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Anomalous cyclotron-resonance line splitting of two-dimensional holes in (311)A $Al_xGa_{1-x}As/GaAs$ heterojunctions

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We have studied the far-infrared cyclotron resonance (CR) of high-mobility two-dimensional holes in $Al_xGa_{1-x}As/GaAs$ single interface heterojunctions grown on (311)A GaAs substrates. An anomalous anticrossing behavior was observed in the CR spectra for Landau-level filling factor $\nu < 1$. By comparing the CR spectra with the intersubband transition spectra measured at zero magnetic field, we have successfully identified the anomalous CR line splitting as a crossing of the Landau levels associated with the heavy-hole and light-hole subbands.

The $Al_xGa_{1-x}As/GaAs$ two-dimensional (2D) hole system[1] is very attractive as a microelectronic material. It has been shown that the system can be used to effectively realize complimentary logic circuits[2] and high-performance infrared detectors.[3] This system is also interesting from the physics point of view. The orbital degeneracy at the top of the GaAs valence band leads to a complex, nonparabolic subband dispersion.[4–8] Magnetotransport experiments successfully demonstrated the effect of reduced symmetry of the potential well on the 2D hole band structure.[9–11] Also, because of the heavier effective mass, the relative importance of carrier-carrier Coulomb interaction energy to kinetic energy is more significant in the 2D hole system than in the 2D electron system. Very recently, a reentrant insulating phase has been observed near Landau-level filling factor $\nu=\frac{1}{3}$ in the fractional quantum Hall regime in the high-mobility $Al_xGa_{1-x}As/GaAs$ 2D hole system.[12] However, complete understanding of the 2D hole band structure has not been achieved yet; attempts to understand the cyclotron-resonance (CR) data have been unsuccessful so far.[13–16] Because of the strongly nonparabolic and anisotropic subband dispersion, measured CR spectra often consist of multiple peaks, making peak assignment difficult. Also, theoretical calculations for Landau levels, which are supposed to be compared with experimental results, differ with each other even qualitatively.[5–8] Another complication might come from the fact that Kohn's theorem is not applicable to this system; many-body effects might play an important role in the CR spectra.[5,17]

In this work, we studied the far-infrared CR of high-mobility 2D holes in (311)A $Al_xGa_{1-x}As/GaAs$ single interface heterojunctions. Our samples have such low hole densities (P_s) that at most only the lowest two Landau levels are occupied for magnetic field $B > 4$ T, even if we take into account the thermal population effect. We have determined the cyclotron effective mass $m^* = 0.36m_0 - 0.37m_0$ for the lowest heavy-hole Landau level at $B = 5.0$ T and $P_s < 1.4 \times 10^{11}$ cm^{-2}. This is close to the predicted value of $0.4m_0$ for the (100) surfaces.[7] Furthermore, we observed an anomalous anticrossing behavior in the CR spectra for Landau-level filling factor $\nu < 1$. By comparing the CR spectra with the intersubband transition spectra measured at $B = 0$, we have successfully identified the anomalous CR line splitting as a crossing of the Landau levels associated with the heavy-hole and light-hole subbands.

The selectively Si-doped $Al_xGa_{1-x}As/GaAs$ single interface heterojunctions used in the present study were grown on (311)A GaAs substrates by molecular-beam epitaxy. On this surface, Si atoms preferentially occupy As sites and become acceptors, which generate high-mobility 2D holes on the GaAs side of the heterojunction. The samples were wedged 2°–3° to avoid Fabry-Pérot interference. Ohmic contacts were made by alloying InZn to perform *in situ* transport measurements. P_s can be varied by using a semitransparent Ti front gate. dc mobilities of the samples are $(1-3) \times 10^5$ cm^2/V s at 4.2 K. Far-infrared (FIR) transmission spectra of the 2D holes were measured at 4.2 K by using a Fourier transform spectrometer in the Faraday geometry with B up to 8 T. The resolution of the spectrometer was 1–2 cm^{-1}.[18] The FIR radiation was chopped at 390 Hz, while the front gate electric field was modulated at 20 Hz to improve the sensitivity.

