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Interaction of above-Fermi-edge magnetoexciton states from different subbands in dense two-dimensional electron magnetoplasma

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Photoluminescence spectra from δ-doped n-type $\mathrm{Al}_y\mathrm{Ga}_{1-y}\mathrm{As}/\mathrm{In}_{1-x}\mathrm{Ga}_x\mathrm{As}/\mathrm{GaAs}$ quantum wells have been investigated in magnetic fields $H \leq 14$ T and $T = 1.8$–18 K. The Fermi level of the quasi-two-dimensional electron gas E_F was slightly below the second subband. Interband Landau-level (LL) transitions between the j_eth electron LL ($j_e = 1,2$) and the first hole LL, j_e-1_h, were analyzed. Their intensity was found to increase anomalously when the transition energy intersected that of the magnetoexciton state involving the electron from the second subband, 0_e^2-0_h. The intensity of the 0_e^2-0_h line oscillated with magnetic field and its maxima coincided with the intersection between the 0_e^2-0_h energy and either the j_e-0_h or j_e-1_h transitions or both of them, depending on the energy separation between E_F and the second subband. Taking into account that the j_e-1_h and 0_e^2-0_h transitions involve no common particle, the anomalous behavior is explained by the interaction between two magnetoexciton states, 0_e^2-0_h and j_e-1_h.

I. INTRODUCTION

Coulomb effects in a dense quasi-two-dimensional electron gas (2DEG) have attracted much attention during the last decade.[1–15] Modulation-doped quantum wells (MDQW's) provide a nearly ideal system for study of many-body phenomena, such as band-gap renormalization, magneto-optical oscillations, exciton screening at high densities, and Fermi-edge singularities. The excitons in photoexcited MDQW's can be formed between empty hole subband and occupied ground or empty second-electron subbands. The binding energy of the exciton states with the electrons from the first $n_z = 1$ subband decreases with 2DEG density. There are two reasons for this. First, the electrons screen the Coulomb potential and, second, they fill the low-energy band-edge states and leave only the states near Fermi energy for exciton formation.[2,3] These effects suppress the excitonic correlations, but are not sufficient to remove them completely,[1–10] in contrast to the 3D case. In a dense 2DEG the first subband exciton state transforms into a Fermi-edge singularity or Fermi-edge exciton states.[3,6,7]

Excitonic effects are strongly enhanced for states including an electron from an empty second subband.[2,4,8–10] This is primarily connected to the absence of the band-edge filling effect. The excitonic behavior of such states has been demonstrated in previous magnetoluminescence studies.[8,13]

In general, a magnetic field normal to the QW plane transforms the 2D electron system into a quasi-0D one that leads to enhancement of effects related to Coulomb interaction. Recent magnetoluminescence studies of a 2DEG with its Fermi energy close to the second-electron subband have shown a strong increase of the intensity of dipole-forbidden j_e-0_h $(j > 1)$ transitions near their intersection with an allowed 0_e^2-0_h one.[8,13] Here j denotes the Landau-level (LL) number, the superscript 2 indicates the second subband, and e and h correspond to the electron and hole states, respectively. The observed effect was connected with the mixing of electron states in the Coulomb potential of a 0_h hole, which is common in the considered transitions.[8,13,14]

In the present paper we discuss anomalous behavior of the j_e-1_h ($j = 1$ and 2) transitions that occurs near the 0_e^2-0_h recombination energy. In contrast to the case of the resonance of the j_e-0_h and 0_e^2-0_h energies, the transitions we studied do not contain any common electron or hole. Nevertheless, we observed a strong resonant enhancement of the j_e-1_h transition intensity. Such a behavior can hardly be explained in terms of a resonance free-particle scattering. It can be described in terms of an interaction of the j_e^1-1_h^1 and 0_e^2-0_h^1 magnetoexciton states which are at or above the Fermi edge.

