample with an electron density of $1.6\times10^{15}\ \mathrm{m}^{-2}$. The PL intensity is represented by contour lines as the function of both energy and magnetic field. Two major peaks are observed. The higher energy peak (E_1) comes from the excitonic recombination between photogenerated electrons in the second subband and the photogenerated holes. The second subband widely distributes into the substrate side and strong excitonic recombination with photoexcited holes occurs. The emission energy and its shift as a function of magnetic field are nearly equal to the exciton PL line in bulk GaAs. The lower-energy peak (E_0) is originated from the recombination between electrons in the ground subband and the photogenerated holes. The intensity maximum of the E_1 emission and the discontinuity of E_0 emission at 6.53 T correspond to $\nu=1$, and another maximum of E_1 emission at 3.26 T corresponds to $\nu=2$. In the low magnetic-field region where $\nu>2$ electrons distribute into several LL's in the ground subband. The lowest LL of the ground subband $(N, L_e)=(0,0)$, where N is the subband index and L_e is the LL index of electrons, is completely filled by electrons. The electrons in this LL cannot recombine with the holes because these electrons cannot scatter and cannot screen the potential of holes. Furthermore, the recombination between electrons in the higher LL's of the ground subband $(0, L_e>0)$ and holes in $L_h=0$, where L_h is the LL index of holes, is forbidden by the selection rule. On the other hand, recombination is allowed between electrons in the lowest LL of the second subband (1,0) and holes in $L_h=0$. As a result, E_1 emission becomes strong and E_0 emission quenches for $\nu>2$.[6] The recombinations originating from higher LL's have been observed for $\nu>2$ in the acceptor-doped single heterostructures as shown in Ref. 4. In such a structure, electrons recombine with the holes bound in acceptors without being limited by the selection rule. However, it is not the case for the conventional modulation-doped single heterostructures. In the high magnetic field region for $\nu<2$, the electrons in the partially filled (0,0) can recombine with the holes. As a result, E_0 becomes stronger and E_1 quenches except at $\nu=1$, where the up-spin level is completely filled and the down-spin level is empty. Because the completely filled level cannot contribute to the emission just as the case of $\nu>2$, E_1 emission has an intensity maximum at $\nu=1$.[6] The discontinuity of the E_0 emission energy at the $\nu=1$ has been understood as the Skyrmion effect.[19–21] In the low magnetic-field region, the E_0 emission seems to be enhanced again when the magnetic field is close to zero. In the low electron-density single heterostructures as shown in Ref. 7, the emission coming from the electrons in the ground subband is observed even when $\nu>2$. In particular, the recombination of the electrons in the Fermi edge is enhanced, what is called FES.[9] In our results, however, the Fermi energy from the bottom of the ground subband is 5.8 meV at 0 T and the expected emission energy is about 1.514 eV, where the bottom energy of the ground subband is estimated by the fitting shown later. The observed emission peak is not explained by the FES. One possible origin is the excitonic recombination of the Fermi-edge electrons, which has some small exciton binding energy around 1.5 meV due to the separation between electrons and holes. However, the emission-shaped sharp PL at 1.5125 eV is difficult to understand. Another possible origin is the acceptor (carbon) bound exciton recombination from the bulk GaAs region. If this were the origin, the reason for the intensity decreasing with increasing magnetic field would not be clear. In this paper, we mainly discuss the change in the PL intensity due to the CR absorption in high magnetic-field regions; an explanation of the emission peak in the low magnetic-field region requires further study.

We measured the changes in the PL intensity due to CR absorption of FIR irradiation. The dotted lines in Figs. 1(a), 1(b), and 1(c), which correspond to Figs. 2(a), 2(b), and 2(c), respectively, indicate the CR magnetic fields for the three FIR lines used in this experiment. Figure 2(a) shows the PL spectrum (PL), the PL spectrum under 163.0-μm FIR irradiation (FIR-PL), and their difference (Δ) at the CR magnetic field of $B=4.38$ T, which corresponds to $\nu=1.50$. Both the E_0 and E_1 emissions slightly decrease. And this decrease is explained as a carrier heating due to the FIR absorption under the CR condition.[14] On the other hand, in Figs. 2(b) (FIR: 118.8 μm, $B=6.02$ T, and $\nu=1.09$) and 2(c) (FIR: 96.5 μm, $B=7.39$ T, and $\nu=0.89$), the E_0 peak is suppressed and the E_1 peak is enhanced. The enhancement of