Because of the lower crystal symmetry for the (311) orientation, there is a finite coupling between heavy- and light-hole bands even at $k_\parallel = 0$, where $k_\parallel$ is the in-plane momentum of the 2D hole subband.[19,20] However, since the lowest and the second excited subbands have predominantly the heavy-hole band character and the first excited subband has the light-hole band character,[20] we use the conventional labeling for these three bands throughout this paper. Figure 1(a) shows the CR spectra measured at several B's for $P_s = 1.1 \times 10^{11}$ cm^{-2}. An intense sharp peak and a weak satellite peak are observed when $B < 6$ T. It is also noted that there is a broadband background absorption of the order of $\sim 0.2\%$ for frequencies above 20 cm^{-1} in the whole magnetic-field range studied here. The origin of this broadband absorption will be discussed later. The intense main CR peak is assigned to the transition from the lowest spin-up heavy-hole (HH) Landau level to the next spin-up HH Landau

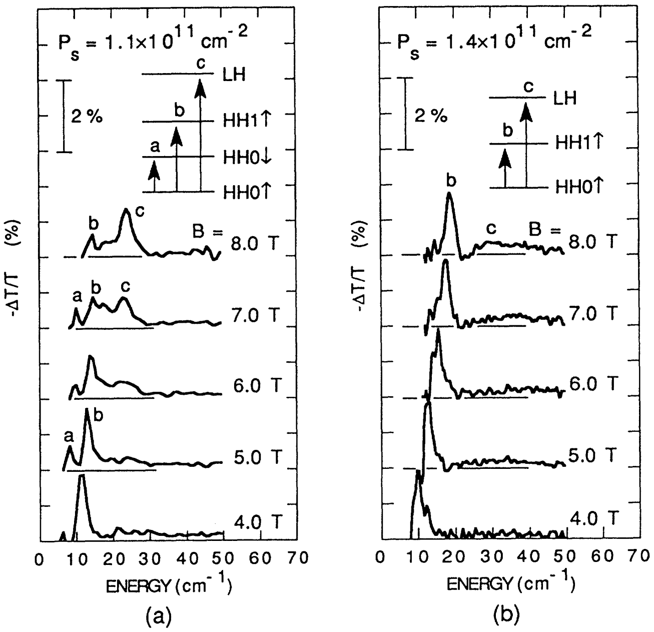

FIG. 1 Cyclotron resonance (CR) of two-dimensional holes in two (311)*A* $Al_xGa_{1-x}As/GaAs$ single interface heterojunctions measured at several magnetic fields: (a) $P_s = 1.1\times10^{11}$ cm^{-2} and (b) $P_s = 1.4\times10^{11}$ cm^{-2}. Each curve is displaced by 2% for clarity. The insets show schematic diagrams for the CR transitions. ↑ and ↓ denote spin-up and spin-down levels, respectively.

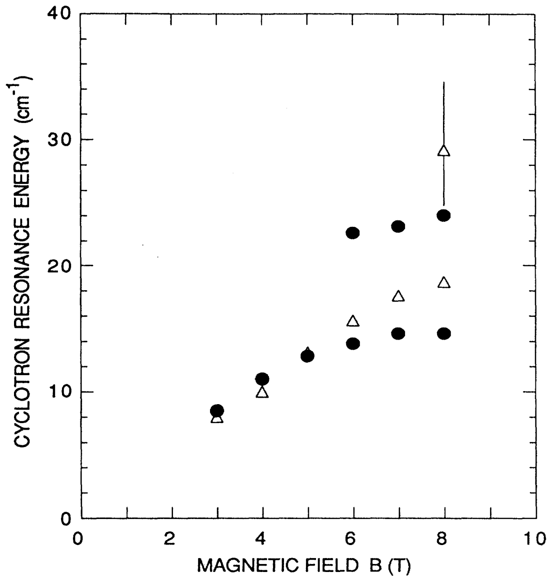

FIG. 2. Energy positions of the main cyclotron-resonance peaks (transition *b* and *c*) are shown as functions of magnetic field for $P_s = 1.1\times10^{11}$ cm^{-2} (full circles) and $P_s = 1.4\times10^{11}$ cm^{-2} (triangles).