II. EXPERIMENT

We have investigated the magnetoluminescence of n-type $\mathrm{Al}_y\mathrm{Ga}_{1-y}\mathrm{As}/\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}/\mathrm{GaAs}$ MDQW's with $x = 0.13$, $y = 0.25$, and $L = 250$ Å (sample $A1$), and $x = 0.15$, $y = 0.3$, and $L = 200$ Å (sample $A2$) grown by solid source molecular-beam epitaxy. The Si δ-doped layer was separated from the QW layer by a 40-Å-thick undoped $\mathrm{Al}_y\mathrm{Ga}_{1-y}\mathrm{As}$ spacer layer. This provided an electron concentration in the QW and 2×10^{12} cm^{-2} in samples $A1$ and $A2$, respectively. Samples of $\sim200\times200$ μm^2 were placed inside of a high-pressure cell with diamond anvils. The hydrostatic pressure was used to control the electron density and hence the position of the Fermi level with reference to the bottom of the second subband.[15] The high-pressure cell was located in a liquid-He cryostat with superconducting solenoid. The sample was excited with light from a He-Ne laser. A 0.6-mm quartz fiber was used both to excite the sample and to collect the photoluminescence (PL) signal. The PL light was dispersed by a grating monochromator and recorded with a cooled photomultiplier. The excitation power was smaller than 10 mW/cm^2 and did not change the equilibrium 2D electron density.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. PL spectra of the samples in the absence of magnetic field

We investigated the LL transitions between the first subbands near the excitonic transition including an electron in the empty second subband. Their behavior was found to depend strongly on the energy gap between the 2DEG Fermi level E_F and the second subband (see the inset in Fig. 1). To control this gap we used a hydrostatic pressure that changed the carrier concentration in the QW through the variation of the mutual position of Γ and X valleys in a Si-doped Al$_y$Ga$_{1-y}$As layer. When the X valleys approach the Γ minimum with a pressure, the Si donor states transform into highly bound states and capture electrons resulting in a decreased 2DEG density in the QW.

The influence of the pressure is illustrated in Fig. 1, which displays the 2DEG luminescence spectra recorded from the same sample Al at three values of the hydrostatic pressure, $P=21$, 23, and 25 kbar. At 21 kbar the Fermi level coincides with the second subband, resulting in a strong emission line $S2$ from it. The emission band $S1$ from the first subband with a large (about 30 meV) width, reflecting the large 2DEG Fermi energy, is much weaker due to a smaller matrix element. The width of the $S1$ line becomes smaller with the pressure, indicating a decreased 2DEG concentration. In addition, the lowering of the Fermi level as compared to the second subband causes a strong decrease of the emission from it, peak $S2$.

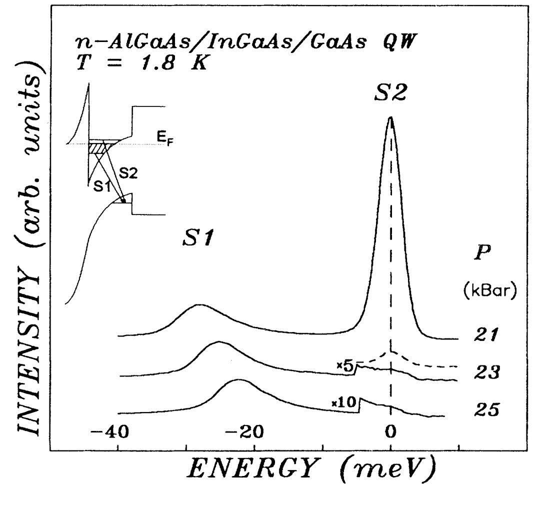

FIG. 1. PL spectra from a 25-nm-thick QW in an n-Al$_{0.25}$Ga$_{0.75}$As/In$_{0.13}$Ga$_{0.87}$As/GaAs heterostructure at 1.8 K for different hydrostatic pressures. The energy is calculated from the second subband emission line. The dotted line for $P=23$ kbar corresponds to 8 K. The inset illustrates the bands and transitions in the MDQW's.