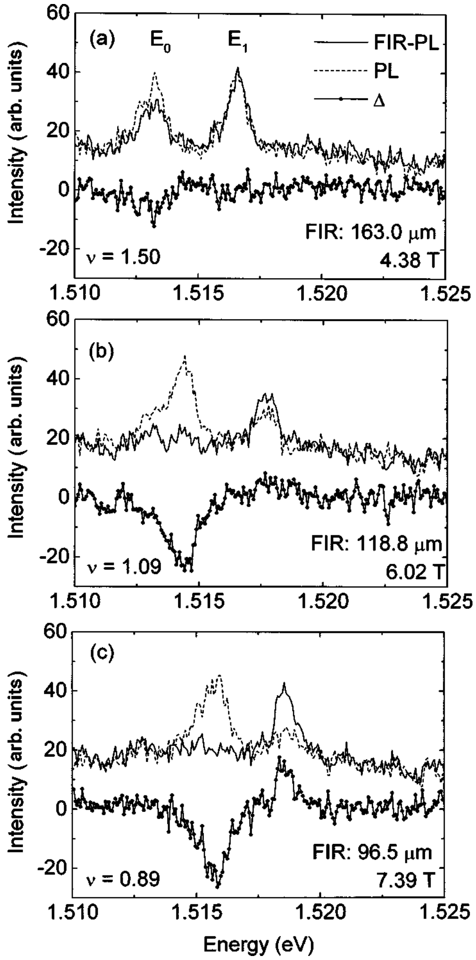

FIG. 2. Normal PL spectra (dotted line), PL spectra under FIR irradiation (solid line), and their differences (circle and solid line) at each CR magnetic field. (Sample *A*).

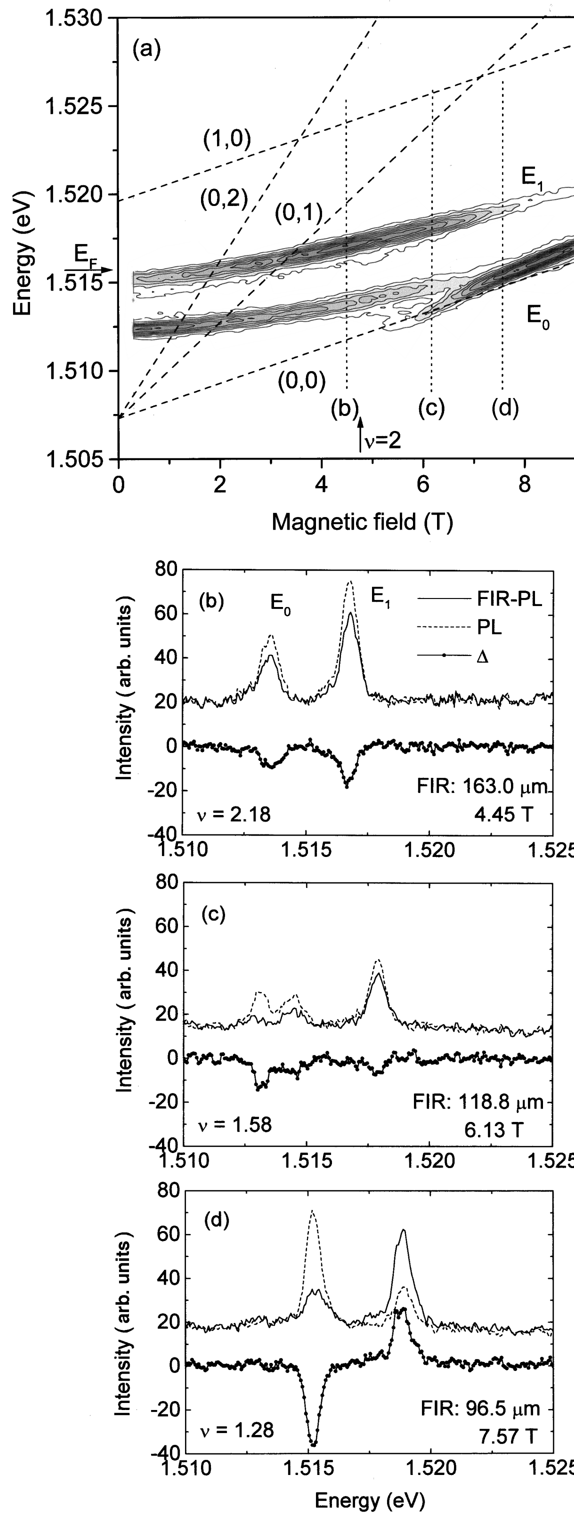

FIG. 3. Magneto-PL spectrum, and PL spectra (dotted line), PL spectra under FIR irradiation (solid line), and their differences (circle and solid line) at each CR magnetic field. (Sample *B*: Electron density is $2.4\times10^{15}\ \mathrm{m}^{-2}$.)

