Interparticle interaction in spin-aligned and spin-degenerate exciton systems and magnetoplasmas in II-VI quantum wells

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Magnetoluminescence studies of highly excited undoped CdTe/$Cd_{0.88}Mn_{0.12}Te$ and $Cd_{0.97}Mn_{0.03}Te$/$Cd_{0.75}Mg_{0.25}Te$ quantum wells (QW's) have been carried out in magnetic fields up to 14 T at 4.2 K. Qualitatively different excitonic systems, spin aligned in (Cd,Mn)Te QW and spin depolarized in CdTe QW, have been generated. The interaction of spin-aligned excitons are found to be weakly repulsive. In contrast, an additional well pronounced emission line *M* has been found to appear at approximately 5 meV below the excitonic line in the spectra of the spin-degenerate system. This line is assigned to the emission of excitonic molecules consisting of excitons with different spins. Finally, we have shown that the renormalization of Landau-level transitions in dense electron-hole magnetoplasmas with several occupied Landau levels depends on their spin state, it is markedly weaker in the spin-polarized plasmas. [S0163-1829(96)10331-3]

I. INTRODUCTION

During the last few years a number of studies have addressed the properties of quasi-two-dimensional (2D) electron-hole (*e-h*) systems in semiconductor structures. Many body effects in these systems were discussed in a number of investigations of III-V semiconductor quantum wells (QW's) both with and without magnetic fields.[1–11] With increasing density, the excitonic system in a high magnetic field transforms into an *e-h* magnetoplasma. Many-particle interaction in the magnetoplasma results in a renormalization of the band gap and the Landau-level spacings. In neutral quasi-2D *e-h* plasmas in GaAs and (InGa)As QW's, the magnitude of the band gap renormalization (BGR) was found to increase monotonically with the plasma density[1–9] whereas most of the change in the effective masses occurs at intermediate densities where the interparticle separations in the plasma become comparable with the exciton radius.[10,11] A decrease of the plasma temperature results in a strong enhancement of the *e-h* correlations at the Fermi edge, especially when a magnetic field normal to the (InGa)As QW plane is applied.[12–15]

In contrast with III-V QW's, optical investigations of II-VI QW's have up to now mainly addressed the low excitation density range. At the same time the behavior of a dense *e-h* system in these QW's is expected to exhibit some peculiarities. For example, the effects of exciton-exciton interactions in a dense excitonic system should be more pronounced because of an enhanced Coulomb interaction. For the same reason, much stronger excitonic correlations are expected in the dense magnetoplasma. In addition, semimagnetic semiconductors being used as a QW material make it possible to realize qualitatively new, spin-aligned exciton and *e-h* systems.[16]

In the present paper we study the behavior of photoexcited *e-h* systems in undoped CdTe/$Cd_{0.88}Mn_{0.12}Te$ and $Cd_{0.97}Mn_{0.03}Te$/$Cd_{0.75}Mg_{0.25}Te$ QW's at 4.2 K and magnetic fields up to 14 T. The systems are qualitatively different. The spin splitting for electrons and holes located in the CdTe QW is relatively small due to the small penetration of carrier wave function into semimagnetic barrier layers. Therefore the dense system of excitons or of electrons and holes is polarized relatively weakly, similar to that in GaAs QW's. The addition of 3% Mn ions into the QW layer results in a spin splitting (both for electrons and for holes) which exceeds the cyclotron energy. In such a QW we succeeded in creating excitons and magnetoplasmas with a strong spin alignment.

We have found that the properties of a dense excitonic system are determined by its spin state. The spin-aligned excitons created in the $Cd_{0.97}Mn_{0.03}Te$ QW reveal a weakly repulsive interaction. With increasing density, the emission spectrum transforms from an excitonic one (with a single narrow polarized exciton emission line) to that of a dense magnetoplasma (with several lines corresponding to allowed transitions between occupied Landau levels j_e and j_h and strongly broadened due to many particle interaction). In contrast, in the spectra of a dense spin-depolarized excitonic system generated in the CdTe QW, an additional well pronounced emission line *M* was observed to appear at approximately 5 meV below the excitonic line. This line indicates a rather strong attractive interaction between excitons and can be assigned to the emission of excitonic molecules consisting of excitons with different spins of electrons and holes.

The paper is organized as follows. In Sec. II we describe the experimental technique. In Sec. III the dependence of emission spectra from the CdTe and $Cd_{0.97}Mn_{0.03}Te$ QW's on the excitation density is described. Both the dense excitonic system and the magnetoplasma with several Landau levels occupied with carriers are considered and the different behavior of spin-aligned and spin-depolarized systems has been demonstrated. Finally, in Sec. IV the experimental results are compared with theoretical predictions and the reasons for a qualitatively different behavior of the excitons and *e-h* magnetoplasmas in CdTe and $Cd_{0.97}Mn_{0.03}Te$ QW's are discussed in detail.