B. PL spectra from 2DEG in magnetic field

Figure 2 shows photoluminescence spectra from 2DEG in a magnetic field recorded from sample $A1$ at 1.8 and 18 K (inset) for $P=23$ kbar. The spectra consist of a few emission lines corresponding to transitions between different Landau levels (LL's) in the conduction (j_e) and valence (j_h) bands. The dipole-allowed 0_e-0_h transition dominates in the spectra both at 1.8 and 18 K. The transitions j_e-0_h observed at 1.8 K involve occupied electron LL's j_e. They are dipole forbidden and appear in the spectrum mainly due to impurity scattering.[13] The emptying of the excited electron LL's with magnetic field results in the subsequent disappearance of these emission lines.

In addition, Fig. 2 shows that in the range of magnetic fields $H=6$ and 10 T there appears a strong emission in the spectrum near the Fermi edge. We denoted the cor-

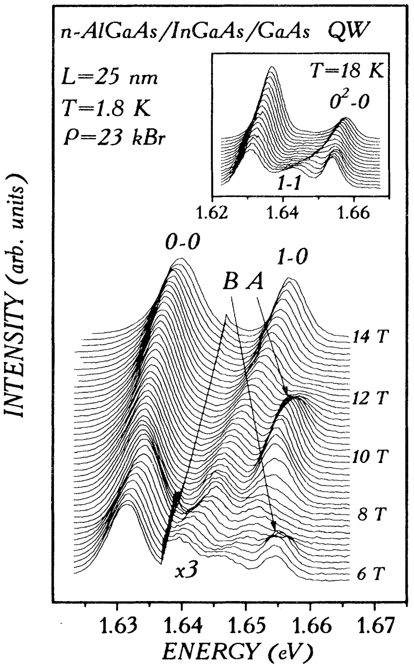

FIG. 2. PL spectra from a 25-nm-thick n-Al$_{0.25}$Ga$_{0.75}$As/In$_{0.13}$Ga$_{0.87}$As/GaAs QW at 1.8 K and $P=23$ kbar for different magnetic fields applied perpendicularly to the QW. In the inset, PL spectra at 18 K from 5.8 to 11.8 T in 0.4 T are shown.

responding emission lines as B and A, respectively. The energy of these transitions are very close but do not coincide with the energy of the 0_e^2-0_h transition. The latter can be observed at elevated temperatures, as illustrated in the inset in Fig. 2. It shows that with increased temperature the dipole-allowed 1_e-1_h and 0_e^2-0_h transitions become dominating in the spectrum due to the thermal filling of the excited hole and electron LL's.

Figures 3–5 display the dependences of the transition energies and intensities in samples $A1$ and $A2$ for a few hydrostatic pressures. In Fig. 3(a) the transition energies and intensities for sample A1 at a hydrostatic pressure $P=25$ kbar and $T=1.8$ K as a function of magnetic field are shown. In this case the electron Fermi level E_F is located several meV below the second subband. The 0_e^2-0_h emission intensity at 1.8 K is very weak, indicating a short relaxation time of photoexcited electrons from the second to the ground subband. Therefore, we were able to determine the 0_e^2-0_h transition energy only at small magnetic fields, $H \leq 2$ T, when the emission band from the first subband had no pronounced structure. To determine it at higher values of H, we used the spectra recorded at elevated (8–18 K) temperatures. The dependence found in this way is displayed by the dashed line in Fig. 3(a).

