Singlet and triplet trion states in high magnetic fields: Photoluminescence and reflectivity spectra of modulation-doped $CdTe/Cd_{0.7}Mg_{0.3}Te$ quantum wells

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Photoluminescence (PL) and reflectivity spectra from modulation-doped $CdTe/Cd_xMg_{1-x}Te$ quantum well structures containing a two-dimensional electron gas have been studied in magnetic fields up to 45 T. In high fields, the recombination from the dark triplet trion state was found to be one of the most intense PL lines. A "bright" triplet line is revealed in both reflectivity and PL in magnetic fields above 35 T. PL spectra were calculated as a function of magnetic field, taking into account exciton, singlet, and triplet trion states. We show that the intense PL from the dark triplet trion is due to the field-induced suppression of singlet trion formation, and a corresponding enhancement of dark trion formation.

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I. INTRODUCTION

Charged excitons, or trions, represent bound states of three particles. They are formed from two electrons and one hole in the case of negatively charged excitons, and from two holes and one electron in the case of positively charged excitons.[1] The ground state of the trion in zero magnetic field is a singlet, i.e., the two electrons (two holes) have opposite spin alignment. The triplet state of the trion, in which the two electrons (holes) have the same spin alignment, is unbound at zero field. Triplet states become bound only in finite magnetic fields. Theoretical calculations show that both optically dark and optically active triplet trion states can exist, and suggest that the optically dark state is the lowest-energy triplet state.[2]

Despite the fact that dark triplet trions are (nominally) optically inactive, dark triplets are sometimes identified as relatively intense lines in photoluminescence (PL) spectra. Observations of dark triplets were reported in a number of studies of quantum wells based on ZnSe,[3,4] CdTe,[5–7] and GaAs.[8–10] As a result, questions naturally arise as to (i) whether the observed PL lines are appropriately identified, and (ii) why PL emission from the dark triplet trion is so intense. These (and related) questions are posed in nearly every published study of triplet trion states. A concentrated attempt to answer these questions was performed in Ref. 11, where the observation of triplet states was explained by the enhancement of the oscillator strength due to interaction of the triplet trion with additional electrons.

We suggest here an alternative and more natural explanation for these phenomena, based on the fact that the PL intensity from any state is defined by the product of the oscillator strength of the state, and its population. Consequently, small oscillator strengths can be compensated by high population. In this work, trion states were studied in CdTe-based modulation-doped quantum well structures. Bright (optically active) and dark (optically inactive) triplet trions were observed in high-field reflectivity and PL spectra. A theoretical model is developed which addresses and explains the intense PL emission from the dark triplet trion. The dark triplet line in PL is shown to gain intensity in comparison with the other lines, since the population of the singlet state is suppressed by the magnetic field while in contrast, the population of the triplet state is enhanced.

II. BACKGROUND

Similar to a helium atom or a negatively charged hydrogen ion (H^-), the negatively charged exciton complex (X^-) has two sets of states—triplet and singlet.[12] The solution of the Schrödinger equation for H^- or X^- is the following wave function: $\varphi(1,2)=U(1,2)\chi(1,2)$, where U is the spatial and χ is the spin part of the wave function. Symmetrized and normalized spatial wave functions can be chosen as

$$U^0_{nlm} = \frac{1}{\sqrt{2}}[u_1(\vec{r}_1)u_{nlm}(\vec{r}_2) \pm u_1(\vec{r}_2)u_{nlm}(\vec{r}_1)]. \qquad (1)$$

Here, u_1 corresponds to electrons in the ground $1S$ state (we assume that one of the electrons is in the ground state); n, l, and m are the main, azimuthal, and magnetic quantum numbers, respectively. Plus (+) indicates the singlet state; minus (−) indicates the triplet states.

The singlet state corresponds to the total spin of two electrons $S_e=0$. The spin part of the wave function is antisymmetric with respect to permutation of the electrons. The spatial part of the singlet wave function is therefore symmetric with respect to permutation of the electrons ["+" in Eq. (1)]. In this case both electrons can be in the $1S$ state, each with its own Bohr radius.

Triplet states correspond to the total spin of two electrons $S_e=1$ with three possible projections on the z axis $S_z=\pm 1,0$. The spatial part of the triplet wave function is antisymmetric with respect to permutation of the electrons ["−" in Eq. (1)]. It is obvious that if both electrons are in the ground state [$n=1$, $l=m=0$ in Eq. (1)] then the wave function is zero. The triplet wave function will be nonzero only if the electrons occupy different spatial orbitals, each with zero orbital momentum [e.g., 1S and 2S, where 2S corresponds to $n=2$, $l=m=0$ in Eq. (1)], or alternatively, if the two orbitals have nonzero total orbital momentum [one electron in a 1S orbital, and the second in a 2P orbital, which corresponds to $l\neq 0$ in Eq. (1)]. The internal structure of trions has been thoroughly studied by optically detected resonance spectroscopy in Ref. 13. Optical transitions between these states should satisfy the following conditions: $\Delta S_z=\pm 1$, $\Delta L=0$. The scheme of the sublevels and optical transitions for trion states has been previously published, see, for example Ref. 9.

