Temperature Effects on Exciton and Trion States in CdTe Quantum Well Structures

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We study the temperature-dependent modifications of trion and exciton photoluminescence (PL) spectra in modulation-doped CdTe/CdMgTe quantum wells in high magnetic field. We find that, in magnetic field, the temperature-dependent redistribution of exciton and trion PL intensities is opposite to that expected from a simple Boltzmann distribution model. Solving a system of rate equations that describe the exciton-trion energy levels, we calculate the temperature dependence of the exciton and trion PL intensities. The calculations show good agreement with the experimental data.

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I. INTRODUCTION

The many-electron problem is a central problem encountered in many fields of modern physics, including plasma, nuclear and condensed matter physics. In condensed matter systems, one of the most important examples of a many-electron system is a multi-electron complex in a semiconductor nanostructure. The primary of them is the negatively charged “trion” - and exciton-electron complex consisting of one hole bound to two electrons. The properties of trions in semiconductors are in many respects similar to those of the negatively charged hydrogen ion (one proton bound to two electrons) observed in the spectra of stellar atmospheres. Trions in semiconductor quantum wells were first experimentally observed in 1993 [1]. Since then, trions have been intensively studied in various semiconductor heterostructures. Singlet and triplet trion states have been studied in electron-doped quantum wells based on different semiconductor materials and at different electron concentrations in magnetic field. To date, however, many trion properties remain unresolved. In this work we study temperature-dependent changes in the trion and exciton photoluminescence spectra in modulation-doped CdTe/CdMgTe quantum wells in high magnetic fields from 0 to 45 Tesla.

II. EXPERIMENT AND RESULTS

CdTe/Cd$_{0.7}$Mg$_{0.3}$Te structures with a single 100Å quantum well (QW) grown on (100) GaAs substrates are studied. An iodine-doped δ-layer is located 100Å from the QW. We study a series of such heterostructures grown during one epitaxial growth using a wedge-doping technique: the structures are different only in the doping level in the δ-layer (and therefore the 2DEG density). The electron concentration in the QW varies from $10^{10}$ cm$^{-2}$ to $10^{12}$ cm$^{-2}$. Polarized photoluminescence (PL) from these samples was measured with magnetic fields applied in the Faraday configuration. A capacitor-driven 50T pulsed magnet having a 400 ms pulse duration was used. The samples were excited by a frequency-doubled diode-pumped YAG laser at $\lambda=532$ nm. A complete set of field-dependent PL spectra was collected during each magnet pulse, at a temperature of 1.6K, 4.2K and 15K. Optical fibers were used for optical illumination of the sample and collection of PL, and the PL was detected in both circular polarizations $\sigma^+$ and $\sigma^-$. Figure 1 shows a set of PL spectra taken from a CdTe/Cd$_{0.7}$Mg$_{0.3}$Te quantum well structure having electron concentration $n_e = 3 \times 10^{10}$ cm$^{-2}$ in magnetic fields from 0 to 45T at T=1.6K in $\sigma^-$ circular polarization. We do not show here the spectra in $\sigma^+$ circular polarization because they are less informative.

In zero magnetic field the spectrum is dominated by the PL line of the singlet trion state $T_s$. With increasing magnetic field the recombination line of the exciton $X$ is revealed in the spectra starting from ∼3T. In higher magnetic fields (H≥20T) an additional PL line from dark triplet trion states $T^d_t$ emerges in the spectra. At the same time the singlet trion line loses amplitude, while the exciton line retains its intensity. In very high magnetic fields (H≥35T) the PL line of the bright triplet state $T^b_t$ separates from the exciton line. The intensity of the bright triplet line is comparable to that of the exciton.

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However, due to a small binding energy of this state and appreciable widths of the lines, they partially overlap. A detailed classification of the spectral lines of the CdTe-based QW is given in [12].

Fig. 2 shows temperature-induced modification of PL spectra taken from this sample in circular polarization in a magnetic field of 5T. It is evident that the singlet trion PL line \( T_s \) gains intensity with increasing temperature, while the intensity of the exciton PL line \( X \) falls. The integrated intensity is conserved. Such redistribution of intensities is unusual, since one should expect that increasing temperature should populate higher energy states and deplete the lower-lying states according to Boltzmann factor \( \exp(-\Delta E/KT) \) - in direct contrast to the data. This observation directly indicates the nonequilibrium nature of the observed PL.