The behavior of the transition energies 0_e-0_h and 1_e-0_h

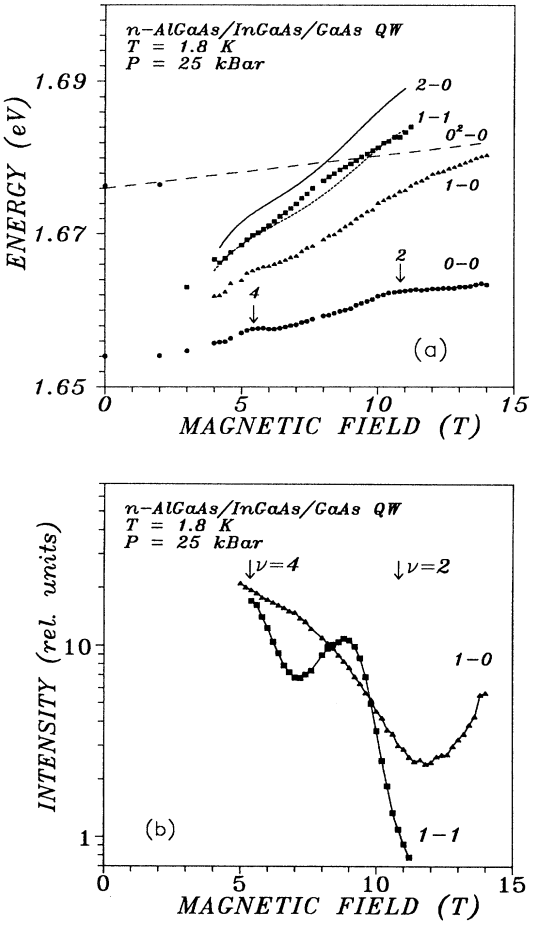

FIG. 3. (a) Transition energies as a function of the magnetic field for a 25-nm-thick n-$Al_{0.25}Ga_{0.75}As/In_{0.13}Ga_{0.87}As/GaAs$ QW at 1.8 K and a pressure of 25 kbar. The dashed line indicates the spectral position of the 0_e^2-0_h transition obtained from measurements at 10 K. The solid and dotted lines show calculated transition energies for the 2_e-0_h and 1_e-1_h transitions, respectively. Arrows indicate magnetic fields corresponding to the filling factors 2 and 4. (b) Luminescence intensity of the 1_e-0_h and 1_e-1_h transitions as a function of magnetic field for the 25-nm-thick n-$Al_{0.25}Ga_{0.75}As/In_{0.13}Ga_{0.87}As/GaAs$ QW at 1.8 K and $P=25$ kbar. Arrows indicate magnetic fields corresponding to the filling factors 2 and 4.

