# Spin-splitting renormalization in the neutral dense magnetoplasma in $In_xGa_{1-x}As/InP$ quantum wells

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Photoluminescence spectra of the neutral dense ($n_{eh}<2\times10^{12}$ cm$^{-2}$) magnetoplasma photoexcited in $In_xGa_{1-x}As/InP$ single quantum wells have been investigated in $\sigma^+$ and $\sigma^-$ polarizations. Fine structure of Landau-level transitions has been observed which is caused by the mixture of hole-spin states. A considerable enhancement of electron and hole spin splittings of the zero and first Landau levels arises when the uppermost occupied Landau levels with different spins are unequally filled. An explanation is offered in terms of the exchange inter-Landau-level interactions.

## I. INTRODUCTION

Many-body interactions in neutral dense magnetoplasmas in semiconductor quantum wells (QW's) lead to a series of renormalization effects.[1] Recently, the renormalization of band gap,[2] carrier effective masses,[3,4] and subband splitting[3,4] were investigated in the $In_xGa_{1-x}As$ and GaAs QW's by optical spectroscopy. Here we are interested in the renormalization of the spin splitting of the electron and hole Landau levels in neutral quasi-two-dimensional (2D) magnetoplasmas.

Earlier, the renormalization of the spin splitting was investigated both experimentally[5–11] and theoretically[12] for the 2D electron gas (2DEG). In particular, a strong enhancement of the spin splitting for the uppermost occupied Landau level (LL) has been found in optical studies of the 2DEG in Si metal-oxide-semiconductor field effect transistors (MOSFET's) and $Al_xGa_{1-x}As/GaAs$ QW's with different filling of spin states. It is connected with the difference in the many-body self-energy appearing due to the difference in the intra-Landau-level interaction of particles with identical and opposite spins. This enhancement manifests itself as a spectral shift of the transition energies,[8,9] a striking temperature dependence of the optical absorption,[10] and a change of the degree of polarization,[11] and is most pronounced at odd filling factors.

In the case of neutral e-h magnetoplasma in symmetrical QW's, the changes in the spin splitting due to the intra-Landau-level interaction cannot be observed in the photoluminescence (PL) spectra because of the identity of the electron-electron and electron-hole interaction.[13] Therefore, in contrast to the phenomenon observed in the 2DEG, in this case the main contribution to the spin-splitting renormalization observable in PL is due to the inter-Landau-level interaction.

## II. EXPERIMENT

We have measured $\sigma^+$ and $\sigma^-$ components of PL spectra from a neutral magnetoplasma photoexcited in undoped $InP/In_{0.53}Ga_{0.47}As/InP$ single-QW structures. The structures with QW width $L_z=15$ and 19 nm were grown by low-pressure MOVPE.[2] The sample was located in the superfluid liquid He. Nonequilibrium carriers were excited with a cw $Ar^+$-ion laser ($\lambda=514.5$ nm). To realize high and homogeneous e-h densities by the cw $Ar^+$-ion laser excitation, we have defined mesa structures in the QW plane with dimensions $50\times50$ $\mu$m and used the lasers plot exceeding the mesa size. The mesas were prepared by optical lithography and dry etching. The lateral confinement in the small mesas makes it possible to reach very high densities of about $5\times10^{12}$ cm$^{-2}$ for laser powers of 1 W.

In the considered range of e-h density ($n_{eh}<2\times10^{12}$ cm$^{-2}$), the electron temperature of photoexcited carriers[14] did not exceed $T_e=30-50$ K. This was smaller than the electron and hole spin splitting at a magnetic field $H\sim8$ T used for the study and allowed us to realize a magnetoplasma with markedly different filling of the spin sublevels.

## III. SPIN SPLITTING OF LANDAU LEVELS

Figure 1 shows the emission spectra of the $In_{0.53}Ga_{0.47}As/InP$ single QW at bath temperature $T_{bath}=2$ K and $H=8.65$ T for three carrier densities $n_{eh}=1$, 4.2, and $11\times10^{11}$ cm$^{-2}$. The spectra are presented in the same scale. The dashed and solid lines represent the spectra in $\sigma^+$ and $\sigma^-$ polarizations, respectively. The number of emission lines in the spectra increases with the carrier density in accordance with the number of occupied LL's. (The density of states at one LL at $H=8.65$ T is equal to $2.08\times10^{11}$ cm$^{-2}$.) It was found from the photoluminescence excitation measurements that the light-hole (LH) and heavy-hole (HH) subband splitting in the 15-nm QW is about 25 meV. Therefore, only the lowest (HH) subband[2,3] is occupied at $n_{eh}<5\times10^{12}$ cm$^{-2}$. For small $n_{eh}$, in both $\sigma^+$ and $\sigma^-$ polarizations there is one emission line which corresponds to the radiative recombination of the 0-0 magne-