In the absence of magnetic fields, the triplet trion is unbound over a wide range of electron and hole mass ratio.[14] With increasing magnetic field, triplet states with orbital angular momentum projection $L_z=-1$ will decrease in energy, whereas triplet states with $L_z=+1$ will increase in energy. In very high magnetic fields, the triplet state with $L_z=-1$ becomes the overall ground state of the trion.[15] This conclusion is also confirmed by advanced theoretical calculations.[16,17] The triplet state with $L_z=-1$ is optically inactive, or "dark." The optically active ("bright") triplet state with orbital momentum $L=0$ is energetically higher than this dark state. According to the classification scheme for diamagnetic excitons,[18,19] in high magnetic fields the triplet state with $L=0$ has one electron (from the 1S orbital) occupying the lowest Landau level, and the second electron (from the 2S orbital) occupies the next Landau level. For the dark triplet state, both electrons can occupy the lowest Landau level.

III. EXPERIMENT

We studied CdTe/$Cd_{0.7}Mg_{0.3}Te$ heterostructures, each with a single 100 Å quantum well (QW) grown by molecular-beam epitaxy on (100) GaAs substrates. To minimize dislocations due to a lattice mismatch between the QW and barrier materials, the QW was grown after a 400 nm thick CdTe buffer layer. An iodine n-type δ layer is located at a distance of 100 Å from the QW. At low temperatures, electrons from the δ layer collect in the QW, forming a quasi-2D electron gas (2DEG). A series of these QWs were grown during a single epitaxial growth using wedge doping techniques.[20] All the QWs have the same parameters and are different only in the doping level in the δ layer (and therefore the 2DEG density). The electron concentrations in the QWs varied from 10^{10} to 10^{12} cm^{-2}. The samples were not photosensitive, i.e., the electron concentration did not depend on the fluence of additional illumination.

Polarized PL and reflectivity from these samples were measured in magnetic fields applied in the Faraday configuration. Similar spectra were registered in Ref. 6 and 7. A capacitor-driven 50 T midpulse magnet (400 ms pulse duration) was used to generate high magnetic fields.[21] The samples were excited by a $\lambda=532$ nm solid-state laser, and a complete set of field-dependent PL spectra were collected during each magnet pulse. Data were acquired at 1.6, 4.2, and 15 K. Optical fibers were used for optical illumination of the sample, and the emitted light was detected in both circular polarizations σ^+ and σ^-, allowing identification of the spin components of excitons and trions. A similar setup was used for reflectivity measurements with a halogen lamp as a light source.

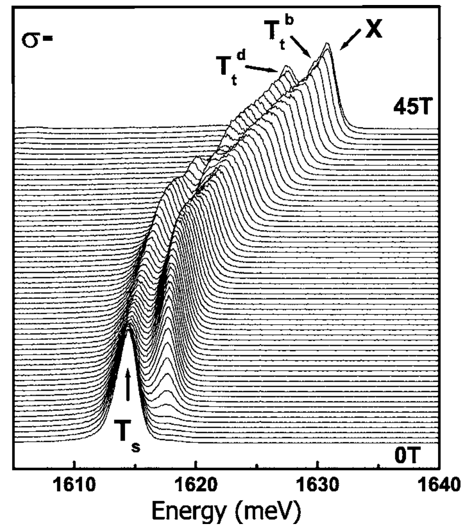

FIG. 1. Set of PL spectra taken in magnetic fields from 0 to 45 T from the sample with $n_e=3\times 10^{10}$ cm^{-2} in σ^- circular polarization. X indicates the exciton line, T_s is the singlet trion line, T_t^d is the dark triplet trion line, and T_t^b is the bright triplet trion line.

IV. RESULTS

A. Photoluminescence

Figure 1 shows a set of PL spectra from the sample with electron concentration $n_e=3\times 10^{10}$ cm^{-2} in the range of magnetic fields from 0 to 45 T in left circular polarization σ^-. We do not show the PL spectra in σ^+ polarization (see Ref. 7) because they are less informative. In low magnetic fields a bright PL line T_s is observed in σ^- polarization at an energy of 1.614 eV. This line corresponds to the singlet state of the trion. In low magnetic field the neutral exciton X is visible only as a weak line 3 meV above the singlet trion line. With increasing magnetic field, the intensity of the T_s line drops while the X intensity increases. An additional line (T_t^d) appears between the T_s and X lines above 20 T. With increasing magnetic field, its intensity increases as well. Figure 2 shows the magnetic field dependence of the energy positions of all PL lines in both circular polarizations. The lines of the neutral exciton X and singlet trion T_s experience nearly equal diamagnetic shifts towards higher energies. The Zeeman splitting of these lines is also identical.