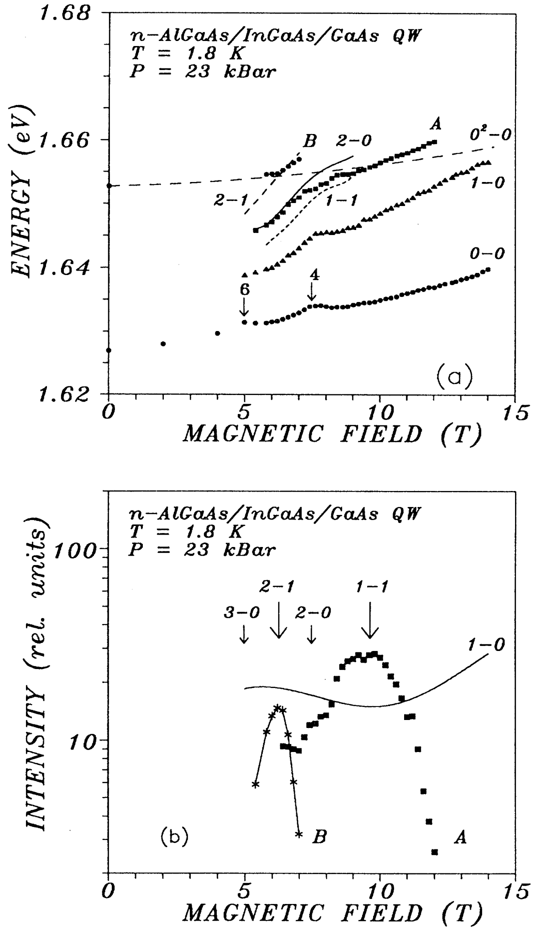

FIG. 4. (a) Transition energies as a function of the magnetic field for the 25-nm-thick n-$Al_{0.25}Ga_{0.75}As/In_{0.13}Ga_{0.87}As/GaAs$ QW at 1.8 K and $P=23$ kbar. The dashed lines indicate the spectral position of the 0_e^2-0_h and 1_e-1_h transition obtained from measurements at higher temperatures. The solid line 2-0 and the dotted line 2-1 show calculated transition energies for the corresponding transitions. The arrows indicate magnetic fields for the filling factors 4 and 6. (b) Dependence of the intensity of the lines 1_e-0_h, A, and B on the magnetic field for the 25-nm-thick n-$Al_{0.25}Ga_{0.75}As/In_{0.13}Ga_{0.87}As/GaAs$ QW at 1.8 K and $P=23$ kbar. The arrows indicate magnetic field corresponding to the resonance of the j_e-1_h and the 0_e^2-0_h transition energies (long arrows) and that of the j_e-0_h and 0_e^2-0_h energies (short arrows).

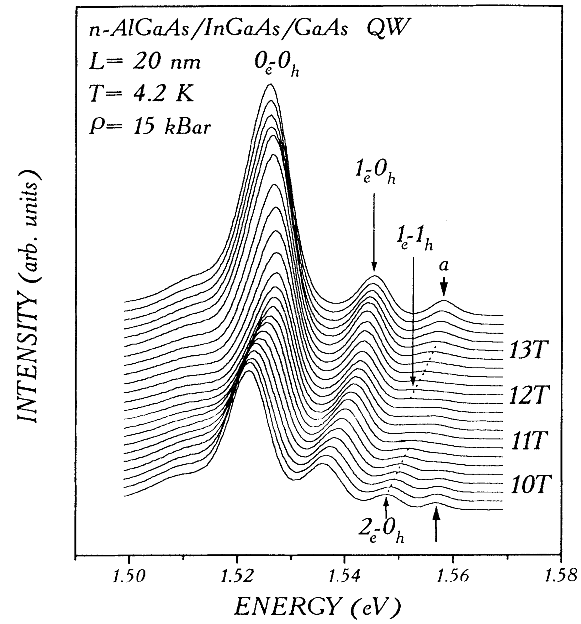

FIG. 5. PL spectra from a 20-nm-thick n-$\mathrm{Al_{0.3}Ga_{0.7}As/In_{0.15}Ga_{0/85}As/GaAs}$ QW at 4.2 K and $P=15$ kbar for different magnetic fields applied perpendicularly to the QW. The arrow a indicates the 0_e^2-0_h energy.

in Fig. 3(a) is typical of a 2DEG with one filled subband. They increase with H, similar to the electron and hole cyclotron energies ($\omega_{\mathrm{ce},h} \sim H$) and, in addition, oscillate weakly near the position of the corresponding LL energies. The latter is connected with an oscillation of the exchange and correlation energies.[9] Figure 3(a) displays one more line shown by solid squares. It is well below the expected position of the 2_e-0_h transition (shown by a solid line) but instead coincides very well with that expected for the 1_e-1_h transition (dotted line).[16] A small deviation of the observed transition energy from the calculated one near 7.5 T might be an influence from the 2_e-0_h transition.

More information can be obtained from studies of the emission line intensities. Figure 3(b) displays the intensity of the 1_e-0_h and 1_e-1_h transitions at $H=5.4$–10.8 T, when 1_e is the uppermost LL occupied by equilibrium electrons. As shown, the intensity of the 1_e-0_h transition decreases monotonically up to 11 T because of the 1_e LL emptying. For $H>11$ T the equilibrium electrons remain only in zero LL. In this range the 1_e-0_h emission is connected with photoexcited electrons. Therefore one can expect that its intensity decreases monotonically with H because the electron relaxation time shortens with increasing number of empty places in the zero LL. Such behavior is typical for samples with a large separation between E_F and the $n_z=2$ subband. In contrast, Fig. 3(b) shows that the 1_e-0_h line increases strongly at $H>12$ T when it approaches the 0_e^2-0_h transition energy. A similar behavior has been observed earlier[8,13] in the sample with the small gap between E_F and the $n_z=2$ subband. It was connected with mixing of electron states from 1_e and 0_e^2 LL's by the Coulomb field from the 0_h hole state.[8,13,14] The admixture of the 0_e^2 states results in a strong enhancement of the 1_e-0_h emission line in spite of decreasing electron concentration in the first LL. This occurs because the oscillator strength for the allowed 0_e^2-0_h transition is more than two order of magnitude larger.

