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Title:

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Filling-factor dependence of magneto-luminescence in II–VI QWs with 2DEG

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ABSTRACT

Photoluminescence spectra of modulation-doped quantum well structures based on II–VI semiconductors (CdTe/CdMgTe and ZnSe/ZnBeMgSe) were studied in high magnetic fields it the range of 2D electron concentrations of $(1-5)\times10^{11}$ cm^{-2}. The following peculiarities were found at low magnetic fields: (*i*) linear increase of the photoluminescence energy with increasing magnetic fields, (*ii*) jumps in this dependence at integer filling-factors, (*iii*) periodical changing of Zeeman splitting. The observed behavior are interpreted in a frame of a model which takes into account combined exciton electron recombination processes in the presence of magnetic fields.

Keywords: quantum wells, 2D electron gas, excitons, trions

INTRODUCTION

Several recent publications reported about investigations of photoluminescence (PL) spectra of quantum well (QW) structures based on III–V and II–VI semiconductors with two-dimensional electron gas (2DEG) in concentration range from 10^{10} up to 10^{12} cm^{-2} (i.e. with Fermi energy from 1 to 5 meV). These studies were carried out at high magnetic fields. A linear shift of observed PL lines to the high energies with increasing magnetic fields [1], jumps in the PL/absorption line position at integer filling-factors [2] and jumps of the PL intensity at integer filling factors [3, 5] were found. The observed picture is typical for 2D electron gas of high density — "metallic regime". The observed behavior was interpreted in the terms of integer and fractional quantum Hall effects. On the other side when the filling-factor is less than 2, PL/absorption shows a behavior typical for the dielectric phase with the presence of exciton and trion lines [4]. Till now there is no satisfactory explanation for the observed effect of the "metal–insulator" transition.

In the present paper we analyze the PL spectra in magnetic fields up to 50 T taken from modulation-doped QWs based on CdTe/CdMgTe and ZnSe/ZnBeMgSe semiconductors with 2DEG concentration $(1-5)\times10^{11}$ cm^{-2}. A qualitative explanation of the observed results by combined exciton electron recombination processes is presented.

EXPERIMENT

We have studied modulation-doped CdTe and ZnSe -based single quantum well structures (SQW) grown by molecular-beam epitaxy on (100)-oriented GaAs substrates. The electron density in the QWs was varied from $n_e \approx 5\times10^{10}$ to 5×10^{11} cm^{-2}.

A CdTe/$Cd_{0.7}Mg_{0.3}Te$ structures contain a 120 Å-thick SQW separated from the surface by a 750 Å-wide $Cd_{0.7}Mg_{0.3}Te$ barrier. These structures contain δ-layer doped by Iodine to a concentration of 2×10^{17} cm^{-3} at a distance of 100 Å from the QW. Samples with different electron densities were fabricated at the same substrate using the wedge growth mode. It allows to vary the doped level keeping all other QW parameters (QW width, barrier height, background impurity concentration, *etc.*) constant.

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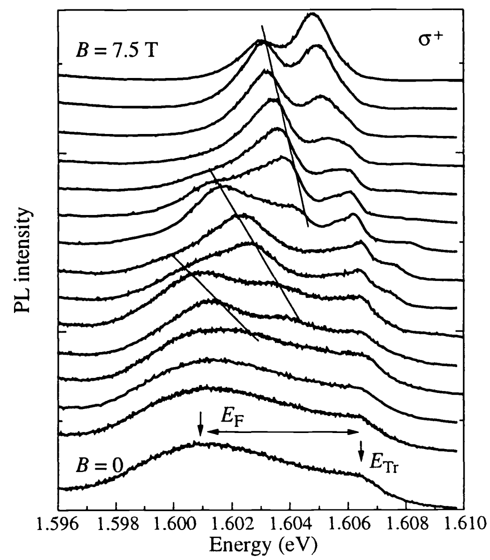

Figure 1: Photoluminescence spectra taken from a 120 Å $CdTe/Cd_{0.7}Mg_{0.3}Te$ SQW with electron concentration of 2.5×10^{11} cm^{-2} in magnetic fields from zero to 7.5 T.