II. EXPERIMENTAL

The measurements were performed on undoped $CdTe/Cd_{0.88}Mn_{0.12}Te$ and $Cd_{0.97}Mn_{0.03}Te/Cd_{0.75}Mg_{0.25}Te$ heterostructures each with a single 10-nm thick QW grown by molecular-beam epitaxy on a (001)-oriented CdTe substrate.[17] The samples were immersed in liquid helium in a cryostat with a superconducting coil. The plane of the QW was oriented normally to the magnetic field. Photoluminescence (PL) spectra were recorded at T = 4.2 K and magnetic fields B=0–14 T with the use of a picosecond pulsed dye (R6G) laser (pulse duration τ_p = 1 ps) and a grating monochromator. The emission was detected by a cooled photomultiplier and processed by a time-correlated photon counting system with a gate of 200 ps.

To avoid problems arising from electron-hole plasma inhomogeneity, first, the same optical fiber located very close (0.1 mm) to the QW surface has been used both for excitation and for collection of the QW PL and, second, the PL has been recorded just after the ps photoexcitation pulse with a gate as narrow as 200 ps. Experimentally it has been found that under these conditions the influence of lateral plasma expansion becomes negligible when the fiber diameter exceeds 0.6 mm. In particular, in this case the emission of a highly excited QW has a well pronounced steplike shape reflecting the 2D density of states of electrons and holes. Note that such spectra can be never obtained in the case of inhomogeneous plasma because the emission from the region with smaller plasma density will increase the PL signal near the band edge.[3–5]

III. PHOTOLUMINESCENCE SPECTRA

A. (CdMn)Te QW

Figure 1(a) illustrates the magnetic field dependence of PL spectra from a 10-nm thick $Cd_{0.97}Mn_{0.03}Te/Cd_{0.75}Mg_{0.25}Te$ QW for low excitation density. The spectrum at B= 0 T consists of a relatively broad (~ 4 meV) emission line corresponding to a bound exciton recombination.[18] With increasing magnetic field, the line shifts strongly to lower energies. The shift is mainly caused by an exchange interaction between carriers and the Mn-ion spin system. It increases with B because of Mn-ion spin polarization.[19]

With increasing magnetic field one more line X appears at the high energy side of the D_0X line. Its energy is very close to the free exciton energy as determined from PL excitation spectra. Therefore line X is assigned to the emission of excitons weakly localized at potential fluctuations in the QW. Only this line is observed at high B. The line D_0X disappears from the PL spectrum at $B>$ 4 T because a complex with two electrons in a spin singlet state becomes unstable when the electron spin splitting exceeds its binding energy.[18]

It is seen from Fig. 1(a) that the band gap shrinkage in the QW reaches ~ 24 meV. Taking into account that the exchange integral ratio for holes and electrons is equal[20] to

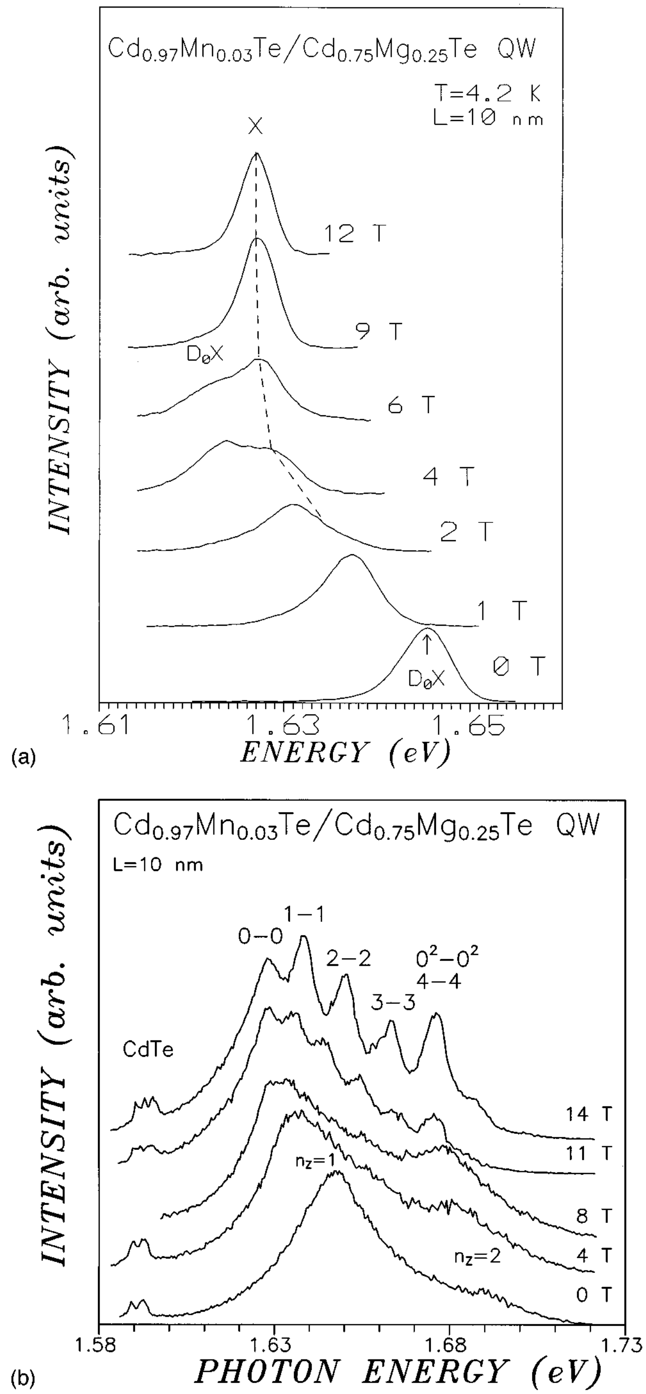

FIG. 1. (a) PL spectra from a 10-nm thick $Cd_{0.97}Mn_{0.03}Te/Cd_{0.75}Mg_{0.25}Te$ QW at low excitation density ($\sim 3\times10^{-3}$ W/cm^2) and various magnetic fields. (b) PL spectra from a 10-nm thick $Cd_{0.97}Mn_{0.03}Te$ QW at high excitation density, $P=5\,\mu$J/cm^2 and various magnetic fields. The *e-h* magnetoplasma was excited with a picosecond laser; the PL signal was collected within 200 ps gate just after the excitation pulse.

