TITLE: Spectroscopy of Negatively Charged Excitons Interacting With 2DEG in CdTe/[Cd,Mg]Te QWs

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Spectroscopy of negatively charged excitons interacting with 2DEG in CdTe/(Cd,Mg)Te QWs

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Abstract. We report on experimental observation of a combined exciton-electron processe in which an incident photon creates a trion (negatively charged exciton-electron complex) and promotes an inter-Landau level transition of an additional electron.

Introduction

Until recently the prevailing opinion has been that the exciton-electron interactions in the presence of a two dimensional electron gas (2DEG) reduce solely to the screening of excitons by free electrons or to the band filling. Thus, the system of excitons and 2DEG was viewed as a homogeneous system without any internal structure. Here we show that in a 2DEG of low and moderate density, i.e., when $E_F \ll Ry$ (E_F is the Fermi energy of the 2DEG, and Ry is the exciton Rydberg), the internal structure of the system of excitons coexisting with electrons is quite rich.

A new type of electron-hole bound state, namely, negatively charged exciton or trion has been experimentally found in 1993 in quantum well (QW) structures with a 2DEG [1]. Since that many papers devoted to trions have been published. Trions were observed in a number of QW structures based on different semiconductor compounds, such as CdTe/CdZnTe, CdTe/CdMgTe, CdTe/CdMnTe, GaAs/AlGaAs, ZnSe/ZnMgSSe [2–4]. Negatively charged trions and positively charged trions, related to heavy holes as well as to the light holes were found and studied experimentally [5, 6]. Trion triplet states, in addition to the singlet ground states, were observed in high magnetic fields [5].

In addition to bound exciton-electron states, resonances involving three-particles have been observed in the presence of magnetic fields [7]. Such states were classified as *Combined Exciton-Cyclotron Resonances* (ExCR), meaning that in an external magnetic field an incident photon creates an exciton in its ground state and simultaneously excites one of the resident electrons from the lowest to one of higher Landau levels. The energy of these transitions is equal to the sum of the exciton energy and a multiple of cyclotron energy.

In the present paper we report the first observation of another type of combined exciton-electron process. This process involves four particles — one hole and three electrons and is similar to the ExCR. In this new process an incident photon creates a trion and simultaneously excites one of the resident electrons from the lowest to one of higher Landau levels. It appears as a pronounced resonance line in reflectivity and photoluminescence excitation spectra. By the analogy with ExCR we call this resonance as *Combined Trion-Cyclotron Resonance* (TrCR).

1. Experiment

For this study we used modulation-doped CdTe/($Cd_{0.85}$, $Mg_{0.15}$)Te QW structures with a 2DEG of low and moderate density (in this paper we report data for two structures with the electron density in the QW 8×10^{10} cm^{-2} and 1.8×10^{11} cm^{-2}). The structures contain a 120 Å single QW and are modulation doped in the barriers at 100 Å distance from the QW. A special design of the structures made it possible to control the electron concentration keeping all other QW parameters (QW width, barrier height, background impurity concentration, etc.) constant with a high accuracy [8]. We studied reflectivity and photoluminescence excitation (PLE) spectra in magnetic fields applied in the Faraday geometry in σ^+ and σ^- circular polarizations. Electron concentration in the QW has been found from magnetoreflectivity spectra. The details of method for determination of 2DEG density are presented in Ref. [9].

Figure 1(a) shows a reflectivity spectrum taken from 120 Å thick CdTe/$Cd_{0.85}Mg_{0.15}$Te single QW with electron concentration 8×10^{10} cm^{-2} at 1.6 K. Only the trion line X^- reveals in this spectrum. Strong modifications of this spectrum are observed in magnetic fields [Fig. 1(b)]. In addition to the trion (X^-) and the weak exciton (X) reflectivity lines two new lines appear in magnetic fields, namely, the Combined Exciton-Cyclotron Resonance (ExCR) line and the Combined Trion-Cyclotron Resonance (TrCR) line. The ExCR line appears at energies higher than that of the exciton ground state and the TrCR line is observed between the exciton and the trion reflectivity lines.

Photoluminescence excitation spectra show even more remarkable modifications in the presence of magnetic fields. Figure 1(c) shows the PLE spectra for the structure with the electron concentration 8×10^{10} cm^{-2} at zero magnetic field. Two lines (of about equal intensities) were observed in the PLE spectrum — the exciton line (X) and the trion line (X^-). In the presence of magnetic fields again two new lines ExCR and TrCR appear in the PLE spectra [see Fig. 1(d)]. The behavior of these lines in PLE spectra is similar to that in reflectivity spectra.