$ZnSe/Zn_{0.71}Be_{0.11}Mg_{0.18}Se$ structures consists a 67 Å-thick ZnSe SQW embedded between 1000 Å-thick $Zn_{0.82}Be_{0.08}Mg_{0.10}Se$ barriers. The structures contain a δ-layer at a distance of 100 Å from the QW doped by Chlorine. A set of structures with different doping level varied from 6×10^{17} cm^{-3} to 8×10^{18} cm^{-3} was fabricated [5].

In the PL spectrum (Fig. 1) of the studied structures a wide band with two maxima was observed at zero magnetic field. The lowest in energy maximum of the line is located close to the trion resonance energy in weakly doped structure ($\hbar\Omega_{\rm Tr}$). The main, high energy, maximum is located at the energy ($\hbar\Omega_{\rm Tr} - E_{\rm F}$), (where $E_{\rm F}$ is the Fermi energy of the 2D electron gas).

In the presence of external magnetic fields the PL spectra modified strongly. First, the wide PL band starts narrowing and its low energy maximum moves to high energy one (i. e. to $\hbar\Omega_{\rm Tr}$). A weakly pronounced structure of maxima and minima appears on the line contour. This structure depends strongly on magnetic fields: the maxima shift to the low energies, the intensity of the maxima increases initially and then goes down at higher fields. At high enough magnetic fields instead of the wide PL band an arbitrary narrow PL line was observed. Such behavior was observed in CdTe-based structures as well as in ZnSe-based structures. Figure 1 illustrates the described above on an example of CdTe/CdMgTe SQW with electron density 2.5×10^{11} cm^{-2}.

In Fig. 2 we show an example of the magnetic field dependence of the main (i. e. most intensive) PL maximum for ZnSe/ZnBeMgSe SQW structure. Here we can see that the main PL maximum moves to the high energies and has leaps at integer filling-factors. The similar behavior of the main maximum was observed also in QW structures based on GaAs [1] and CdTe [2].

DISCUSSION

We explain these modifications of the PL spectra by the following way: In the absence of magnetic fields we have a trion in an initial state. The binding energy of this trion, of cause, depends on the electron density because of screening, but in 2D case a weakly bound state is still remains. After the trion annihilation we have a photon plus one electron in the final state: $Tr \to \hbar\omega_{\rm Tr} + e^*$. This residual electron e^* can be placed the empty states above the Fermi level only. Consequently, the energy of the emitted photon is: $\hbar\omega_{\rm Tr} = E_{\rm Tr} - E^*$, here: $E^* \in (E_{\rm F}, \infty)$ is the energy of the residual electron, $E_{\rm Tr}$ is the energy of the trion in the initial state.

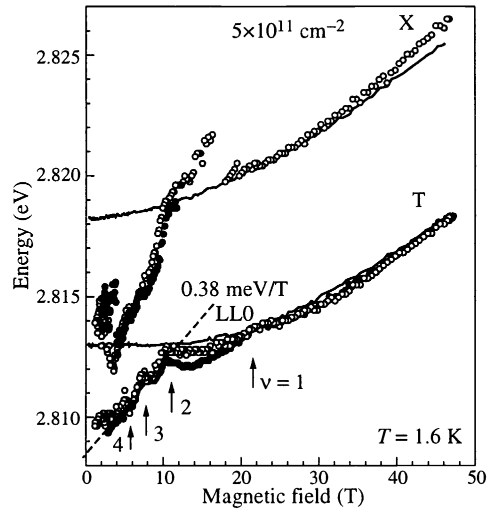

Figure 2: Energies of PL maximums vs magnetic field for an 67Å-thick $ZnSe/Zn_{0.71}Be_{0.11}Mg_{0.18}Se$ SQW 5×10^{11} cm^{-2} detected in σ^+ (open circles) and σ^- (solid circles) polarizations. (X) and (T) show exciton and trion lines in high magnetic fields [5]. Their diamagnetic shifts shown by solid lines are moved to lower energies by 7.7 meV.