~ 4:1 we have estimated that the hole and electron spin splitting are equal to ~ 39 and ~ 10 meV, respectively.

PL spectra from a highly excited QW are shown in Fig. 1(b). The signal was collected within a 200 ps gate just after the 1 ps excitation pulse. The emission consists of a very broad band with the main maximum at ~ 1.646 eV and a small additional hump at 1.69 eV. This emission originates from the e-h recombination in the dense plasma. The main peak corresponds to the transition between the lowest, $n_z=1$, QW subbands for electrons and holes, whereas the additional hump at 1.69 eV originates from the recombination of carriers in the second subbands.

The plasma density, n_{e-h}, and its temperature, T_e, were estimated with the use of the emission band shape analysis by line shape fits with calculated spectra.[3] The carrier effective masses[12] for the empty QW ($m_e \sim 0.1m_0$, $m_h \sim 0.3m_0$) have been used. We have found that T_e increases strongly with n_{e-h}. It reaches $\sim$ 200 K at $n_{e-h} \sim 1.5\times10^{12}$ cm^{-2}.

Similar to the exciton line the plasma emission band shifts quickly to lower energies at small magnetic fields and only very little at high B. The shift is mainly connected to an exchange interaction of electrons and holes in the plasma with the Mn-ion spin system. A comparison of Figs. 1(a) and 1(b) shows that the shift of the plasma line occurs up to somewhat higher fields than that of the exciton line. The difference is due to unavoidable heating of the Mn-spin system in the highly excited QW's. To determine the Mn-ion spin temperature T_s we have extrapolated the dependence of the shift of the plasma emission line at fixed excitation power and delay time on the magnetic field with Brillouin function. In particular, it was found that the shift of the plasma line in Fig. 1(b) corresponds to T_s = 12 – 15 K. Note that the Mn-ion system is not in thermal equilibrium with the e-h plasma, the temperature of the latter is more than one order of magnitude larger ($T_e >$ 200 K).

In general, the Mn-spin temperature depends strongly on the conditions under which plasma was obtained. It increases with the excitation pulse duration and/or with the time delay for the registration. Therefore, to obtain a possibly smaller T_s, the plasma was excited by a very short, picosecond, pulse and the spectra were recorded with a time delay $\tau_d <$ 200 ps.

Figure 1(b) shows as well that the steplike shape of the plasma emission which is characteristic of the emission of a degenerate 2D plasma becomes more pronounced with increasing magnetic field. This is due to the lifting of the electron and hole spin degeneracy which decreases the density of states in the conduction and valence bands and, hence, leads to a significant increase of carrier Fermi energies.

The quantization of the electron states in the magnetic field causes an additional structure in the plasma emission spectra. Figure 1(b) shows that it appears in the spectra only at $B >$ 10 T. The humps, marked $j-j,(j=0,1,\ldots,)$ are connected with allowed transitions ($j_e=j_h$) between the occupied electron (j_e) and hole (j_h) Landau levels (LL's) in the first subband. The energy spacing $\Delta_{j,j+1}$ between the humps is $\sim$ 10 meV at 11 T and increases to $\sim$ 12 meV at 14 T. At the high energy side of the spectrum there is an additional emission from the transition between the occupied LL's in the second subbands labeled 0^2-0^2.

The change of the emission spectra from $Cd_{0.97}Mn_{0.03}Te$ QW at B=14 T with excitation density is shown in Fig. 2. The number of observed LL transitions in the spectra increases in accordance with filling of the excited LL's. The LL transition energies increase slightly with plasma density as displayed in Fig. 3. The latter is in contrast to a well pronounced lowering of the LL transition energies which is observed in the magnetoplasma in GaAs QW's because of Coulomb interaction in a dense plasma.[4,5]

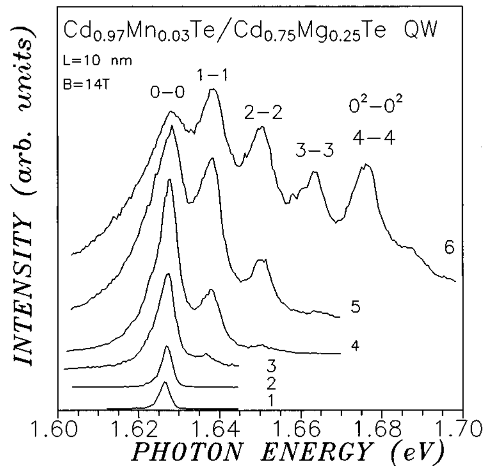

FIG. 2. PL spectra from a $Cd_{0.97}Mn_{0.03}Te$ QW at B = 14 T for different n_{e-h}. The QW was excited with a picosecond laser. The PL signal was collected within 200 ps gate just after the excitation pulse. $n_{e-h}(10^{12}$ cm$^{-2})$ = 0.06(1), 0.1(2), 0.25(3), 0.5(4), 0.85(5), and 1.9(6).