The T_t^d line is observed only in σ^- polarization. It shifts from the exciton line towards lower energies. In the maximum field of 45 T, its splitting from the exciton line approaches 3 meV. From the energy and polarization of the T_t^d line, we associate this line with the recombination of the

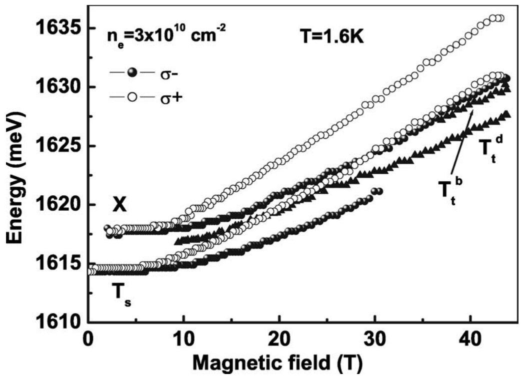

FIG. 2. Magnetic field dependence of the energy positions for all PL lines. Open circles stand for σ^+ polarization; closed circles stand for σ^- polarization. Triangles indicate triplet trion states observed only in σ^- polarization. X indicates the states of optically active exciton in the corresponding polarization σ^+ or σ^-. T_s—indicates the states of the singlet trion in corresponding polarization. T_t^d is optically dark due to the orbital momentum triplet trion state and T_t^b is the bright triplet trion state with $L=0$.

optically forbidden (dark) triplet trion having total spin projection $S_z^t=-\frac{1}{2}$ and total orbital angular momentum projection $L_z=-1$.

In fields higher than 35 T, another PL line is observed in σ^- polarization shifted by $\sim$1 meV below the exciton line. It is marked in Figs. 1 and 2 as T_t^b. The triplet trion also has optically active states[15,17] that are energetically higher than the dark state. In this case, in high magnetic field limit, one of the electrons occupies the first and the other occupies the second Landau level [$n=2$, $l=m=0$ in Eq. (1)]. This state has orbital momentum $L=0$ and total spin projection $S_z^{tot}=-\frac{1}{2}$. Therefore the corresponding transitions are optically allowed. We ascribe the PL line T_t^b to one of the optically active triplet trion states.

B. Reflectivity

Optically inactive states cannot be observed in reflectivity, which means that the T_t^d line observed in PL should be absent in reflectivity. At the same time, the bright trion states with orbital momentum $L=0$ should appear in reflectivity. In Fig. 3, reflectivity spectra from the sample with electron concentration $n_e=3\times10^{10}$ cm^{-2} are compared with the corresponding PL spectra at 6, 27, and 45 T in σ^- and σ^+ polarizations. The energy positions of the T_s and X lines in reflectivity coincide with the positions of these lines in the PL spectra. The Stokes shift does not exceed 0.3 meV. The singlet trion reflectivity line is fully polarized in magnetic fields as low as 6 T and is observed in σ^+ polarization only, which indicates the full spin polarization of the 2DEG.[22]

We have found no feature in the reflectivity which corresponds to the T_t^d line in the PL spectra, even though the T_t^d PL intensity is very high. This confirms the notion that the T_t^d line in PL does indeed correspond to the recombination of the dark triplet trion.

In high magnetic fields, a pronounced shoulder marked as T_t^b in Fig. 3 appears in the reflectivity spectra in the vicinity

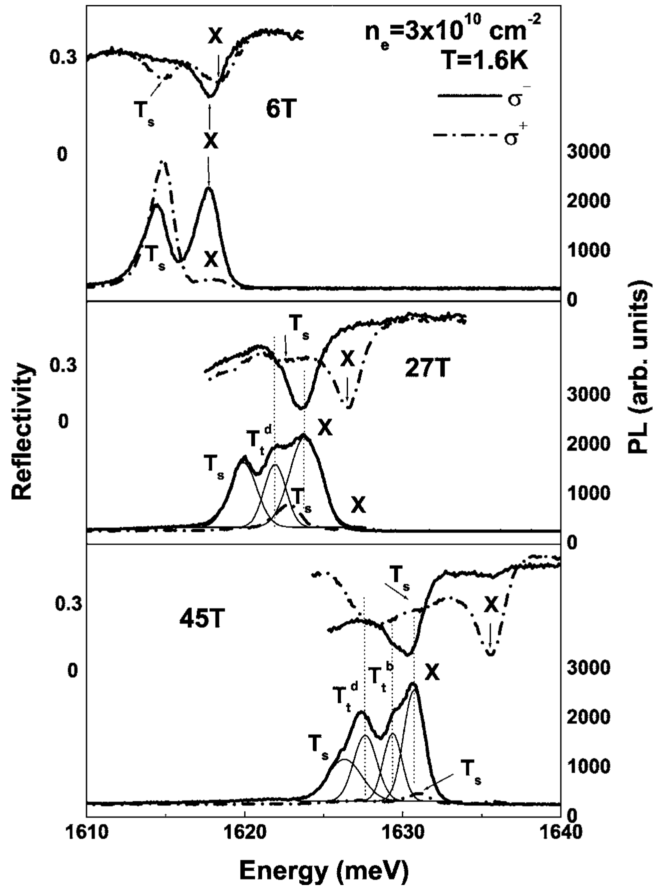

FIG. 3. Reflectivity and photoluminescence spectra taken from the sample with electron concentration $n_e=3\times10^{10}$ cm^{-2} in the magnetic fields 6 T, 27 T, and 45 T. Heavy solid lines are used for σ^- polarization, dashed-dotted lines − for σ^+ polarization. Light solid lines are the result of the deconvolution of the PL spectra by Gaussian fits. Dotted straight lines are comparison of PL and reflectivity spectral features.

of the lowest Zeeman component of the exciton line. Its energy position at 45 T ($\hbar\omega=1629.5$ meV) coincides with that of the T_t^b line in the PL spectra. This feature in the reflectivity spectra, as well as the line T_t^b in the PL spectra, corresponds to the optically active triplet trion state with orbital momentum $L=0$. The same conclusion has been drawn in Refs. 5–7. We fit the PL data with Gaussian functions to separate the contributions from exciton, singlet, and triplet trion as shown in Fig. 3.