the E_1 peak is strong in Fig. 2(c), but it is weak in 2(b). These observations clearly indicate that the change in the PL spectrum by CR absorption, i.e., ODCR signals, in the conventional modulation-doped single heterostructures is largely affected by several parameters, including filling factor ν. And the signal is much larger than those of bulk and quantum-well structures. To further investigate the ODCR mechanism in the modulation-doped single heterostructures, we first estimate the energy levels of electron subbands from the PL spectrum. Although the jump of the emission energy at $\nu=1$ causes ambiguity, the linear increase in the E_0 emission energy for $\nu<2$ suggests a nonexcitonic nature of the E_0 emission in this regime. The dashed line, noted (0,0), is the fitted value of the transition energy between electrons in (0,0) and photogenerated holes in $L_h=0$. The photogenerated holes are not confined and almost located in the valence band of a GaAs layer. We use the equation $E=E_g-\Delta E+\frac{1}{2}\hbar\omega_e+\frac{1}{2}\hbar\omega_h$ where E is the transition energy, E_g is the band gap of GaAs, ΔE is the energy reduction due to the band bending, and $\omega_{e,h}=eB/m_{e,h}$ are the cyclotron frequency of holes and electrons. $m_{e,h}$ are the effective masses of the electrons and holes, respectively. The heavy-hole mass of bulk GaAs $0.475m_0$, is used as m_h and $0.068m_0$, which is experimentally determined from the CR condition (6.02 T at 118.8 μm), is used as m_e. For simplicity, we neglect a spin splitting here because of its much smaller energy separation than $\hbar\omega_e$. The upper LL's of the ground subband, such as (0,1), are obtained by adding $L_e\hbar\omega_e$ on the (0,0) curve. For the second subband (1,0) we regard the energy level as that of the bulk GaAs conduction band because the wave function spread widely into the substrate side. Therefore, the dashed line, (1,0), in Fig. 1 is calculated by the equation, $E=E_g+\frac{1}{2}\hbar\omega_e+\frac{1}{2}\hbar\omega_h$. Although the second subband (1,0) is not occupied for the electron density studied here, the photogenerated electrons make the E_1 emission coming from the (1,0) possible. The E_1 emission energy becomes smaller than that of the (1,0) curve because of the exciton binding energy.

When we compare the estimated energy levels with the measured ODCR signals, the following becomes clear. At conditions (b) and (c) in Figs. 1 and Fig. 2, the energy of (0,1) exceeds that of (1,0). Therefore, electrons, excited from (0,0) to (0,1) by CR absorption of FIR, relax to (1,0) and recombine with holes since the transition between electrons in (1,0) and holes in $L_h=0$ is allowed by the selection rule and the overlap of the wave functions is large. So the E_0 emissions are suppressed in Figs. 2(b) and 2(c) by CR absorption. The transfer of the recombination path for E_0 to E_1 and the enhancement of the E_1 emission is clear in Fig. 2(c); however, it is less clear in Fig. 2(b), where the E_1 emission is relatively intense even without FIR irradiation because of $\nu\simeq 1$. On the other hand, the energy of (0,1) is lower than that of (1,0) for the condition (a) in Figs. 1 and 2. Electrons excited from (0,0) to (0,1) relax to (0,0) and finally recombine with holes without being scattered to any states. Therefore, the observed change in the PL intensity caused by CR absorption is a weak reduction of emission intensity both for the E_0 and E_1 lines. This change is usually observed for bulk GaAs and quantum wells caused by a carrier-heating effect.

These characteristics were further studied by using a different sample with a higher electron density. Figure 3(a) shows the magneto-PL spectrum and Figs. 3(b)–3(d) show the PL, FIR-PL, and Δ spectra at each CR magnetic field. The electron density of this sample is 2.35×10^{15} m^{-2}. For this sample, the CR magnetic fields of each FIR line are slightly different from those of the low electron-density sample because of the band nonparabolicity. The CR magnetic field corresponds to $\nu=2.18$ in Fig. 3(b). Then, electrons distribute to (0,1) and are excited to (0,2) by the CR absorption. The energy of (0,2) is higher than that of (1,0), and some electrons may relax to (1,0) and recombine with holes. However, the E_0 emission is suppressed and E_1 emission is enhanced without FIR irradiation for $\nu>2$ and the transfer of the recombination path from E_0 to E_1 has a small effect. The E_1 peak intensity is rather decreased by a heating effect. The enhancement of E_1 emission does not appear for $\nu>2$ even when electrons are excited above the (1,0) level by the CR absorption. In the condition in Fig. 3(c), electrons only distribute to (0,0) because $\nu<2$. However, the energy of (0,1) does not exceed that of (1,0), and the intensity of E_1 emission does not increase but decreases due to the heating. When $\nu=1.28<2$ and (0,1) exceeds (1,0), i.e., the CR energy ($\hbar\omega_e$) exceeds the energy separation between the ground and the second subbands, E_1 emission is strongly enhanced and E_0 is quenched by the CR absorption as shown in Fig. 3(d). This situation is the same as that in Fig. 2(c) where $\nu=0.89$.

IV. CONCLUSION

We measured the magneto-PL spectra and the change in the PL intensities due to the FIR irradiation at the CR magnetic fields for the conventional modulation-doped $Al_{0.33}Ga_{0.67}As$/GaAs single heterostructures. The magneto-PL spectra show the well-known two main lines E_0 and E_1 corresponding to the recombination from the ground and second subbands, respectively. The PL intensities of E_0 and E_1 lines are modified by the CR absorption of FIR irradiation. When $\nu<2$ (except just $\nu=1$) and the CR energy is more than the intersubband energy separation, electrons excited by CR absorption from the lowest LL of the ground subband to the next LL relax to the lowest LL of the second subband. As a result, the luminescence from the ground subband is quenched and that from the second subband is greatly enhanced. The strong ODCR effect is a great contrast to the slight change in the PL intensity by the CR absorption generally observed in the ODCR experiments for quantum-well structures.

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