Next we discuss the behavior of the dipole allowed 1_e-1_h transition intensity. Figure 3(b) shows that it also demonstrates an anomalous behavior at 6–11 T. As mentioned above, in this range of H the first electron LL is partially filled with equilibrium electrons, whereas the first hole LL is occupied only with nonequilibrium photoexcited holes. At 5 T the intensities of the dipole-allowed 1_e-1_h and forbidden 1_e-0_h lines are comparable to each other. Note that the hole concentration in the 1_h LL is much smaller than for 0_h. The difference in concentration between the 1_h and 0_h holes is nearly compensated for by the higher magnitude of the oscillator strength for the dipole-allowed transition. With magnetic fields the intensity of the 1_e-1_h line decreases because of reduced electron concentration in the 1_e LL (similar to the 1_e-0_h transition) and, in addition, because of reduced concentration of holes in the excited 1_h level (as a result of increased LL splitting). We observed such normal behavior over the whole range of magnetic field in samples with a large electron subband splitting. However, Fig. 3(b) displays another behavior. The 1_e-1_h emission decreases with H only for $H<7$ T and $H>10$ T. In the intermediate range there is an enhanced intensity with a maximum at ~ 9 T. A comparison of Figs. 3(a) and 3(b) shows that this corresponds to the resonance between the 1_e-1_h and 0_e^2-0_h transition energies.

Figure 4 illustrates the behavior of the emission lines with a slightly decreased separation between the Fermi level and the second subband (sample $A1$, $P=23$ kbar, cf. Fig. 1). We have found that in this case the intensity of the dipole-forbidden 1_e-0_h transition increases, and demonstrates a well-pronounced anomalous behavior near the second subband, as reported earlier[8,13] (cf. Fig. 2, $H=10$–14 T). As shown in Fig. 2 we did not succeed in spectrally resolving the 1_e-1_h line in the whole range of magnetic field because of the influence of the 2_e-0_h emission line. (The relative intensity of the 2_e-0_h line at $P=23$ kbar is markedly larger than at $P=25$ kbar, which is connected with increased filling of the second LL due to the higher electron density of a 2DEG.) However, the 1_e-1_h line was well pronounced near the resonance with the 0_e^2-0_h transition. The 0_e^2-0_h transition energies, shown by a dashed line, were again determined from measurements at elevated temperature. Figure 4(a) shows that variation of the 0_e-0_h and 1_e-0_h energies are quite similar to those in Fig. 3(a).

The line marked A cannot be assigned to one single transition. It is seen from Figs. 2 and 4(a) that it corresponds to the 2_e-0_h transition in the range of $H=5$–7 T. The second LL loses its equilibrium electrons with magnetic field, and we see that line A shifts to the position of the dipole-allowed 1_e-1_h transition. As shown in the inset in Fig. 2, the intensity of the 1_e-1_h emission line increases strongly with temperature. Therefore we have used the measurements at $T=12-15$ K to determine the magnetic-field dependence of the 1_e-1_h transition energy in a wide range of $H=5-12$ T. The result is shown in Fig. 4(a) by dotted line. Thus we can conclude that line A is due mainly to the 2_e-0_h transition at small H, and to the 1_e-1_h transition at high H, whereas in the intermediate range $H=7.5-10$ T both of them contribute.

Line B appears in the spectrum within a very narrow interval, 6–8 T. Its spectral position is rather far from that expected from either the 3_e-0_h or 2_e-2_h transitions.[16] It can be best fitted to the forbidden 2_e-1_h transition, i.e., between the partially filled 2_e LL having nonequilibrium holes.