level (transition *b*), since this peak remains strong even for $\nu < 1$. The satellite peak is assigned to the transition from the lowest spin-up HH Landau level to the spin-down HH Landau level (transition *a*). Because of the band mixing effect, transition *a* is much stronger than ordinary spin-flip transitions observed in *n*-type structures. Figure 2 shows the dispersion of the main CR peaks (transition *b* and *c*). The cyclotron effective mass for the spin-up HH subband at $B = 5$ T is determined to be $0.36m_0$–$0.37m_0$, close to the predicted value $(0.4m_0)$ for the (100) surface orientation.[7]

For $B > 6$ T ($\nu < 0.75$), however, the intense CR peak associated with the transition from the lowest HH Landau level exhibits a strong anticrossing behavior at ~ 19 cm^{-1} with an energy splitting of ~ 8 cm^{-1} around $B = 7$ T. The broad and complicated feature of the spectra suggests that more transitions become allowed in this regime. It should be noted that only the lowest Landau level is partially filled at this magnetic field. When P_s is 1.4×10^{11} cm^{-2}, the magnetic field where the anticrossing behavior occurs shifts to higher value. However, it is clearly seen in the spectra that the linewidth of the main peak (transition *b*) becomes broader and a new broad feature starts to appear on the higher-energy side of the main peak (~ 25 cm^{-1}) at 8 T. Similar CR line splittings were observed by Schlesinger and Wang[16] (hereafter referred to as SW). In Fig. 3, the energy positions, $\hbar\omega_0$, where the line splittings are observed are plotted as a function of 2D hole density P_s. Data by SW are also included in the figure. Note that $\hbar\omega_0$ depends on P_s, approximately as $\hbar\omega_0 \propto P_s^{0.6}$.

SW suggested two mechanisms as the origin of the observed anomalous CR line splitting:[16] (i) anticrossing of excited-state Landau levels in the HH subbands, and (ii) many-body effects. Since there is no detailed Landau-level calculation available for the (311)*A* orientation, it is not easy to examine the first mechanism. However, according to the theoretical results for the (100) orienta-

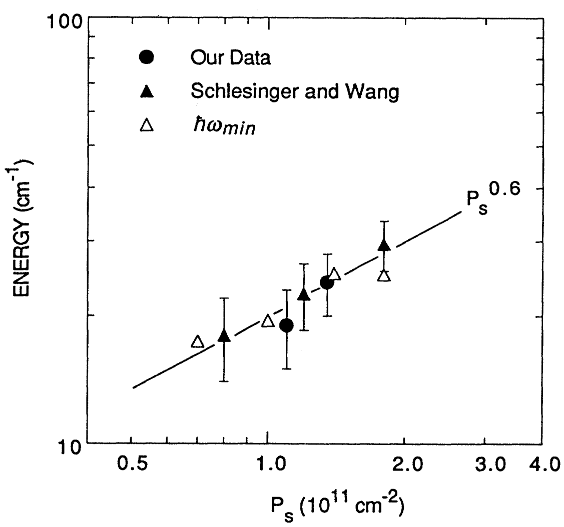

FIG. 3. The energy positions where the anomalous cyclotron-resonance line splittings are observed are plotted as a function of 2D hole density. The filled symbols and error bars denote the center energies $\hbar\omega_0$ and the energy separations of the split peaks, respectively. Data by Schlesinger and Wang (Ref. 16) are shown by filled triangles. $\hbar\omega_{min}$ are also plotted by open triangles. The line in the figure is a guide to the eye.

tion,[5–8] it seems unlikely. The main reasoning for many-body effects as a possibility is the fact that the energy positions where the CR line splittings are observed in the 2D hole system, $\hbar\omega_0$, roughly coincide with those where the CR anomalies are observed in the 2D electron systems in $Al_xGa_{1-x}As/GaAs$ heterojunctions[21] and Si-MOS (metal-oxide semiconductor) inversion layers.[22,23] However, the CR anomaly in the 2D electron systems has not yet been satisfactorily explained by many-body effects.[24] Another problem with this interpretation is that the magnitude of the CR line splitting in the 2D hole system (~ 8 cm^{-1}) is much larger than that in the 2D electron system (≤ 2 cm^{-1}). Judging from these facts, we believe that the above two mechanisms cannot explain the observed CR anomaly.