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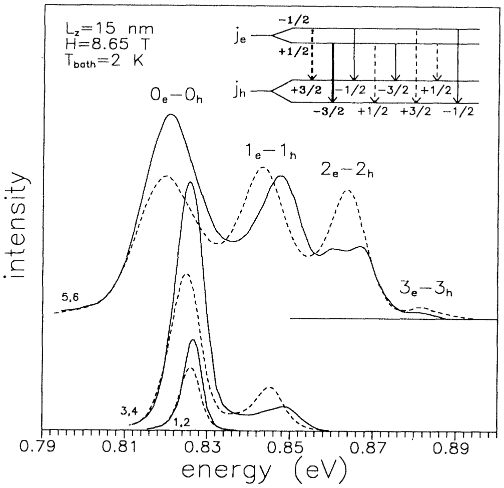


FIG. 1. The emission spectra of a $In_{0.53}Ga_{0.47}As/InP$ single QW in $\sigma^+$ (dashed lines) and $\sigma^-$ (solid) polarizations at $H=8.65$ T for $n_{eh}=10^{11}$ cm$^{-2}$ (curves 1 and 2), $4.2\times10^{11}$ cm$^{-2}$ (3 and 4), and $1.1\times10^{12}$ cm$^{-2}$ (5 and 6). Excitation densities are 10, 50, and 300 W/cm$^{-2}$, respectively. All spectra are presented in the same scale. Inset: The scheme of possible optical transitions in $\sigma^+$ (dashed arrows) and $\sigma^-$ (solid) polarizations for the $j$th Landau level.

toexcitons consisting of the electron and the hole in the lowest LL's ($j_e=j_h=0$). At higher density, new lines appear in the emission spectra corresponding to allowed ($j_e=j_h$) transitions between the occupied LL's. The saturation of the $j$-$j$ emission-line intensities at high $n_{eh}$ indicates the complete filling of the $j$th electron and hole LL's. The plasma densities were determined by the filling of the LL's which is directly given by the number of emission lines as the oscillator strength of the different Landau-level transitions was calculated to be independent of LL number and plasma density.[15] The electron temperature of photoexcited carriers was estimated from the ratio of the emission-line intensities for large values of $j_{e,h}$.

To identify spin sublevels involved in the observed transitions, the spin wave functions of particles in different sublevels should be considered. Electron LL's are split into two sublevels with spin projection $s=+\frac{1}{2}$ (lower) and $-\frac{1}{2}$ (upper).[16] Heavy-hole LL's are also split into two sublevels $j^+$ and $j^-$. Just near the band edge, they consist mainly of $m=+\frac{3}{2}$ and $-\frac{3}{2}$ spin states, respectively.[17] However, in contrast to the electron ones, in these states there is an essential admixture of other spin states with $m=\pm\frac{1}{2}$ and $\pm\frac{3}{2}$ which increases with magnetic field and LL number.

The scheme of the optical transitions in magnetic field is shown in the inset of Fig. 1. For pure $m=+\frac{3}{2}$ and $-\frac{3}{2}$ states, there is only one allowed optical transition in $\sigma^+$ and $\sigma^-$ polarizations, respectively, for each LL (shown by the thick dashed and solid lines in Fig. 1). An admixture of other spin states in the hole LL should result in the appearance of additional transitions. These are shown in the scheme by thin solid ($\sigma^-$) and dashed ($\sigma^+$) lines.

Figure 1 shows that in the case of the 0-0 transition, there are observed one $\sigma^+$ and one $\sigma^-$ emission line which correspond to allowed transitions. The relative intensities of these lines change slightly with increased excitation density. However, they remain markedly different even in the case when both spin sublevels are completely filled (c.f. curves 3 and 4 or 5 and 6 in Fig. 1). It indicates that the $j=0$ LL states are not pure $\pm\frac{3}{2}$ ones. The weight of admixed spin states seems to be not too large as there are no additional resolved lines in the emission spectra.