Note that in highly excited semimagnetic QW's there is an additional contribution in the emission line shift connected to the heating of the Mn-ion spins. The latter decreases Mn-spin polarization and hence leads to the reduction of contribution from exchange interaction of the carriers and Mn-ion spin system.[19] As was mentioned above the Mn-ion spin temperature for any fixed excitation power can be determined from an analysis of the magnetic field dependence of the plasma line shift with rather high accuracy. We have carried out such an analysis and estimated the contribution to the line shift, Δ_s^* due to the heating of the Mn-ion spin system for various excitation densities. The magnitude of Δ_s^* changed from 0 at low excitation densities to $\sim$ 5 meV at the highest ones. The renormalization due to many-particle Coulomb interaction in a dense plasma was obtained from experimental data by extracting Δ_s^*. This is discussed in more detail in Sec. IV.

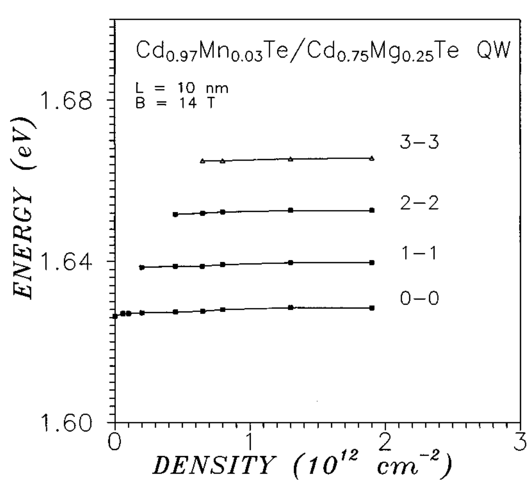

FIG. 3. Density dependence of LL transition energies in the first subband of a $Cd_{0.97}Mn_{0.03}Te/Cd_{0.75}Mg_{0.25}Te$ QW at 14 T and T = 4.2 K.

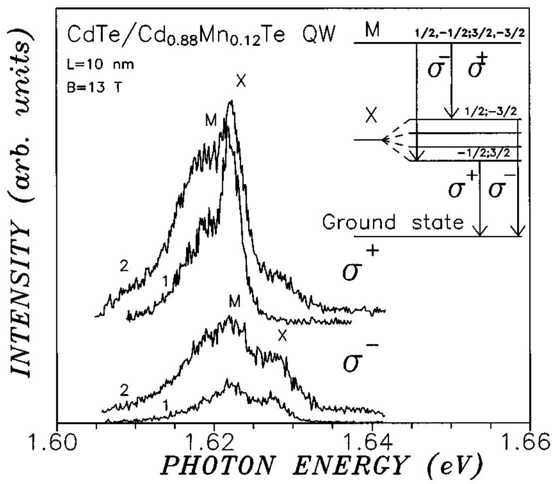

FIG. 4. Polarized spectra from a 10-nm thick CdTe QW at T = 4.2 K, B = 13 T and various excitation densities $P=1(1)$ and 0.3μJ/cm^2 (2). The inset displays the allowed transitions for excitons and excitonic molecules.

B. CdTe QW

In the 10-nm thick CdTe/$Cd_{0.88}Mn_{0.12}$Te QW heterostructure with Mn ions in the barrier layers, the Mn spin alignment does not influence the energies of electrons and holes in the ground subband because of a weak penetration of carrier wave functions into the semimagnetic barrier layers. Figure 4 displays magnetoexciton emission spectra of the CdTe QW at B = 13 T recorded in σ^- and σ^+ polarizations at 4.2 K. It is seen that the spin splitting is within 5 meV. The ratio of intensities of the exciton emission for these two polarizations is of the order of 10. This ratio corresponds to the exciton spin temperature within 20–25 K that is markedly larger than the bath temperature, T = 4.2 K.

The change of the emission spectra of the CdTe QW with excitation density is shown in Fig. 5. At low excitation level (spectrum 1) the exciton emission line X with a maximum at 1.622 eV has a low energy shoulder. This shoulder is due to the excitons localized at the QW impurities and therefore its intensity was expected to saturate with excitation density. To the contrary, the relative intensity of the shoulder starts to increase strongly at higher excitation densities, and the

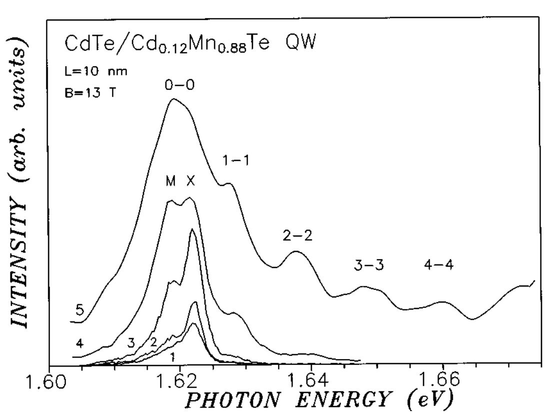

FIG. 5. Emission spectra from CdTe QW at T = 4.2 K, B = 13 T and various excitation densities. $n_{e-h}(10^{12}$ cm$^{-2})$ = 0.15(1), 0.25(2), 0.35(3), 0.63(4), and 1.8(5).