Figure 4 shows the intensities of all the PL lines in the sample with electron concentration $n_e=3\times10^{10}$ cm^{-2}. In low magnetic fields the intensity of the PL line of the singlet trion significantly exceeds that of the exciton due to the fast trion formation rate. As the magnetic field grows, the intensity of the singlet trion PL line falls in both circular polarizations while the exciton line intensifies in σ^- polarization and remains weak in σ^+ polarization. The suppression of the singlet trion luminescence is determined by the spin-dependent processes of the trion formation. This spin-dependent trion formation leads also to the "nonequilibrium" polarization of the singlet trion PL line in magnetic fields below 10 T, which manifests as a higher intensity of the upper trion Zeeman

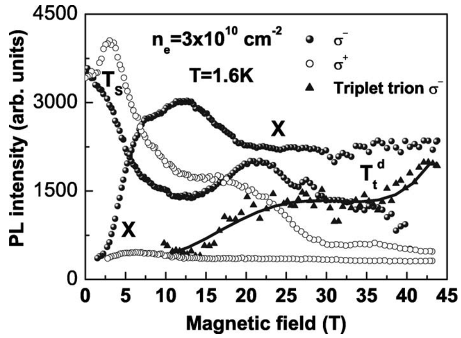

FIG. 4. The magnetic field dependence of the intensities of all PL lines. The dependence of the triplet line intensity was built by the Gaussian fit of the exciton and triplet trion line. The designations are similar to those in Fig. 1. The intensity of the bright triplet line (not shown in the figure) is nearly equal to the intensity of the exciton line in the range of magnetic fields from 35 to 45 T where it is observable.

component as compared with the lower component. A detailed analysis of this behavior is given in Refs. 23–26.

The triplet trion PL line becomes very intense in the spectra at roughly 20 T. Its intensity weakly depends on the magnetic field in the range between 25 and 40 T. We note that there are no remarkable changes in the intensity of the triplet line at its crossing with the singlet state at 24 T.

Below 20 T, the triplet trion and exciton lines merge with each other in energy and they cannot be visually resolved as two separate lines. In order to separate their contributions, we fit the data with two Gaussians with half-widths of about 0.9 meV. This allows us to plot the field dependence of the triplet trion PL intensity down to 10 T. At lower magnetic fields the accuracy of the contour splitting noticeably falls. However one can claim that the triplet trion line is observable down to 7–10 T. This conclusion is also confirmed by Fig. 3(c) in Refs. 5 and 6. Therefore, it means that in such low magnetic fields the triplet trion state remains bound in spite of its PL line merging with that of the exciton. In the samples with higher electron concentration the dark triplet was observed as a separate line in the PL spectra even at 10–12 T. In Fig. 5 the magnetic field dependence of all the PL lines of the samples with $n_e=3.7\times10^{11}$ cm^{-2} and $n_e=3\times10^{10}$ cm^{-2} are compared. It is seen that for the sample with higher electron density the triplet trion line is clearly observed down to 13 T.

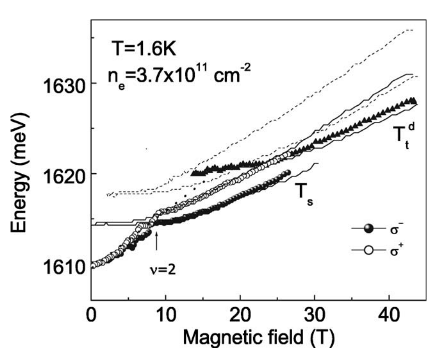

FIG. 5. Comparison of energy positions of PL lines in heavily doped ($n_e=3.7\times10^{11}$ cm^{-2}) and lightly doped ($n_e=3\times10^{10}$ cm^{-2}) QW structures. Symbols correspond to the heavily doped sample, lines to the lightly doped sample.

V. DISCUSSION

We now consider how the spectral positions of the exciton, triplet, and singlet trion lines in PL correspond to the energy levels of these states. In the case of (neutral) exciton recombination, the energy of the emitted photon is equal exactly to the energy of the initial exciton. In the case of trion recombination, however, part of the initial trion energy is taken by the remaining electron, so that the energy of the emitted photon no longer exactly equals the initial trion energy.