The resolved multiplet structure for the inter-Landau-level transition due to mixture of hole-spin states appears in the case of 1-1 and 2-2 transitions. This is illustrated in Fig. 2 which shows the pairs of $\sigma^+$ and $\sigma^-$ emission spectra from a 15-nm QW for excitation densities corresponding to the beginning of the filling of the first LL. Curves 1 and 2 correspond to the filling factor of the first LL, $\nu_1\approx0.02$, the curves 3 and 4 correspond to $\nu_1\approx0.05$, and 5 and 6 to $\nu_1\approx0.15$. The multiplet structure is clearly observed both in $\sigma^+$ and $\sigma^-$ polarizations at small filling of the first LL ($\nu_1=0.02$ and 0.05). For higher densities this structure disappears because of the marked broadening of the emission peaks. From the fine structure of the 1-1 emission line, both the electron and hole spin splitting have been determined: $\Delta_{e,1}=3\pm0.3$ meV ($g_e=-6\pm0.6$, which agrees with $|g_e|=5.6$ found earlier[18]) and $\Delta_{h,1}=6\pm0.3$ meV. The emission line broadening at higher LL filling smooths the spectrum. As a result, only one broad emission band is observed both in $\sigma^+$ and $\sigma^-$ polarizations at high filling of the first LL.

In the case of the 2-2 transition, there are three well-resolved emission lines—two in $\sigma^-$ and one in $\sigma^+$ polarizations which remain in the spectra up to the high filling of these LL's (c.f. curves 5 and 6 in Fig. 1). To identify these lines, we have measured the magnetic-field depen-

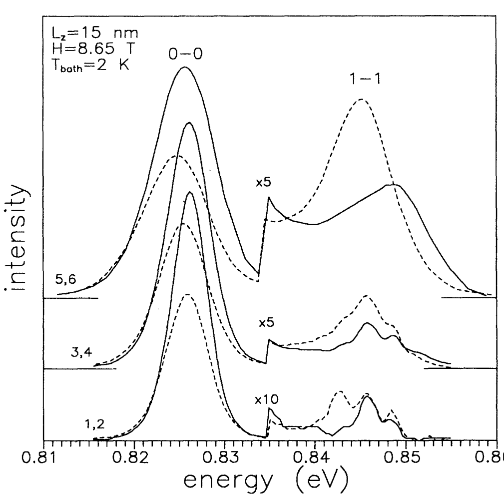


FIG. 2. The emission spectra of a $In_xGa_{1-x}As/InP$ QW in $\sigma^+$ (dashed lines) and $\sigma^-$ (solid) polarizations at $H=8.65$ T for the small filling of the first Landau level: $\nu_1=0.02$ (curves 1 and 2), 0.05 (3 and 4), and 0.15 (5 and 6). The scheme of 1-1 transition fine structure is presented in the inset of Fig. 1.

dence of the transition energies in the QW for different plasma densities. Figure 3 displays the dependence of LL transition energies in $\sigma^+$ (solid circles) and $\sigma^-$ (open circles) polarizations at $n_{eh}=6.7\times10^{11}$ cm$^{-2}$ for the 19-nm-thick QW. It clearly shows that there are three lines belonging to the 2-2 transition. The transitions between the LL's from the next, $n_z=1$ subband ($0^1$-$0^1$) have higher energy and essentially smaller slope. Note also that the weak $\sigma^-$ line cannot be assigned to the "forbidden" $2_e$-$1_h$ transition[19] as in this case we should suppose the electron mass to be $0.075m_0$ (here $m_0$ is free electron mass) which is too heavy.[3]

We attribute this $\sigma^-$ emission line with smaller energy (and smaller intensity) to the recombination of a $+\frac{1}{2}$ electron with a hole in the lower spin sublevel which occurs due to an admixture to the latter sublevel of the $m=-\frac{3}{2}$ spin state. The existence in the spectrum of three transitions allowed us to determine independently $\Delta_e$ and $\Delta_h$ for the second LL: $\Delta_{e,2}=3.5\pm0.3$ meV ($g_e=-7\pm0.6$), $\Delta_{h,2}=7\pm0.3$ meV. These are close to the values of $\Delta_{e,1}$ and $\Delta_{h,1}$ determined from the splitting of the first LL. Assuming $g_e$ independent of energy, we can also estimate the spin splitting of a zero hole LL: $\Delta_{h,o}\approx4.5$ meV. This value is smaller than $\Delta_{h,1}$ and $\Delta_{h,2}$, indicating strong dependence of the hole-spin splitting on LL number.

It would be interesting to follow the spin splitting of the LL's with $j>2$. However, in the investigated QW's this turns out to be impossible. At small magnetic fields ($H<5$ T) the spin structure of these transitions is not resolved because of the small spin splitting, whereas at higher fields the structure cannot be resolved because of the crossing of these levels with those from the next electric subband, as shown in Fig. 3.

