Spin properties of trions in a dense 2DEG

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Abstract. Reflectivity and photoluminescence spectra from CdTe/CdMgTe modulation doped quantum well structures were studied. We have found that the value and the sign of the trion reflectivity line’s Zeeman splitting depends on the electron concentration in the quantum well, whereas the value and sign of the exciton line splitting are absolutely equal for all studied electron concentrations. In the photoluminescence spectra the sign and value of the exciton and trion Zeeman splittings are found to be equal. Such “renormalization” of the trion g-factor is explained in the model of combined exciton electron processes.

1. Introduction

Trions in semiconductor quantum wells (QW) have been under study for a relatively long time [1, 2, 3] but there are still many unclear features in their nature. The most surprising one is the trion properties in the presence of a dense electron gas. In experimental spectra of QWs which contain a two dimensional electron gas (2DEG) it was found that the exciton absorption line disappears from the spectra at very low electron concentrations for which the Fermi energy is much less the exciton binding energy. At the same time the trion absorption liner is still conserved even at large electron concentrations where the Fermi energy is larger the trion binding energy [4]. Moreover some narrowing of the trion line was observed in these conditions. This looks strange because the trion binding energy is one order of magnitude less than the exciton binding energy and one could expect that the 2DEG should first act on the trions but not on the excitons. Additionally the trions are charged quasi particles and they must easy be scattered by electrons contrary to the excitons.

Even more unusual are the behavior of the exciton and trion spectra in the presence of magnetic fields. In magnetic fields new lines emerge in absorption, reflection and photoluminescence spectra of doped QWs. These lines move linearly with increase of magnetic field. It is remarkable that there are lines that shift to high energies with increase of magnetic field and there are lines that shift to low energies. In zero magnetic field these lines converge to the exciton absorption line that indicates the relation of these lines to the exciton state. At the same time the linear shift with magnetic field indicates their association with the free electrons [5, 6].

In the present paper we study the concentration dependence of the Zeeman splitting on the 2DEG density using reflectivity and photo luminescence in magnetic fields.
Figure 1. Reflectivity spectra taken from the CdTe/CdMgTe 80 Å width QWs with modulation doping in magnetic fields from 0 to 7.4 T in $\sigma^+$ and $\sigma^-$ circular polarizations. A). electron concentration is $2 \times 10^{10} \text{cm}^{-2}$; B). electron concentration is $8 \times 10^{10} \text{cm}^{-2}$; C). electron concentration is $3 \times 10^{11} \text{cm}^{-2}$.

Figure 2. Magnetic field dependences of the energy positions of all the lines presented in Fig.1. (X) – exciton, (T) – trion, (ExCR) – Combined exciton cyclotron resonance, (TrCR) - Combined trion cyclotron resonance. A), B) and C) correspond to Fig.1.

2. Experiment

We studied modulation-doped CdTe/(Cd$_{0.7}$Mg$_{0.3}$)Te quantum well structures with 2DEGs of different densities (from $n_e = 10^{10}$ up to $n_e \sim 10^{12} \text{cm}^{-2}$). The structures contained a 100 single quantum well (SQW) and were $\delta$-doped in the barriers at 100 distance from the QW. A special design of the structures made it possible to control the electron concentration keeping all other parameters constant with high accuracy.

In this study we compare Reflectivity and PL spectra taken from the QWs with different electron densities in magnetic fields from 0 T to 7.5 T.

Figure 1 shows the set of reflectivity spectra taken from QW structures with different electron concentration in magnetic fields from 0 to 7.4 T. The electron concentration was varied for different specimens $n_e = 2 \times 10^{10} \text{cm}^{-2}$ (Fig.1a), $n_e = 8 \times 10^{10} \text{cm}^{-2}$ (Fig.1b) and $n_e = 3 \times 10^{11} \text{cm}^{-2}$ (Fig.1c).

At very low electron concentrations (Fig.1a) in the QW only the exciton reflection line (X) is present in the spectra. Even at rather low electron concentration in the QW (Fig.1b), additionally to the exciton line (X) a trion line (T) appears in the reflectivity (absorption) spectrum. At the same time the exciton line get some broadening. In relatively high magnetic fields, the trion line becomes strongly polarized. This polarization is due to the singlet character of the trion ground state. As a result in high enough magnetic field the trion can be created in one circular polarization of photons only [1]. At higher electron concentrations the exciton reflection line nearly disappears, and the trion line gains intensity (Fig.1c). In magnetic fields, additionally to the exciton and trion lines, new lines ExCR and rCR appear in the spectra. These lines were analyzed in our publications [5, 7]. At the highest electron concentration the exciton line disappears from the spectra and the trion line conserves its amplitude.

Figure 2 shows the dependence of the energy positions of all lines taken from the reflectivity
spectra in magnetic fields for the three specimens with different electron concentrations and corresponds to Fig.1. From these dependences one can easy see that the exciton and trion lines show a normal diamagnetic shift to high energies with increasing magnetic field. At the same time lines \(\text{ExCR}\) and \(\text{TrCR}\) shift linearly with increasing magnetic field.

Additionally all these lines are split in magnetic field. At low electron concentrations the value and the sign of the exciton and trion Zeeman splittings are equal. But at high concentrations (Fig 2b and Fig 2c) the sign of the trion Zeeman splitting becomes opposite to the exciton splitting and to the splitting of other lines.