After recombination of an electron (e) and heavy hole (hh) within a trion, an electron remains in a Zeeman sublevel (upper or lower, depending on the momentum of the hole). For the singlet trion state we have:

$$(e\uparrow + e\downarrow + hh\Uparrow) \Rightarrow ph\sigma^+ + e\uparrow$$

or

$$(e\uparrow + e\downarrow + hh\Downarrow) \Rightarrow ph\sigma^- + e\downarrow. \qquad (2)$$

This leads to the conclusion that the energy of the trion PL line differs from the real trion energy by half of the electron Zeeman splitting:[27] $(\frac{1}{2})g_e\mu H$, where g_e is electron g factor and μ is the Bohr magneton. The observed Zeeman shift of the PL lines $E_{ph}^{\sigma^\pm}=\pm(\frac{1}{2})\mu H|g_e-g_{hh}|$ is defined by the exciton g factor, while the splitting of the singlet trion energy levels $\pm\frac{1}{2}\mu g_{hh}H$ is defined by the hole g factor g_{hh} only. For the observed dark triplet state T_t^d, recombination results in emission of a σ^- photon, and the second electron remains in the $S_z=+\frac{1}{2}$ final state

$$(e\uparrow + e\uparrow + hh\Downarrow) \Rightarrow ph\sigma^- + e\uparrow.$$

Similar to the singlet state, the observed Zeeman shift of the PL line in σ^- polarization is $E_{ph}^{\sigma^-}=-(\frac{1}{2})\mu H|g_e-g_{hh}|$, while the Zeeman shift of the energy level is $E^{\sigma^-}=-(\frac{1}{2})\mu H|2g_e-g_{hh}|$. The electron g factor in CdTe based QW structures is well known: $g_e=-1.56$.[28] The hole g factor depends on the magnetic field. In high magnetic fields it is equal to $g_{hh}=+0.74$; in low magnetic fields $g_{hh}=-0.2$.[26,28] The field dependence of the hole g factor has been presented in Ref. 26.

Thus the shift of the Zeeman component of this triplet state in high magnetic field is characterized by g factor $|2g_e-g_{hh}|/2=1.93$. However, the observed Zeeman shift is characterized by g factor $|g_e-g_{hh}|/2=1.15$ due to Zeeman splitting of the final state. The shift of the T_t^d line observed in the experiment in 45 T magnetic field equals $\Delta E=3$ meV. Because the diamagnetic shift is the same for all exciton and trion states we can derive the value of the triplet trion binding energy in the magnetic field. In 45 T this value appears to be 3 meV.

The dependence of the binding energy of the singlet, dark triplet, and bright triplet trion states is shown in Fig. 6 as a difference of the exciton energy and corresponding trion en-

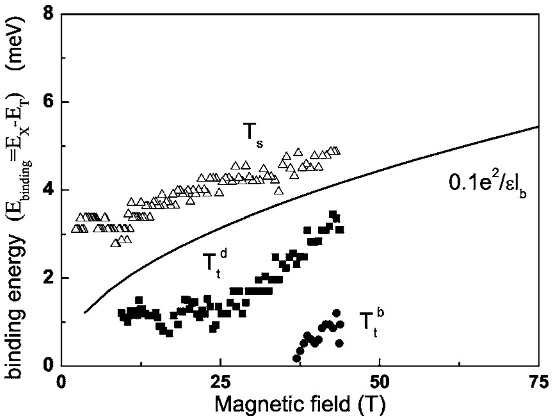

FIG. 6. Binding energies of the singlet T_s and triplet T_t^d, T_t^b trion states as a function of the magnetic field. Symbols, experiment; solid line, calculation (Ref. 29).

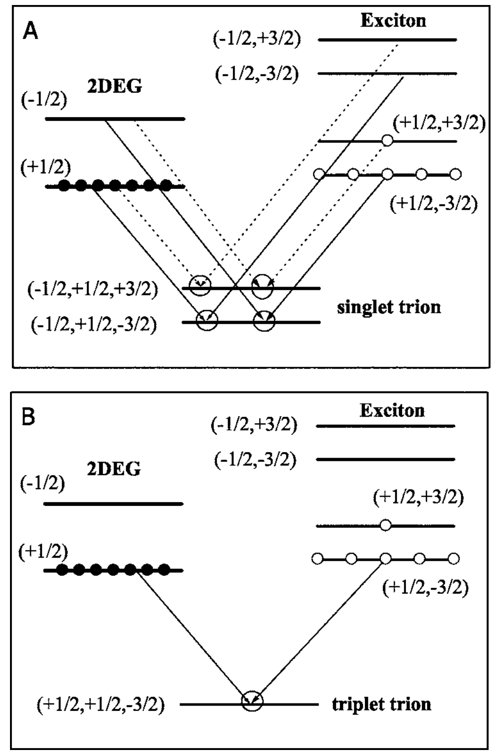

FIG. 7. The scheme of (a) singlet and (b) triplet trion formation mechanism.

ergy. The result is in qualitative agreement with theoretical calculations of the binding energy of the dark triplet trion state.[2,15,17,30] Following Ref. 29, we present here a calculated curve with the coefficient: $0.1e^2/\varepsilon g$, here ε is the dielectric constant, e is the charge of the electron, and l is the magnetic length.

As previously mentioned,[2,15,17] the optical transitions into (from) the triplet states are dipole forbidden due to orbital momentum considerations. Why, then, do these optically forbidden states appear so prominently in PL?[11] To answer this question we consider the mechanism of singlet and triplet trion formation in high magnetic field.