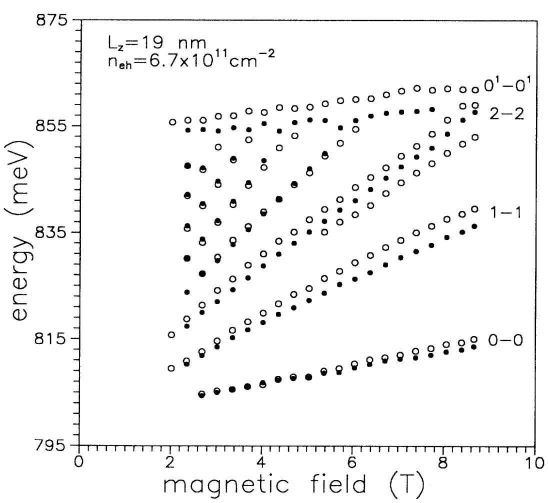


FIG. 3. Magnetic-field dependences of Landau-level transition energies in $\sigma^+$ (solid circles) and $\sigma^-$ (open circles) polarizations at $n_{eh}=6.7\times10^{11}$ cm$^{-2}$. $j$-$j$ transitions correspond to ground electric subbands and $0^1$-$0^1$ corresponds to that between the first excited subbands.

## IV. MANY-BODY RENORMALIZATION OF THE SPIN SPLITTING IN THE DENSE MAGNETOPLASMA

Figure 4 shows the density dependence of the optical transition energies between three lowest electron and hole LL's at $H=8.65$ T in $\sigma^+$ (solid circles) and $\sigma^-$ (open circles) polarizations. The figure shows that all transition energies remains approximately constant for the uppermost occupied LL ($\sigma^+$ and $\sigma^-$ transitions with the highest energy at fixed density). The energies of transitions between the filled LL's below the Fermi energy decrease with carrier density. Such a density dependence of the transition energies in the neutral magnetoplasma was found to be well described at low temperature in terms of magnetoexcitons.[13–15,20,21] The interaction of magnetoexcitons within one Landau level is repulsive at small distances $r<l_H$ ($l_H$ is magnetic length, which determines the magnetoexciton radius) due to the Pauli exclusion principle, and attractive at large distances due to the exchange interaction. In the magnetoplasma, these two contributions to the scattering amplitude cancel exactly in the high-magnetic-field limit and the magnetoexcitons can be considered as noninteracting.[13] However, the interaction between the magnetoexcitons in different LL's is attractive due to the strong suppression of the Pauli repulsion (as these magnetoexcitons are constructed from different momenta).[14,15,20,21]

In high magnetic fields the interaction between the electrons (holes) with different spins is small as compared to that from particles with the same spin. Therefore, in first approximation, the $i$-$i$ LL magnetoexcitons can cause a reduction of the $j$-$j$ LL magnetoexciton transition energy only if they contain the electron or hole with the same spin. As a consequence, any difference in the filling of the different spin states at one LL should result in the renormalization of the magnitude of the spin splitting at the other LL's.

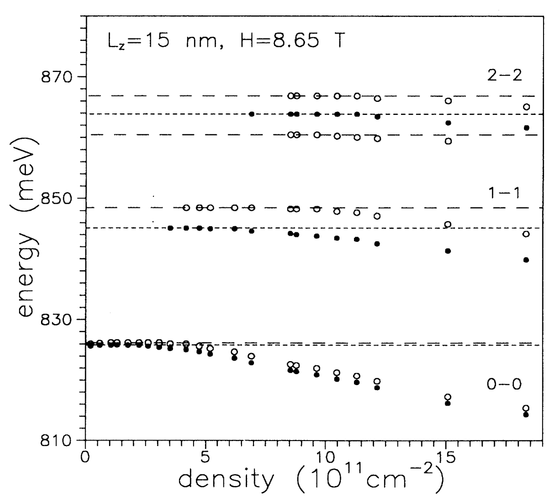


FIG. 4. Landau-level transition energies in $\sigma^+$ (solid circles) and $\sigma^-$ (open circles) polarizations at $H=8.65$ T as a function of $n_{eh}$.

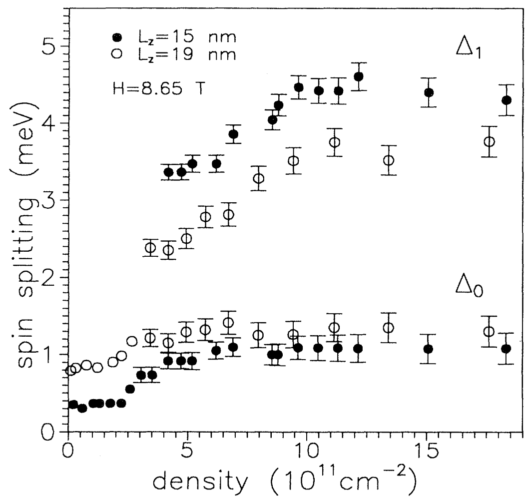


FIG. 5. Spin splitting ($\Delta_j = \Delta_{h,j} - \Delta_{e,j}$) renormalization for the zero and first Landau levels ($j=0$ and 1) at $H=8.65$ T as a function of carrier density.