An unusual temperature-dependent behavior of the trion and exciton PL was also observed in high magnetic fields. Figure 2b shows the PL spectra of the same sample at 28 Tesla for three temperatures: 1.6K, 4.2K and 15K. Along with the exciton \( X \) and the singlet trion \( T_s \) PL lines, a PL line of the dark triplet trion \( T^d_t \) was observed in these spectra. It is obvious that in this case the temperature-induced redistribution of the intensities of the different spectral lines also takes place. However in this case the picture is reversed: the PL intensities of singlet and dark triplet trion states fall when temperatures rise, while the intensity of the higher-energy exciton line increases. Since the temperature-dependent intensity redistribution in low magnetic field (5T) is reversed from the one observed in high field (28T), one may expect at some intermediate field that no temperature-dependent intensity redistribution between exciton and trion lines exists at all. Indeed, in the range of the magnetic fields between 14 and 18T such redistribution of intensities is not observed in the spectra. At the highest magnetic fields the scenario changes yet again. Figure 2c shows temperature-dependent PL spectra at 43 Tesla. In magnetic fields of this magnitude the PL intensities of the singlet trion \( T_s \) and the dark triplet trion \( T^d_t \) fall with growing temperature, while the intensity of the bright triplet PL line \( T^b_t \) significantly increases. The intensity of the exciton line does not noticeably change. This also appears surprising since the binding energy of the bright triplet trion \( T^b_t \) \((\sim 1 \text{ meV at } 40 \text{ Tesla})\) is small compared to the binding energy of the dark triplet \( T^d_t \) \((\sim 3.5 \text{ meV at } 40 \text{ Tesla})\). Moreover, the binding energy of the \( T^b_t \) state is comparable to temperature.

III. DISCUSSION

This unusual temperature-dependent behavior of exciton and trion PL indicates its non-equilibrium nature.
we solved a system of rate equations with parameters. In order to calculate the PL intensities, inclusions are confirmed by calculating exciton and trion be opposite and should comply with a Boltzmann distribution will change the sublevel populations of dark (+2) exciton (+1).

As a result, the lower trion Zeeman component (-3/2) which is active in \( \sigma^- \) polarization will be populated by an electron (+1/2) bound with a dark exciton (-2), while the upper trion Zeeman component, active in \( \sigma^+ \) polarization will be populated by an electron (+1/2) bound with a bright exciton (+1).

When the temperature increases, a redistribution of electron and exciton populations within these sublevels occurs according to the Boltzmann factor. The redistribution will change the sublevel populations of dark (+2) and bright (-1) excitons in favor of the dark exciton and background electrons (+1/2) and (-1/2) because of the small value of the hole g-factor. As a result, the exciton PL intensity in polarization will fall, while the intensity of trion radiation in the same polarization will rise. As seen from Figure 3, the temperature-induced redistribution of exciton and trion PL intensities in \( \sigma^+ \) polarization should be opposite and should comply with a Boltzmann distribution, as also observed in the experiment. These conclusions are confirmed by calculating exciton and trion PL intensities. In order to calculate the PL intensities, we solved a system of rate equations with parameters used in.

\[
\frac{\partial n_i}{\partial t} = \sum (n_j w_{ji} - n_i w_{ij}) + g_i - n_i / \tau_i^0. \tag{1}
\]

Here \( n_i \) is the population of the sublevel, \( w_{ij} \) is the transition rate from \( i \)-th sublevel to \( j \)-th sublevel, \( g_i \) is the generation rate on \( i \)-th sublevel, \( \tau_i^0 \) is the radiative lifetime of the \( i \)-th sublevel. Figure 4a shows the calculated results of the temperature dependences of the exciton and trion PL intensities and the experimental data for 1.6K, 4.2K and 15K temperatures at 5T. The experimental data and calculated curves show very good agreement. We have also performed a calculation for other values of magnetic field. As seen from the experiment, in high magnetic fields the temperature dependence of the spectra is qualitatively different from the one in low fields. Figures 4b and 4c present the calculation results of temperature dependences of exciton and trion PL for 28T and 43T magnetic fields. The qualitative agreement between experiment and calculation is also observed here. According to theoretical predictions and experimental observations, in high magnetic fields triplet trion states appear along with the singlet states. The dark triplet line \( T_d^3 \) is distinctly observed in the PL spectra starting from 15T, while the bright triplet line \( T_b^3 \) appears as separate spectral line at fields exceeding 35T. At low fields this line merges with the exciton PL line. This explains the intensity increase of the dark triplet PL in the field range between 22T and 30T. At higher field, when the exciton and bright triplet lines are well separated, it is evident that increasing temperature leads to the enhancement of the bright triplet line instead of the exciton line. Therefore, figures 4b and 4c also show the calculated curve for the sum of exciton and bright triplet intensities.

We explain the enhancement of the bright triplet trion intensity by the influx into this state from the reservoir of dark triplet trions. The concentration of the dark triplet states is very high due to its short formation time and its long lifetime, which is at least three orders of magnitude different. This qualitative argument is fully supported by the calculated PL intensities of all the spectral lines, presented in figures 4b and 4c.

IV. CONCLUSIONS

Modifications of trion and exciton PL spectra with temperature in modulation-doped CdTe/CdMgTe quantum wells in magnetic fields have been studied. We found that in magnetic field the temperature redistribution of the exciton and trion PL line intensities is opposite to the one expected in a simple Boltzmann distribution model. Solving a system of kinetic equations that describe the exciton-trion system, we calculate the temperature dependence of the exciton and trion PL intensities. The calculated dependences show good agreement with the experimental data.
FIG. 4: Calculation results of temperature dependences of exciton and trion PL for 5T (a), 28T (b), and 43T (c) magnitudes of the magnetic fields. The designations of the PL features are the same as in previous figures. $T^b_1 + X$ stands for total contribution from the bright triplet and exciton PL lines. In (a) closed triangles and open rectangles stand for scaled experimental values of singlet trion and exciton PL intensities correspondingly.

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