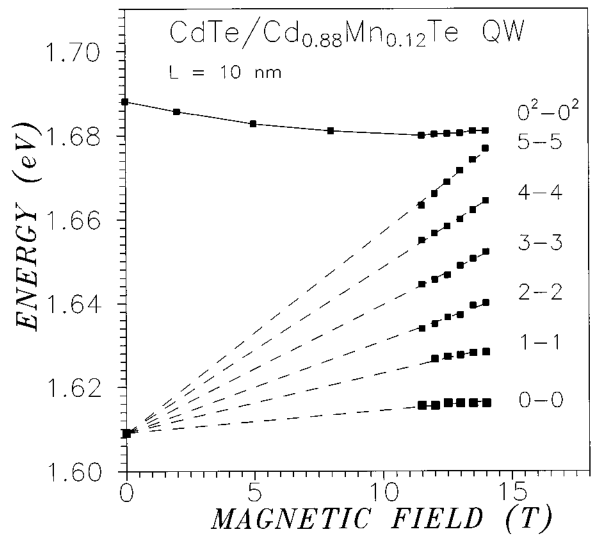

FIG. 6. Landau fan plot for allowed magnetoplasma transitions from a 10-nm CdTe QW.

shoulder transforms into a separate line marked M. This line is well resolved in the spectra in the range of $n_{e-h}=(4-8)\times10^{11}$ cm^{-2}. The superlinear dependence of line M intensity suggests that it should be assigned to exciton complexes consisting of more than one exciton, e.g., to excitonic molecules. At $n_{e-h}>10^{12}$ cm^{-2} the lines X and M broaden and merge into one broad band labeled 0-0.

The comparison of Figs. 2 and 5 shows that the behavior of the spectra from spin-aligned [(CdMn)Te QW] and markedly spin-depolarized (CdTe QW) exciton systems is qualitatively different. In the first case (i) there is no bound exciton emission at low excitation level, and (ii) no additional line appears at the low energy edge of the exciton emission line with increasing excitation level. The origin of these differences will be discussed in more detail in Sec. IV A.

The energies of electrons and holes in the ground subband of a dense magnetoplasma in the 10-nm thick CdTe/$Cd_{0.88}Mn_{0.12}$Te QW are weakly influenced by the Mn-ion spin alignment in the barrier layer because of the weak penetration of carrier wave functions into the barrier layers. In particular, the shift of the emission band connected with the recombination of carriers in the first subbands does not exceed[16] $\sim$ 1 meV.

The LL structure in the CdTe QW emission appears, same as in (CdMn)Te QW, approximately at B = 11.5 T. The field dependence of the LL transition energies is represented in Fig. 6. The fan of lines $j-j$ converging to 1.61 eV at B = 0 T is connected with allowed transitions between the occupied LL's in the first subband. The line at 1.68 eV which is only weakly dependent on magnetic field at high B, is due to the transition between zero LL's in the second subband. It is labeled 0^2-0^2.

Figure 7 displays the density dependence[22] of interband transition energies in the emission spectrum of the CdTe QW at 14 T. In addition, the open triangle at n_{e-h} = 0 shows the 1-1 transition energy in the ''empty'' QW determined by PL excitation measurements. It is seen from Fig. 7 that the exciton energy is nearly independent of density. Two lines (X and M) corresponding to the recombination of particles from zero LL are observed in the emission spectra at densities

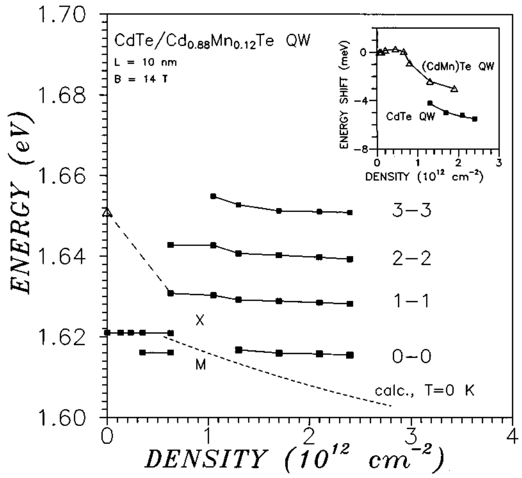

FIG. 7. Density dependence of LL transition energies in the first subband at 14 T and $T = 4.2$ K. The dotted line shows the density dependence of the 0_e-0_h transition energy calculated for $T = 0$ K taking into account the finite QW width but neglecting the electron-LO-phonon coupling.[8] The open triangle shows the spectral position of the 1_e-1_h transition in the empty QW determined by PL excitation measurements. The inset displays the shift of the main 0-0 transition energy in the dense spin-degenerate (CdTe QW) and spin-aligned (CdMnTe QW) systems compared to the free exciton energy.

$n_{e-h} \sim (4-8)\times 10^{11}$ cm^{-2}. At higher n_{e-h} they broaden and transform into one broad band, 0-0.