Figure 3 shows the dependences of the exciton and trion Zeeman slitting on magnetic field for the samples with different electron concentrations corresponding to Fig.1. One can see that at low concentrations the exciton and the trion splittings are the same, but with increase in electron concentration the exciton splitting is conserved but the trion splitting changes its value and even its sign.

We have also recorded PL spectra from these samples. We found that in the PL spectra the value and the sign of the trion Zeeman splitting are exactly the same as for the exciton and dose not depend on the electron concentration.

Such a concentration dependence of the trion Zeeman splitting could be interpreted as a renormalization of the trion g-factor. But in this case it is not clear why this effect is absent for the exciton and why it is absent in PL spectra.

We will try to explain the observed effect in the framework of the model of combined exciton/trion electron processes which was applied successfully to the ExCR and TrCR transitions.

3. Discussion
Let us consider the trion formation in detail. The trion absorption (reflectivity) line is formed by the binding of one photo-created exciton and one electron from the 2DEG. In the initial state of this process we have an electron \(e\) and in the final state we have a singlet trion \(Tr^s\). The scheme of such reaction is the following:

\[
e + ph \rightarrow Tr^s
\]

The energy of this transition is therefore:

\[
E_{ph} = E_{Tr} - E_e
\]

In magnetic fields the background electrons occupy Landau levels which are below the Fermi level. In the case if the filling factor \(\nu \leq 1\) the trion can form by binding of an exciton and a resident electron from the first Landau level. The energy of the corresponding optical transition is:

\[
E_{ph} = E_{Tr}(H) - \hbar\omega_c/2
\]

Because the second electron is bound very weakly to the exciton, in high enough magnetic fields (apparently higher 2T) we have:

\[
E_{Tr}(H) \propto \hbar\omega_c/2
\]

Consequently, the energy of the optical transition at the trion formation is constant with magnetic field (omitting the diamagnetic shift) as is observed in the experiment.

\[
E_{ph} = \text{const}
\]
It is easy to see that the value and sign of the trion absorption line’s Zeeman splitting is exactly the same as the value and sign of the exciton line’s Zeeman splitting [1].

At higher filling factors, when $2 > \nu > 1$, electrons can occupy two Landau levels. In such conditions one can observe the so called phenomenon of Combined Trion Cyclotron Resonance TrCR [7]. In this effect the incident photon creates a trion and simultaneously initiates a transition of an additional electron from lowest to one of the higher Landau levels. The scheme of the corresponding reaction is:

$$e_{1}^{\uparrow} + e_{1}^{\uparrow} + ph \rightarrow Tr^{s} + e_{2}^{\downarrow}$$

(2)

Here $e_{1}^{\uparrow}$ - is an electron on the first Landau level with spin $\uparrow$, $e_{2}^{\downarrow}$ - is an electron on the second Landau level with spin $\uparrow$. The energy of the optical transition in magnetic fields in this case is:

$$E_{ph} = E_{Tr}(H) + \frac{1}{2}\hbar \omega_c$$

Consequently the absorption line shifts with increase of magnetic fields to higher energies as $\hbar \omega_c$. It is obvious, that because the initial and the final spin state of the additional electron are the same the value and the sign of the observed Zeeman splitting will be the same as for the exciton line.

In these conditions another process is also possible. In this process, an incident photon creates a virtual trion in the triplet state [8, 9]. This trion produces a spin-flip with one of the electrons on the first Landau level. As a result, in the final state, we get a trion in the singlet state plus an electron on the second landau level with opposite spin. This is possible in the case if the second level is filled only partially. The scheme of the reaction looks as:

$$e_{1}^{\uparrow} + e_{2}^{\downarrow} + ph \rightarrow Tr^{t} \rightarrow Tr^{s} + e_{1}^{\downarrow}$$

(3)

The energy of the optical transition in this case is the same as for singlet trion formation. It is easy to see that the sign of the Zeeman splitting of the absorption line for this process is opposite to the Zeeman splitting of the singlet trion line in the normal process (1) and (2). Indeed, because the initial and the final spin state of the additional electron are different it will give a double contribution into the observed Zeeman splitting of the singlet trion line.

To observe such processes we need to fill two Landau levels (even neglecting spin). Consequently the anomaly of the Zeeman splitting can be observed at high enough electron concentration.

Additionally the trion line that corresponds to the process (1) and the trion line that corresponds to the process (3) are overlap. At low electron concentrations the process (1) will dominate and at high concentration the process (3) will be more important. This gives the concentration dependence of the value of the Zeeman splitting.

These can explain the observed paradoxes related to the trion Zeeman splitting without any g-factor renormalizations.

Figure 3. Exciton (X) and trion (T) Zeeman splitting as a function of electron concentration. A), B) and C) correspond to Fig.1.
4. Conclusion
In the reflectivity spectra of modulation doped QW structures, it has been found that the value and sign of the trion line’s Zeeman splitting depend strongly on the electron concentration whereas the exciton Zeeman splitting does not depend on electron concentration. We found also that the Zeeman splitting of the trion and exciton are absolutely equal in the PL spectra. The observed phenomena are explained by trion triplet – singlet conversion with simultaneous transition of an additional electron between Landau levels.

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