In order to clarify the origin of this anomalous splitting of the CR, we have measured the intersubband absorption spectra at $B=0$. It should be noted that, even without a metallic coupling grating, it is possible to measure intersubband absorption spectra with normal incidence geometry by utilizing the band mixing effect. Figure 4 shows the measured intersubband absorption spectra for several 2D hole densities, which were varied by the front gate electric field. Very broadband absorption is observed in the frequency range from 20 to 100 cm^{-1}, which originates from the transition from the filled HH ground subband to the empty higher subbands. The LH ground subband has an anomalous negative (i.e., electronlike) dispersion near $k_\parallel \sim 0$ and goes in the direction opposite to that of the HH ground subband.[4–8] This peculiarity in the band structure is the origin of the broadband nature of this transition. The frequency range of this broadband absorption peak in the intersubband transition spectra coincides with that of the broad background absorption observed in the CR spectra. It indicates that the background absorption seen in the CR spectra is due to transitions from the HH Landau levels to the Landau levels associated with the higher subbands.

We note that near the low-energy cutoff of the broad absorption spectrum, an absorption minimum is observed at $\hbar\omega_{min}$, which we attribute to the energy minimum of the dispersive LH ground subband. The peak structure below $\hbar\omega_{min}$ is considered to be the transition from the spin-up HH subband to the spin-down HH subband, which are split by the lifting of the Kramers degeneracy due to the triangular confinement potential.[9–11] $\hbar\omega_{min}$ is plotted as a function of P_s in Fig. 3, together with $\hbar\omega_0$. It is clearly seen that $\hbar\omega_0$ coincides with $\hbar\omega_{min}$. This fact strongly suggests that the anomalous CR line splitting is due to crossing of the Landau levels associated with the HH subband and the LH subband.

In the triangular potential well, the quantization energy for the ground subband, E_0, is approximately proportional to $(1/m_3)^{1/3}P_s^{2/3}$, where m_3 is the effective mass in

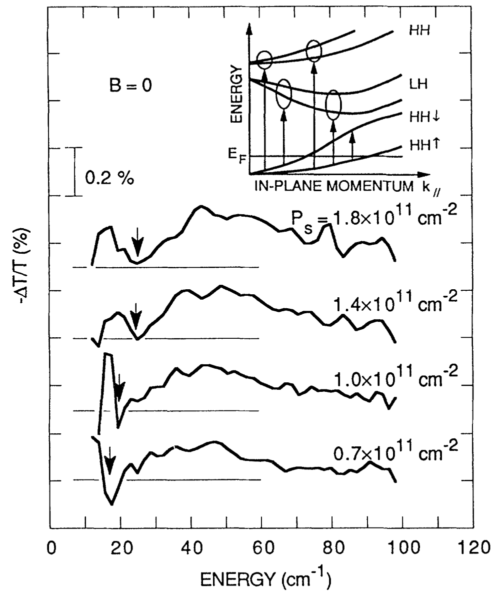

FIG. 4. Intersubband absorption spectra measured at $B=0$ for various 2D hole densities. Arrows show the energy positions of $\hbar\omega_{min}$. The inset shows a schematic illustration of the 2D hole subband dispersions and the intersubband transitions.

the direction normal to the interface.[25] If we substitute m_{HH} and m_{LH} for m_3 for HH and LH subbands, respectively, the energy separation between these two subbands, ΔE_0, can be roughly given as $\Delta E_0 \propto [(1/m_{LH})^{1/3} - (1/m_{HH})^{1/3}]P_s^{2/3}$. This dependence is close to the dependence of $\hbar\omega_0$ on P_s, which further supports our interpretation.

In summary, we studied the far-infrared CR of high-mobility 2D holes in (311)A $Al_xGa_{1-x}As/GaAs$ single interface heterojunctions. We have determined the cyclotron effective mass for the lowest heavy-hole Landau level at $B=5$ T to be $0.36m_0$–$0.37m_0$ for $P_s \leq 1.4\times10^{11}$ cm^{-2}, in agreement with theoretical calculations for the (100) orientation. Furthermore, we observed an anomalous anticrossing behavior in the CR spectra for Landau-level filling factor $\nu<1$. By comparing the CR spectra with the intersubband transition spectra measured at $B=0$, we are able to identify the origin of the anomalous CR line splitting as a crossing of the Landau levels associated with the heavy-hole and light-hole subbands.

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