The 0_e-0_h and 1_e-1_h transition energies in the dense magnetoplasma ($n_{e-h} > 10^{12}$ cm^{-2}) are markedly smaller than in the empty QW. The shift of the 0_e-0_h emission line, δ_0, reaches 5 ± 1 meV at $n_{e-h} = 2.6\times 10^{12}$ cm^{-2}. The shift of the 1_e-1_h emission line, δ_1, is much larger; it exceeds 25 meV. As a consequence, the spacing Δ_{01} decreases from $\sim$ 30 meV in the unexcited QW to $\sim$ 12 meV in the dense magnetoplasma. The spacings between the higher LL's, Δ_{12} and Δ_{23}, in the dense plasmas are also within 12–13 meV. This is very similar to that in the (CdMn)Te QW (cf. Figs. 3 and 7).

IV. DISCUSSION

A. Comparison of exciton-exciton interaction in spin-aligned and spin-depolarized systems

The different behavior of the excitonic systems observed in $Cd_{0.97}Mn_{0.03}Te$ and CdTe QW's arises from the difference in their spin composition. The splitting of exciton states with different electron and hole spins in the $Cd_{0.97}Mn_{0.03}Te$ QW at $B > 10$ T is much larger than kT and exceeds the binding energy of bound excitons and excitonic molecules. Therefore the exciton emission line remains single in the spectrum until the upper LL's are occupied (cf. Fig. 2). As was shown in Sec. III A the shift of the 0-0 emission line in the (CdMn)Te QW is caused both by the many-particle interaction in the exciton system and by the decrease in exchange interaction of the carrier and Mn-ion spins Δ_s^* because of the heating of the latter.

The latter becomes marked at $n > 10^{12}$ cm^{-2}. The contribution to the transition energy renormalization due to many-particle Coulomb interaction in a dense plasma obtained by extracting Δ_s^* is displayed in the inset of Fig. 7. It shows that at low densities ($n < 6\times 10^{11}$ cm^{-2}) the exciton line shifts weakly to the higher energies. The shift is $\sim 0.6n\times 10^{-12}$ meV cm^2. It means that repulsive interaction prevails in a spin-aligned exciton system. This is in agreement with theoretical predictions.[23,24] Note that with magnetic field the repulsion in the excitonic system has to decrease and in the high magnetic field range it should be similar to an ideal gas.[13] However 10–14 T for excitons in CdTe QW's is still far from this limit as the magnetic length is still as large as two exciton Bohr radii.

In the CdTe QW, the spin splitting of exciton states is much smaller. The spin splitting of excitonic states in this QW causes a rather strong polarization of the exciton system at high magnetic field but it is not enough to cause the dissociation of bound exciton complexes, whose emission appears in the spectra in Figs. 4 and 5 as a low energy wing of the exciton emission line.

We believe that line M which appears with increased exciton density at the low energy side of the exciton emission line X in Figs. 4 and 5 can be assigned to the recombination of excitonic molecules with electrons and holes in singlet states. First of all, both the density dependence and the energy position of the line M are consistent with this model. According to calculations[25,26] the binding energy of excitonic molecules in the QW is expected to be within $0.1-0.25\mathcal{R}$, where $\mathcal{R}$ is the exciton binding energy. Figures 4 and 5 show that the line M is at approximately 5 meV (that is $\sim 0.2\mathcal{R}$ for the investigated QW) below the exciton line. Further, line M demonstrates a superlinear density dependence which indicates the presence of more than one exciton. Moreover, no similar line appears in PL spectra of a spin-aligned exciton system of $Cd_{0.97}Mn_{0.03}Te$ QW (cf. Fig. 2). Hence the excitons with opposite spins should participate in the exciton complex. This assumption is supported by the emission spectra from CdTe QW recorded in different polarizations. Figure 4 shows that the splitting of the σ^+ and σ^- components of line M corresponds to that of the exciton line X, but, in contrast to the latter, the intensity of line M does not show any strong dependence on polarization. These are intrinsic to the emission of molecules whose ground state is a spin singlet. The difference in the energies of the σ^+ and σ^- transitions for line M appears due to the spin splitting of the final state (which is the exciton, cf. the transition scheme in Fig. 4). Some difference in the σ^+ and σ^- intensities can be due to an additional emission from impurity bound excitons which is in the same spectral range. The latter is highly polarized because complexes contain only one hole.

B. Comparison of renormalization effects in dense spin-polarized and spin-depolarized magnetoplasmas

The density dependence of the shift of the 0_e-0_h transition energy δ_0 in the magnetoplasma with a few filled LL's is shown in Figs. 3 and 7 for $Cd_{0.97}Mn_{0.03}Te$ and CdTe QW's, respectively.[22] It is unusually weak as compared to that in (InGa)As/GaAs and GaAs/(AlGa)As QW magnetoplasmas.[3,4] The dotted line in Fig. 7 shows the density dependence of BGR for the plasma in the CdTe QW calculated for $T = 0$ K taking into account the finite QW width but neglecting the electron–LO-phonon coupling.[8] Such an approximation is valid for high plasma densities and temperatures when the excitonic effects can be neglected.[4,12,15] The calculated curve is well below the experimental one and the difference increases with n_{e-h}. The difference cannot be explained by an influence of the electron–LO-phonon coupling because this coupling should result in an increased rather than decreased BGR.[8]