A. The trion formation mechanisms

The intensity of any PL line is given by the product of the population and the probability of the optical transition. Let us examine the mechanisms of the singlet trion formation [Fig. 7(a)]. In high enough magnetic field the electrons in 2DEG are completely spin polarized, i.e., they occupy the lowest Zeeman sublevel with $S_z=+\frac{1}{2}$ and leave the upper Zeeman sublevel with $S_z=-\frac{1}{2}$ completely empty. Consequently the singlet trions can be formed only by the bright excitons with momentum +1, or by the dark excitons with momentum −2 [see Fig. 7(a)] because the electron spins in the singlet state must be antiparallel. These excitons levels are the highest in energy and their population is close to zero in high magnetic fields (it is defined by the ratio of the trion formation time and the spin lifetime). Thus the formation of the singlet trion is suppressed by magnetic fields and the population of the singlet state is very small. The scheme is similar to the one that was first suggested in Ref. 23 and then confirmed in Ref. 26 by cyclotron resonance measurements, see also Ref. 31.

In contrast to the singlet trion, the triplet trion can be formed from the excitons and electrons both occupying the lowest Zeeman sublevel [Fig. 7(b)]. As the magnetic field increases, this state becomes predominantly populated. Thus, the intensity of the singlet trion PL line should fall in both polarizations, while the intensity of the T_t^d line rises, as the magnetic field grows. For the same reason, the intensity of the neutral exciton line X increases with increasing magnetic field in σ^- polarization. The intensity of the T_s line is nonzero in high magnetic fields only because of the increased probability for additional population of this state via bright trion states which appear in high field limit. Despite the fact that the optical transition from the lowest triplet trion state is dipole-forbidden by orbital momentum,[2,15,17] this line can be observed owing to its preferable population in magnetic field.

B. Model calculation of the exciton-trion system

A model calculation of the multilevel exciton-trion system using 12 kinetic equations was carried out. We consider four levels of hot excitons, four levels of cold excitons $(\pm 2, \pm 1)$, two levels of singlet trion states $(\pm 3/2)$, two levels of triplet trion states—dark and bright $(-\frac{1}{2})$, and two electron levels. The equations can be represented in the form

$$\frac{\partial n_i}{\partial t} = \Sigma(n_j w_{ji} - n_i w_{ji}) + g_i - n_i/\tau_i^{rec}. \qquad (3)$$

Here n_i is the exciton concentration on the ith level, w_{ij} is the transition rate from the ith level to the jth level, g_i and n_i/τ_i^{rec} are the generation and recombination rates for the ith level, correspondingly. The transition rate between levels i and j is proportional to the inverse relaxation time from the ith to jth level $1/\tau_{ij}$. No fitting parameters are used in this calculation. A similar set of parameters was used in Ref. 26 for CdTe-based quantum wells and was discussed there. The ratio between these parameters are similar to those in Ref. 32

for GaAs QWs and in Ref. 25 for ZnSe based QWs scaled according to the exciton binding energy. To find a relation between the forward (w_{ij}) and reverse (w_{ji}) transition rates, we assume that for infinite lifetime the system should reach an equilibrium condition. We take into account that the relaxation process from exciton to trion is a chemical reaction (see Ref. 26). Therefore the equilibrium condition can be represented as

$$\frac{w_{ij}^{diss}}{w_{ji}^{form}} = \frac{kT}{E_F}\frac{m_X}{m_T}\exp(-E_b/kT). \tag{4}$$

Here m_X and m_T are the exciton and trion masses, E_F is the Fermi energy of the 2DEG, and E_b is the trion binding energy. Note that trion dissociation may play an important role at higher temperature, but is negligible at liquid helium temperatures. To relate the hot exciton sublevels and the cold exciton sublevels we take into account the Boltzmann distribution of the hot excitons among the states with different wave vectors; thus the thermal equilibrium condition has the form

$$\frac{w_{ij}^{cold}}{w_{ji}^{hot}} = \exp(\Gamma_h/kT) - 1, \tag{5}$$

where Γ_h is the light cone energy. The transition rates within the sublevels of the same kind (hot excitons; cold excitons; trions) are simply related by the thermal equilibrium condition described by the Boltzmann distribution $w_{ij}/w_{ji} = \exp(\Delta ij/kT)$, where $\Delta_{ij}=E_i-E_j$ is the energy difference between ith and jth levels. The electron levels are populated according to the Fermi distribution among all the electron Landau levels. We adopted a simplified expression for the distribution taken from Ref. 22. A similar system of equations was solved in Refs. 25 and 26, for the exciton-singlet trion system. In our work we also take into account the dark and bright triplet trion states. For the bright triplet we assume that it is unbound at magnetic fields from 0 to 35 T, and bound in the range from 35 to 45 T.

The energy levels in magnetic fields for exciton and trion are shown in Fig. 8. We used the value of electron g-factor $g_e=1.56$,[28] magnetic field dependence of the hole g factor is taken from the paper[26] and the dependence of the triplet states binding energy is determined in our work. We assumed that the spin of the exciton as a whole can relax independently in addition to the relaxation by consecutive spin-flips of electron and hole. Such a mechanism was discussed in Ref. 32

The values for the characteristic times were chosen as follows: the trion formation time (for triplet and singlet states) $\tau_{form}=10$ ps, the electron spin relaxation time $\tau_e = 150$ ps and the hole spin relaxation time $\tau_h=70$ ps, the spin relaxation time of exciton as a whole $\tau_X=30$ ps, the relaxation time between bright triplet and dark triplet $\tau_m=40$ ps, the hot exciton thermalization time $\tau_k=12$ ps, the exciton and singlet trion radiative lifetime $\tau_X^{rec}=40$ ps and $\tau_{T_s}^{rec} = 60$ ps, respectively, the dark triplet trion radiative lifetime $\tau_{T_t^d}^{rec} = 100\times\tau_{T_s}^{rec}$ and the bright triplet radiative lifetime $\tau_{T_t^b}^{rec} = 80$ ps. The splitting between optically dark excitons with