In our experiments we observe the photoluminescence of the magnetoexcitons with electron and hole spins $s=+\frac{1}{2}$ and $m=-\frac{3}{2}$ or $s=-\frac{1}{2}$ and $m=+\frac{3}{2}$. They will be referred to as $\mathrm{ME}^i\,(+\frac{1}{2},-\frac{3}{2})$ and $\mathrm{ME}^i(-\frac{1}{2},+\frac{3}{2})$, respectively. The upper index denotes the LL number.

The population of $\mathrm{ME}^1(-\frac{1}{2},+\frac{3}{2})$ is larger than that of $\mathrm{ME}^1(+\frac{1}{2},-\frac{3}{2})$ because the electron-spin splitting is smaller than the hole one. In particular, this causes the higher intensity of the 1-1 ($\sigma^+$) emission line under conditions of partial filling of the first LL [under higher excitations when the first LL is filled, the integral intensities of the 1-1 ($\sigma^+$) and 1-1 ($\sigma^-$) lines are approximately equal]. The difference in the filling of the $\mathrm{ME}^1(-\frac{1}{2},+\frac{3}{2})$ and $\mathrm{ME}^1(+\frac{1}{2},-\frac{3}{2})$ states leads to an increasing difference in the energies of corresponding magnetoexcitons at zeroth LL – $\mathrm{ME}^0(-\frac{1}{2},+\frac{3}{2})$ (0-0-$\sigma^+$ transition) and $\mathrm{ME}^0(+\frac{1}{2},-\frac{3}{2})$ (0-0-$\sigma^-$ transition). The dependence of this energy difference $\Delta_0$ ($\Delta_0=\Delta_{\mathrm{h},0}-\Delta_{\mathrm{e},0}$) is shown in Fig. 5 for two investigated QW's with $L_z=15$ and 19 nm. It is seen that the magnitude of $\Delta_0$ does not depend on carrier density at $n_{\mathrm{eh}}<2.5\times10^{11}$ cm$^{-2}$ when only a 0-0 line is observed in the emission spectra. The increase of $\Delta_0$ at $n\sim3\times10^{11}$ cm$^{-1}$ coincide with the appearance of the carriers at the first LL. Figure 5 also shows that the appearance of the carriers at the second LL (at $n\sim6-7\times10^{11}$ cm$^{-2}$) results in an analogous renormalization of $\Delta_1$, and it shows that the renormalization of $\Delta_0$, which appears under the condition of a partly filled first LL, does not disappear with its filling. This is connected with the different filling of the $\mathrm{ME}^2(-\frac{1}{2},+\frac{3}{2})$ and $\mathrm{ME}^2(+\frac{1}{2},-\frac{3}{2})$ at the second LL.

Note that in earlier studies of the 2DEG, a strong enhancement of the electron-spin splitting of the LL's was found for an unequal filling of the spin-up and spin-down states due to the intra-Landau-level interaction.[5–11] This effect cannot be observed as a change in transition energies in the emission spectra of 2DEG with equal electron-electron (e-e) and electron-hole (e-h) interactions due to the cancellation between exchange and excitonic energies.[22] It appears only in terms of peculiarities in the temperature dependence of the optical absorption[10] or change of degree of polarization.[11] We would like to emphasize that the exchange enhancement of the spin splitting observed here for the neutral magnetoplasma occurs due to inter-Landau-level interaction. Therefore, it results in the spectral shift of emission lines even under conditions of equal e-e and e-h interactions.

## V. SUMMARY

The fine structure of Landau-level transitions in photoluminescence spectra of a neutral dense magnetoplasma photoexcited in $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As/InP}$ QW's has been resolved for a certain range of filling factors. It appears in both $\sigma^+$ and $\sigma^-$ polarizations and is caused by the mixture of the hole-spin states. In addition, a considerable enhancement of electron and hole spin splittings was found for the zero and first Landau levels with increased carrier concentration. It appears when the uppermost Landau level starts to be filled with photoexcited carriers. An explanation based on the exchange inter-Landau-level interactions and the unequal filling of different spin states is discussed.

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