The observed discrepancy between calculations and experimental data can be partly associated with the temperature induced corrections which were not taken into account in calculation in Ref. 8. In the experiment the plasma temperature reaches 300 K at $n_{e-h}\sim 2.5\times 10^{12}$ cm^{-2}. The calculations for GaAs QW's carried out in Ref. 9 show that BGR decreases with temperature. In particular, the correction of 10 meV was found at 300 K for $n_{e-h}=(1-5)\times 10^{12}$ cm^{-2}. A similar correction of BGR in our case will decrease the discrepancy between the experiment and calculations but cannot explain the observed difference. It seems that the excitonic corrections in CdTe QW's remain very important even in magnetoplasma with a few LL filled. A reduced screening of magnetoexcitons in the CdTe QW's can be associated with the fact that the exciton binding energy at B = 11 – 14 T exceeds the LO phonon energy.[27] However a theoretical calculation are necessary for the final conclusion.

The insert of Fig. 7 compares the renormalization of the ground 0_e-0_h transition in the CdTe and $Cd_{0.97}Mn_{0.03}Te$ QW's. In the latter case the data were corrected for the shift due to heating of the Mn-spin system.[28] Note that the magnetic field leads to destabilization of bound excitons in the CdMnTe QW and does not do this in the CdTe QW's. As a consequence the accuracy in the plasma parameter determination at intermediate densities in the latter case is worse. Therefore the data for the band gap renormalization at intermediate densities in the CdTe QW are not shown in the inset in Fig. 7 and are not discussed in the text. The inset shows that the carrier spin aligning in the dense magnetoplasma leads to a strong decrease of the transition energy renormalization. It means that the interaction of particles with different spins gives a significant contribution in the case of the spin degenerate magnetoplasma in the CdTe QW.

Figure 7 displays also a very strong (nearly 2.5 times) decrease of the LL spacings when passing from an unexcited CdTe QW to the dense magnetoplasma. Comparison of Figs. 3 and 7 shows that the LL spacings in the dense magnetoplasmas in the CdTe and $Cd_{0.97}Mn_{0.03}Te$ QW's are nearly identical. In general, in the empty QW we deal with well defined stable magnetoexcitons and the spacings between the nearby LL transitions can be defined as

$$\Delta_{j,j+1}=\hbar\omega_c+\mathcal{R}_j-\mathcal{R}_{j+1}. \tag{4.1}$$

Here $\hbar\omega_c=\hbar\omega_{ce}+\hbar\omega_{ch}$ and $\mathcal{R}_j$ is the magnetoexciton binding energy at the jth LL. So, in the empty CdTe QW the value of Δ_{01} at 14 T is equal to $\sim$ 30 meV and consists of $\hbar\omega_c\cong 20$ meV and of the difference $\mathcal{R}_0-\mathcal{R}_1\cong 10$ meV.

The small value of $\Delta_{01}\cong 12$ meV (that is by $\sim\mathcal{R}/4$ smaller than $\hbar\omega_c$) measured in the case of magnetoplasma with one LL filled ($n_{e-h}\sim 7-9\times 10^{11}$ cm^{-2} in the CdTe QW and $\sim 3-5\times 10^{11}$ cm^{-2} in the $Cd_{0.97}Mn_{0.03}Te$ QW with spin-aligned plasma) is not surprising. In such a plasma the recombination of electron and hole from nearly filled LL results in the formation an excitonic like state (referred to as deexciton, an electron is in the valence and a hole in the conduction bands) in the final state of recombination act. As the deexciton state is in the final state of the transition, the excitonic corrections to the interband transition energy turn out to be negative.[15] As a consequence the magnitude of Δ_{01} becomes smaller than $\hbar\omega_c$ which is in qualitative agreement with the experiment.

The excitonic corrections should decrease with increasing plasma density or temperature.[15,29] However, Figs. 3 and 7 show that $\Delta_{j,j+1}$ remain small in a wide range of n_{e-h} both in spin-aligned and spin-degenerate plasmas. Additional calculation are necessary to explain this result quantitatively.

In conclusion, we have presented a magneto-optical study of a dense neutral e-h magnetoplasma photoexcited in an undoped $CdTe/Cd_{0.88}Mn_{0.12}Te$ and $Cd_{0.97}Mn_{0.03}Te/Cd_{0.75}Mg_{0.25}Te$ QW's in magnetic fields up to 14 T at 4.2 K. Qualitatively different excitonic systems, spin aligned in the (Cd,Mn)Te QW and spin depolarized in the CdTe QW, have been generated whose density behavior was found to be qualitatively different. The spin-aligned excitons show a weakly repulsive interaction. In contrast, an additional line M has been found to appear at approximately 5 meV below the exciton line in the spectra of the dense spin-depolarized excitonic system. This line was assigned to the emission of excitonic molecules consisting of excitons with opposite spins. In addition, both the renormalization of the principal 0_e-0_h transition energy and of the energy spacings between the different LL transitions have been measured in the dense magnetoplasmas with several occupied LL's. It was shown that the renormalization of LL transitions is markedly weaker in the spin polarized plasmas. Besides, it was found that in the (CdMn)Te QW the transition energies suffer to an additional shift because of heating of the Mn spin system by photoexcited carriers.