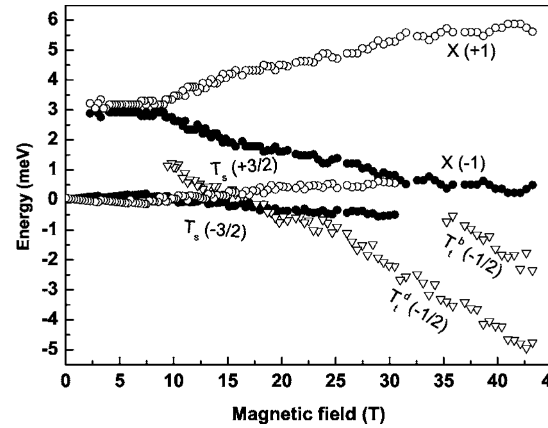

FIG. 8. The relative energies of the X, T_s, T_t^d, and T_t^b states after correction by diamagnetic shift and Zeeman splitting of the final state. Circles—exciton and singlet trion in σ^+ (open symbols) and σ^- (closed symbols) polarizations. Triangles represent dark and bright triplets in σ^- polarization.

$S_z=\pm 2$ and optically active excitons with $S_z=\pm 1$ was taken to be $\tau_X=0.2$ meV.[26] The ratio of the triplet and singlet trion radiative lifetimes was chosen nearly equal to the ratio of the oscillator strengths of $1S$ and $2P$ states in an exciton.[33]

Figure 9 shows the calculated dependence of the PL intensities of all the spectral lines on the magnetic field. There is a good agreement with the experimental data (Fig. 4). Our results coincide also very well with the results presented in Ref. 26 for magnetic fields up to 20 T, particularly describing the negative sign of the circular polarization of the singlet trion. The calculated results are not sensitive to the chosen set of the parameters. It is only important that $\tau_{form} < \tau_X < \tau_h, \tau_e, \tau_X^{rec}$, as discussed in Ref. 26.

Figure 9 shows that the dark triplet trion PL line should be clearly seen down to 7–10 T, even though the probability of the optical transition from the dark triplet trion state was chosen to be two orders of magnitude less than that of the allowed transition. As the magnetic field grows, its intensity rises and saturates at 23 T. The intensity of the dark triplet trion PL line in high magnetic fields becomes comparable

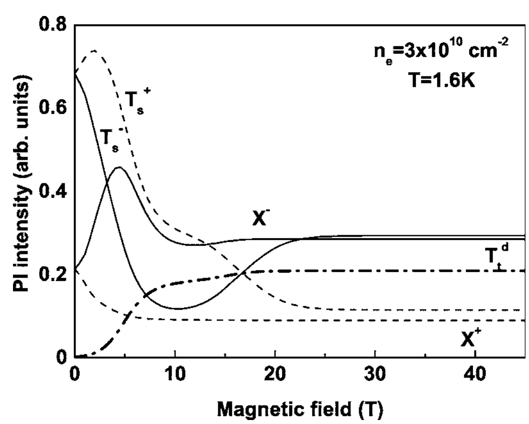

FIG. 9. Calculated magnetic field dependence of the intensities of all the PL lines: Exciton (X) and singlet trion (T_s) in both σ^+ (dashed lines) and σ^- (solid lines) circular polarizations, and also the dark triplet $(T_t^d$, dot-dashed curves).

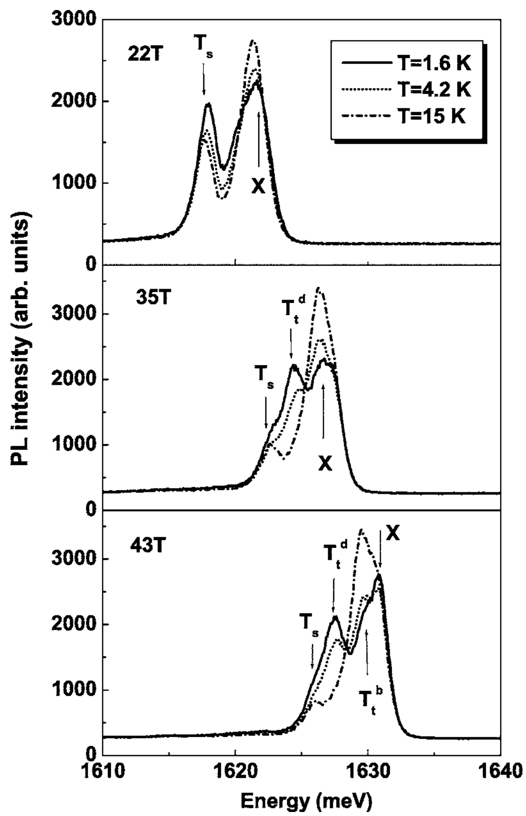

FIG. 10. Modifications of the PL spectra in σ^{-} polarization with temperature at magnetic fields 28, 35, and 45 T. Solid line −1.6 K, dotted line −4.2 K, dashed-dotted line 15 K.