Figure 4(b) displays the intensity variation of lines A and B with magnetic field at 1.8 K. As shown, line A has a strong maximum at $H \sim 9.5$ T, approximately coinciding with the intersection of the 0^2_e-0_h and 1_e-1_h energies. In addition, it has a well-pronounced shoulder at smaller fields (~ 7.5 T) that is near the intersection of the 0^2_e-0_h and 2_e-0_h transitions. This intensity variation indicates two things. First, it supports the previously discussed complex nature of line A and, second, both the 1_e-1_h and 2_e-0_h transition intensities are strongly enhanced near the 0^2_e-0_h energy. Further, Fig. 4(b) shows a well-pronounced resonance behavior of the intensity of line B. Its sharp maximum at $H \sim 5.7$ T corresponds to the intersection of the 2_e-1_h and 0^2_e-0_h transitions. Note that the dipole-forbidden 2_e-1_h transition is not seen in the spectrum far from resonance with the 0^2_e-0_h one.

Thus Fig. 4(b) indicates that the intensity of both the j_e-0_h and j_e-1_h lines increases resonantly near the 0^2_e-0_h transition energy. A similar behavior was found as well in another sample $A2$ with a 200-Å-thick QW. In this sample E_F is even closer to the second subband than in the previously considered cases. In addition, due to smaller QW width the subband splitting is larger and the intersection of the 1_e-1_h and 0^2_e-0_h transition energies occurs at $H \sim 13$ T (cf. Fig. 5). This allows us to observe several oscillations in the emission intensity in the spectral range of the 0^2_e-0_h transition. They are shown in Fig. 6 as a function of the subband splitting to electron cyclotron energy ratio $\Delta_{12}/\hbar\omega_{ce}$. First are observed well pronounced peaks originating from the j_e-0_h transitions located at integer values of $\Delta_{12}/\hbar\omega_{ce}$. In addition, Fig. 6 displays well-pronounced maxima at $\Delta_{12}/\hbar\omega_{ce} \sim 1.5$ and 2.5. They coincide with the intersections of the 0^2_e-0_h transitions with 1_e-1_h and 2_e-1_h, respectively.

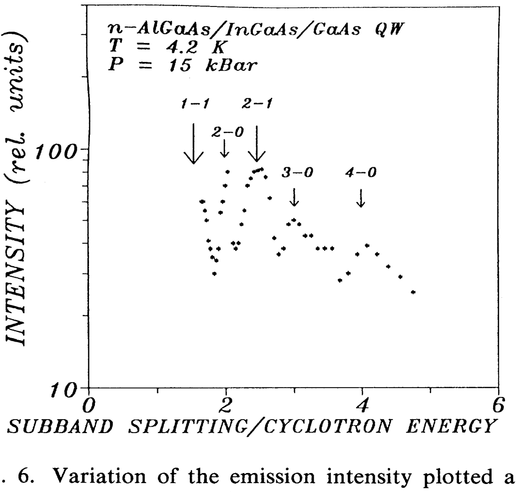

FIG. 6. Variation of the emission intensity plotted against the ratio between the subband splitting and electron cyclotron energy in the spectral range of the 0^2_e-0_h transition for the 20-nm-thick n-$\mathrm{Al_{0.3}Ga_{0.7}As/In_{0.15}Ga_{0.85}As/GaAs}$ QW at 4.2 K and $P=15$ kbar. Short arrows at integer values correspond to the intersection of the j_e-0_h and 0^2_e-0_h transition energies, whereas the long arrows indicate the same for the j_e-1_h and 0^2_e-0_h energies.