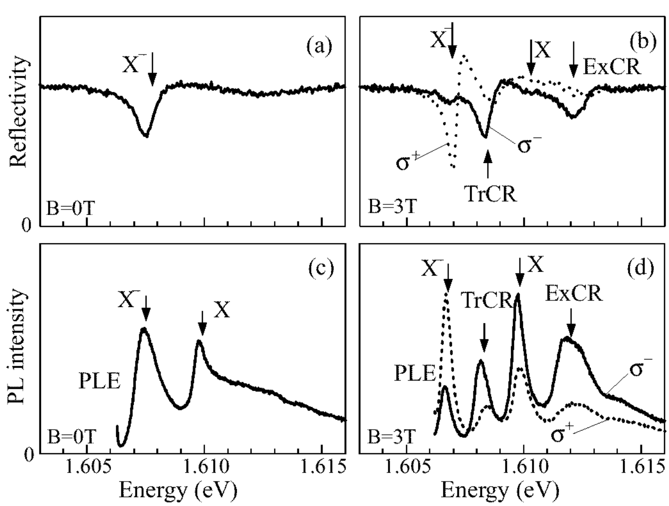

Fig. 1. Reflectivity (a),(b) and PLE (c),(d) spectra taken in a CdTe/$Cd_{0.85}Mg_{0.15}$Te SQW with an electron concentration of 8×10^{10} cm^{-2} in zero magnetic field [(a),(c)] and in a magnetic field of 3 T [(b), (d)] in σ^+ (dotted) and σ^- (solid) circular polarizations.

2. Results and discussion

Figures 2(a) and 2(b) show magnetic field dependencies of the energy position of the exciton (X), trion (X^-), and combined resonance (ExCR) and (TrCR) lines for two electron concentrations in the QWs. The line corresponding to the Combined Exciton-Cyclotron Resonance (ExCR) shows a linear shift to higher energies with increasing magnetic fields. Its position approximated to the exciton ground state when the field goes to zero. The slope of this dependence is described by the relation $E_{\mathrm{ExCR}} = (1 + m_e/M)\hbar\omega_c$ [7], here m_e is the electron effective mass, M is the exciton mass, ω_c — cyclotron frequency. This process could be explained in the following way: an incident photon creates an exciton in its ground state and promotes an excitation of an additional electron from the lowest to higher Landau levels.

The combined trion-cyclotron resonance line (TrCR) appearances different from the ExCR ones. This line can only be observed in the magnetic fields corresponding to the filling factors (ν) between 3 and 1. The fact that the line disappears at the filling factors $\nu < 1$ supports the idea that the process requires two additional electrons, as at filling factors higher than 1 one can find two electrons at the same point of the sample only. The position of this line tends to the trion energy as the magnetic field vanishes. The energy of the line position depends linearly on magnetic fields. The slope of this dependence is described by the relation $E_{\mathrm{TrCR}} = 1/2\hbar\omega_c$.

We assign this line to four-particle processes, which involve three electrons and one hole. Incident photon creates a trion and causes another electron to be excited between the Landau levels. In Fig. 2(b) one can see two transitions of this type: TrCR1 and TrCR2. So, in the initial stage we have two electrons in 2DEG and one photon, then the photon creates an exciton, which binds one electron, and in the final stage we have one trion and one electron in the one of higher Landau levels. The photon energy of this combined transition is:

$$1/2\hbar\omega_c + 1/2\hbar\omega_c + ph \rightarrow Tr + 3/2\hbar\omega_c. \quad (1)$$

The expected energy of the line position is, thus, $E_{\mathrm{TrCR}} = E_{\mathrm{Tr}} + 1/2\hbar\omega_c$.

In conclusion, in CdTe-based QW structures, we found a new type of combined exciton processes, which involve four particles: one hole and three electrons. These combined processes were studied in magnetic fields up to 7.5 T in reflectivity and PLE spectra.

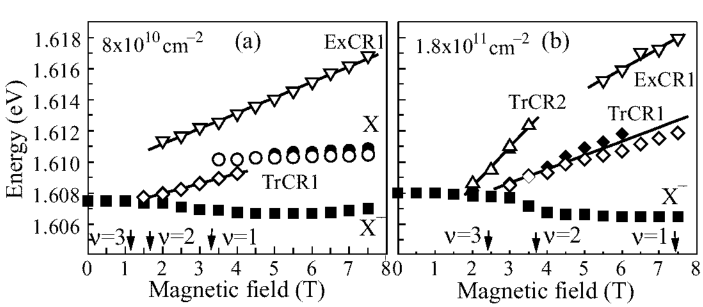

Fig. 2. Magnetic field dependencies of the energy position of the exciton (X), trion (X^-), ExCR and TrCR lines for $CdTe/Cd_{0.85}Mg_{0.15}Te$ SQW with the electron concentrations 8×10^{10} cm^{-2} (a) and 1.8×10^{11} cm^{-2} (b). Arrows indicate the values of the filing factor. Closed symbols correspond to σ^+ and open σ^- polarizations.

Acknowledgements

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