Obviously, in weakly doped samples the energy of the photon emitted in the trion annihilation ($\hbar\omega_{\mathrm{Tr}}$) is equal to the trion energy (E_{Tr}). Although the residual electron after the trion annihilation can has any energy from the Fermi energy to infinity, the probability of such process decreases fast with increasing the electron energy. So, the maximum of the PL intensity is expected to be located at the energies close to ($E_{\mathrm{Tr}} - E_{\mathrm{F}}$).

Therefor, the PL maximum at the trion annihilation in heavily doped samples is shifted to lower energies from the trion PL line position in weakly doped samples. The value of this shift is of the order of the Fermi energy.

In the presence of magnetic fields the energy of the emitted photon is $\hbar\omega_c = E_{\mathrm{Tr}}(H) - E^*$, here: $E^* = (N + 1/2)\hbar\omega_c$, N is integer. In the range of magnetic fields when the magnetic length is smaller the trion radius but higher the exciton radius the trion energy goes up as: $E_{\mathrm{Tr}}(H) \approx E_{\mathrm{Tr}}(0) + 1/2\hbar\omega_c$.

So that, at low temperature a fan of Landau PL lines should be observed shifting linearly to *low energies* from the trion resonance with increasing magnetic fields (these lines are so-called "shake-up" lines).

As the upper Landau levels become empty the maximum of the PL jumps closer to the trion energy. It shifts jumping from the higher Landau levels to the lower Landau levels as higher Landau levels become empty until it reaches the trion energy. It happens just when the filling-factor is equal to 2. These leaps are washed out when the temperature of the 2DEG increases. The similar behavior will be observed due to a broadening of the Landau levels caused by a scattering processes or inhomogenity.

At sufficiently high temperature the leaps will disappear completely and the PL line will shifts to the high energies as $1/2\hbar\omega_c$. This situation is illustrated in Fig. 3 for three different temperatures and for the ZnSe/ZnBeMgSe sample with the same parameters as for the presented in Fig. 2 (see [5]). Qualitative coincidence of Fig. 3 and Fig. 2 is clearly seen.

CONCLUSION

PL spectra of modulation-doped QW structures based on II–VI semiconductors (CdTe/CdMgTe and ZnSe/ZnBeMgSe) were studied at high magnetic fields. The following peculiarities of the observed spectra were found: (*i*) shift of the PL line maxima to the high energies with increasing magnetic fields, (*ii*) leaps in this dependence at integer filling-factors. The observed experimental behavior is interpreted in a model, which takes

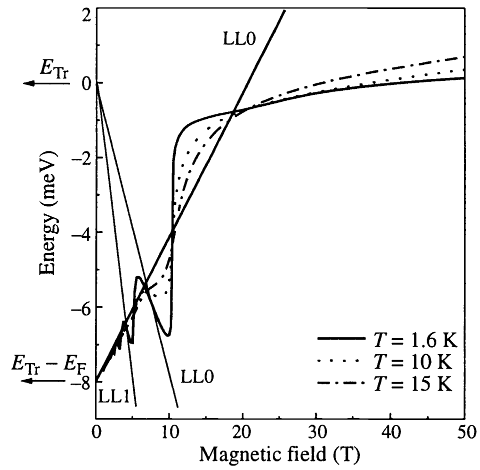

Figure 3: Scheme of magnetic field dependence of the main PL peak position, which corresponds to the case of the trion annihilation when the residual electron is left on the Fermy level. LL0, LL1,. . . : shows the Landau level fan.

into account a dependence of Fermi level on magnetic fields. Although we are speaking about trion processes we should have in mine that at high 2D electron densities the trions are screened and we have to consider them as an exponentially weak bound state of three particles. Nevertheless the processes considered above will conserve in a dense 2DEG until the excitons are unscreened and can be considered as whole particles.

ACKNOWLEDGMENTS

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