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[1] G. Tränkle, E. Lach, A. Forchel, P. Scholz, C. Ell, H. Haug, G. Weimann, G. Griffiths, H. Kreemer, and S. Subbanna, Phys. Rev. B **36**, 6712 (1987); G. Tränkle, H. Leier, A. Forchel, H. Haug, C. Ell, and G.Weimann, Phys. Rev. Lett. **58**, 419 (1987).

[2] K.-H. Schlaad and C. Weber, J. Cunningham, C. V. Hoff, G. Borghs, G. Weimann, W. Schlapp, H. Nickel, and C. Klingshirn, Phys. Rev. B **43**, 4268 (1991).

[3] V. D. Kulakovskii, E. Lach, A. Forchel, and D. Grützmacher, Phys. Rev. B **40**, 8087 (1989).

[4] R. Chingolani, G. C. La Rossa, H. Kalt, K. Ploog, M. Potemski,

and J. C. Maan, Phys. Rev. B **43**, 9662 (1991).

[5] L.V. Butov, V.D. Kulakovskii, E. Lach, A. Forchel, and D. Grützmacher, Phys. Rev. B **44**, 10 680 (1991).

[6] E. Lach, A. Forchel, D. A. Broido, T. L. Reinecke, G. Weimann, and W. Schlapp, Phys. Rev. B **42**, 5395 (1990).

[7] . R. Zimmermann, E. H. Böttcher, N. Kirstaedr, and D. Bimberg, Superlatt. Microstruct. **7**, 433 (1990).

[8] S. Das Sharma, R. Jalabert, and S.-R. Eric Yang, Phys. Rev. B **39**, 5516 (1989); **41**, 8288 (1990).

[9] J. C. Ryan and T. L. Reinecke, Phys. Rev. B **47**, 9615 (1993).

[10] J. C. Maan, M. Potemski, K. Ploog, G. Weimann, in *Spectroscopy of Semiconductor Microstructures*, edited by G. Fasol, A. Fasolino, and P. Lugli (Plenum, New York, 1989), p. 465; in *Proceedings of the 6th International Winterschool, Mauterndorf*, edited by G. Bauer and H. Heinrich (Springer-Verlag, Berlin, 1990).

[11] L. V. Butov, V. D. Kulakovskii, V. D. Egorov and T. G. Andersson, Phys. Rev. B **46**, 15 156 (1992).

[12] L. V. Butov, V. D. Kulakovskii, G. E. W. Bauer, A. Forchel, and D. Grützmacher, Phys. Rev. B **46**, 12 765 (1992).

[13] I. V. Lerner and Yu. E. Lozovik, Zh. Éksp. Teor. Fiz. **80**, 1488 (1981) [JETP **53**, 763 (1981)]; D. Paquet, T. M. Rice, and K. Ueda, Phys. Rev. B **32**, 5208 (1985).

[14] V. D. Kulakovskii and L. V. Butov, Phys. Status Solidi B **173**, 345 (1992).

[15] Yu. A. Bychkov and E. I. Rashba, Phys. Rev. B **44**, 6212 (1991).

[16] M. G. Tyazhlov, M.V. Lebedev, V.D. Kulakovskii, A. Forchel, D.R. Yakovlev, A. Waag, and G. Landwehr, Phys. Status Solidi B **188**, 565 (1995).

[17] A. Waag, S. Schmeusser, R. N. Bicknell-Tassius, D.R. Yakovlev, W. Ossau, G. Landwher, and I. N. Uraltsev, Appl. Phys. Lett. **59**, 2995 (1991).

[18] V. D. Kulakovskii, M. G. Tyazhlov, S. I. Gubarev, D. R. Yakovlev, A. Waag, and G. Landwehr, Il Nuovo Cimento **17D**, 1549 (1995).

[19] J. K. Furdyna, J. Appl. Phys. **164**, R29 (1988).

[20] G. A. Gaj, R. Planel, G. Fishman, Solid State Commun. **29**, 435 (1979).

[21] K. K. Kawasawa and F. C. Brown, Phys. Rev. **135**, 1757 (1964).

[22] The densities n_{e-h} were determined directly from the emission spectra by calculating the number of filled LL's. That is possible as the number of states in LL is determined by the magnitude of the magnetic field and does not depend on n_{e-h} and the oscillator strength of the different Landau level transitions is almost identical (Ref. 12).

[23] T. C. Damen, L. Vina, J. E. Gunningham, J. Shah, and L. J. Sham, Phys. Rev. Lett. **67**, 3432 (1991).

[24] G. Manzke, K. Henneberger, and V. May, Phys. Status Solidi B **139**, 233 (1987).

[25] D. A. Kleinman, Phys. Rev. B **28**, 871 (1983).

[26] A. L. Ivanov and H. Haug, Phys. Rev. Lett. **74**, 438 (1995).

[27] D.R. Yakovlev, W. Ossau, A. Waag, G. Landwehr, and E. L. Ivchenko, Phys. Rev. B **52**, 5773 (1995).

[28] Mn-ion spin temperature was determined from the magnetic field dependence of LL transition energies measured at fixed excitation density and delay time.

[29] G. E. W. Bauer, Phys. Scr. **45**, 154 (1992).