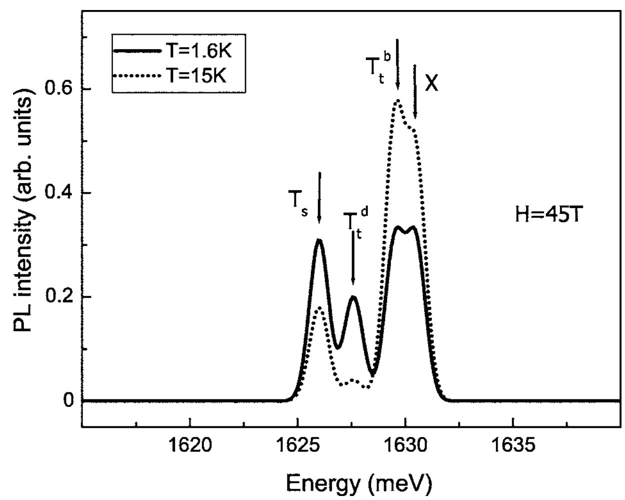

FIG. 11. Calculated PL spectra at temperature 1.6 K (solid line), and 15 K (dotted line) in a magnetic field of 45 T.

with that of the exciton luminescence line. The overall features and trends exhibited by the data are reproduced by the model. However, quantitative agreement between the calculations and the experiment requires precise knowledge of the characteristic times for all processes. These parameters, determined by time-resolved experiments, could be a task for future studies.

C. Temperature dependence

We have also measured the temperature dependence of the PL spectra (Fig. 10). With increasing temperature, emission from the dark triplet line T_t^d is suppressed, while the bright triplet line T_t^b becomes more intense (Fig. 10). The total PL intensity is conserved, indicating weak nonradiative recombination. The intensities of the singlet trion and exciton depend only slightly on the temperature. Thus the temperature redistribution occurs mainly between dark and bright triplet states, but not between T_t^d and T_s states. The fact that the states with higher binding energy disappear and the states with lower binding energy enhance in the spectra looks very unexpected. This clearly indicates that the temperature redistribution of the lines' intensities is related to the kinetics of the population of the respective states.

We assumed that the relaxation time between T_t^b and T_t^d triplet states, being orbital momentum relaxation, is short (40 ps) in comparison with the electron spin relaxation time (150 ps) between triplet and singlet. Hence, the time of the temperature repopulation from T_t^d into T_t^b is relatively short as well. Taking into account the high population of the dark triplet level T_t^d and its long radiative recombination time (3–6 ns), it is natural to expect that temperature-induced repopulation leads to a decrease of the T_t^d line intensity, and a simultaneous increase of the T_t^b line intensity. We note that there might be an exception for the narrow range of magnetic fields close to the crossing of triplet T_t^b and T_t^d and singlet T_s levels.

Using our model we have simulated the PL spectra at 1.6 and 15 K in a magnetic field of 45 T. Figure 11 demonstrates a qualitative agreement between calculated and experimental spectra. It is clearly seen that the intensity of the dark triplet and singlet decreases with an increase in temperature, whereas the intensity of the bright triplet and the exciton increases.

VI. CONCLUSIONS

PL and reflectivity spectra have been measured in $Cd_{0.7}Mg_{0.3}Te/CdTe$ modulation-doped QWs in high magnetic fields. The following results have been obtained.

(1) Optically allowed and optically forbidden triplet trion states have been observed.

(2) Binding energies of the triplet trion states have been measured as a function of magnetic field.

(3) A model that explains the appearance of the dark triplet in the PL spectra has been developed. The model allows to conclude that the formation of optically active singlet trion states is suppressed by magnetic fields, whereas the formation of optically inactive (dark) triplet trion states is enhanced by magnetic fields.

(4) The model calculation of the exciton-trion system has been carried out in order to describe the observed magnetic field dependence of the PL intensities.

The ideas suggested in this paper may also be used to explain the peculiarities of the triplet trion behavior in other, e.g., ZnSe- and GaAs-based, QWs.

Depending on the magnitude and the sign of the electron and hole g factors two cases are possible.

First of all, electron and hole *g* factors can have an identical sign and the magnitude of the electron *g* factor can be smaller than that of the hole *g* factor. In this case the lower Zeeman sublevels of excitons and electrons correspond to different directions of the electron spin. Thus magnetic fields suppress the formation of the triplet state and promote the formation of the singlet state. This leads to a drastic redistribution of the PL intensities between these states. Such redistribution of the intensity from singlet to triplet was probably identified in Ref. 4 as an anticrossing of these states.

Second, electron and hole *g* factors can have different signs. In this case the lower Zeeman sublevels of excitons and electrons correspond to identical electron spin alignment. Such level structure is fulfilled in CdTe-based QWs. Hence, in this case, the magnetic fields suppress the formation of the singlet state and promote the formation of the triplet state. We believe that such a situation takes place in some GaAs-based QWs. The order of the exciton energy levels in GaAs QWs that were studied is the same as in our CdTe QWs.[9] Thus in these structures there is a preferable formation of the triplet states in high magnetic fields. This could explain a bright manifestation of the triplet lines in optical spectra taken from these structures.[8–10,34,35]

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