C. Discussion

The j_e-1_h and 0^2_e-0_h transitions involve neither common electron nor hole, and the resonance energy does not coincide with any intersection of LL's in the conduction band. Therefore, the anomalous behavior of the j_e-1_h intensities shown in Figs. 3, 4, and 6 cannot be explained by the mixing of electron states from crossing LL's from the $n_z=1$ and 2 subbands in the presence of the hole Coulomb potential. In addition, there is no reason for a strong decrease of relaxation of photoexcited holes from the first LL. In contrast, such an energy resonance should lead to an increased scattering of holes from the 1_h to 0_h LL's with simultaneous excitation of the j_e electron into the second subband state 0^2_e. This process can increase the emission intensity if the 0^2_e electron relaxation time is long enough. As a result, an increase of the 0^2_e-0_h rather than the j_e-1_h emission line is expected when the coupling between the j_e-1_h and 0^2_e-0_h states is neglected. This, however, does not agree with experimental data shown in Figs. 3(a) and 4(a). The energy dependences of the observed emission line indicate strongly that we deal with j_e-1_h transitions.

Therefore we suggest that the observed effect is due to the coupling of two magnetoexciton states. In this case the j_e-1_h transition probability increases near the intersection of the j_e-1_h and 0^2_e-0_h energies due to an admixture of the 0^2_e-0_h magnetoexciton state with a high oscillator strength. Such an explanation implies that not only the 0^2_e-0_h transition but also j_e-1_h involving an electron from the filled first subband are excitonic rather than between free particles. The excitonic nature of the considered j_e-1_h transitions can be expected.[17–21] In most details the possible nature of interband LL transitions was discussed in Ref. 17. The j_e-1_h transitions satisfy the main conditions for excitonic transitions. First, they involve the electron from the Fermi-edge Landau level and therefore are stable and, second, the screening of the Coulomb potential is strongly quenched by the magnetic field.

In general, photoluminescence excitation spectra (PLE) give direct information about the coupled excitonic states since they are less influenced by relaxation processes in QW's. Therefore we made an attempt to find an anticrossing of the j_e-1_h and 0^2_e-0_h levels in the PLE spectra but did not reach any definite answer because of the large half-width of the spectral lines. We did not find two spectrally resolved lines, but observed a marked broadening of the strong 0_e^2-0_h transition at the resonant magnetic fields. Note that the broadening of this transition occurs when it intersects the transitions with an oscillator strength more than order of magnitude smaller. We suppose that such a behavior indicates that the j_e-1_h and 0_e^2-0_h levels are not independent.

IV. CONCLUSION

Low-temperature magnetoluminescence studies of n-$\mathrm{Al}_y\mathrm{Ga}_{1-y}\mathrm{As}/\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}/\mathrm{GaAs}$ MDQW's with a quasi-2D electron-gas Fermi level slightly below the second subband have revealed an anomalous behavior of the emission line intensities near the resonance of transition energies from the first and second subbands. We observed a strong increase of the emission intensity of the interband transitions involving both the zero and the first hole LL states. In addition, we investigated the change of emission intensity in the spectral range of the 0_e^2-0_h transition. It oscillates with magnetic field, and the maxima coincided with an intersection of the 0_e^2-0_h energy by either the j_e-0_h or j_e-1_h transitions, or both of them, depending on the energy separation between the 2DEG Fermi level and the second subband. The increase of the intensity of the dipole-forbidden j_e-0_h $(j>1)$ transitions when they intersect an allowed 0_e^2-0_h one was observed earlier.[8,13] It was connected with the mixing of electron states in the Coulomb potential of a hole which is common in the considered transitions.[8,13,14] Here we discuss the anomalous behavior of the j_e-1_h transitions which have no common particle with the 0_e^2-0_h transition. We found this behavior to be connected with an interaction of above-Fermi-edge magnetoexciton states from different subbands in a dense 2D electron magnetoplasma. This interpretation implies that the j_e-1_h transitions are excitonic rather than between free particles, despite the high density of equilibrium electrons in the first subband. The excitonic nature of the considered j_e-1_h transitions can be expected, as they involve the electron from the Fermi-edge Landau level, and the screening of the Coulomb potential is strongly quenched by magnetic field.[17–21]

ACKNOWLEDGMENTS

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