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Magnetoluminescence of a CdTe Quantum Dot with a Single Manganese Ion in Voigt Configuration

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We present a study of the neutral exciton and negative trion recombination spectra of an individual CdTe quantum dot with a single manganese ion, in magnetic field measured in the Voigt configuration. We describe experimental results and compare with a theoretical model. The quantitative agreement between the model and the experiment allows us to determine separately the electron g-factor.

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1. Introduction

Quantum dots (QDs) with single magnetic ions have recently received a lot of interest. The simplicity of this system allows a detailed experimental study and modeling, which helps to understand the phenomena related to optical excitation and recombination of excitons confined in the dots. It has been also shown that optical information storage and read-out on the manganese spin is possible [1, 2]. Therefore, research on this system is a promising field.

The influence of magnetic field on such QDs has been mainly studied in the Faraday configuration [3, 4]. In this paper we present an experiment in the Voigt configuration and a theoretical model description of its results.

2. The sample and experimental setup

The measurements were performed on CdTe/ZnTe self-assembled QDs doped with manganese atoms. A 4 μm CdTe buffer was deposited on a GaAs substrate. Then three essential layers were grown: 0.8 μm of ZnTe, followed by a CdTe QD layer, which was capped by 100 nm of ZnTe. The manganese doping of the QD layer amounted to 0.05%.

The sample was cooled down to 1.7 K in a cryostat. A superconducting magnet produced magnetic field up to 6 T, parallel to the QD plane. The photoluminescence (PL) of the sample was excited above the barrier band gap (at 532 nm). Therefore, the carriers were photocreated outside the QDs. Then they diffused and formed excitons and higher charge states in the QDs [5, 6]. Then the recombination occurred. The laser beam was focused on the sample by a microscope objective placed inside the cryostat. The PL signal was detected with a CCD camera attached to a monochromator.

3. Experimental results

The first step of the experiment was to select a QD with a single Mn ion. Figure 1 presents the spectrum of the QD chosen for further measurements. We can clearly observe the characteristic six-line pattern originating from the neutral exciton (X) recombination in the presence of a Mn atom [7, 8]. These lines correspond to the six possible projections of the Mn spin on the quantization axis. Further groups of lines can be distinguished in the low-energy part of the spectrum. They originate from recombination of higher occupied states (X^+, X^-, XX).

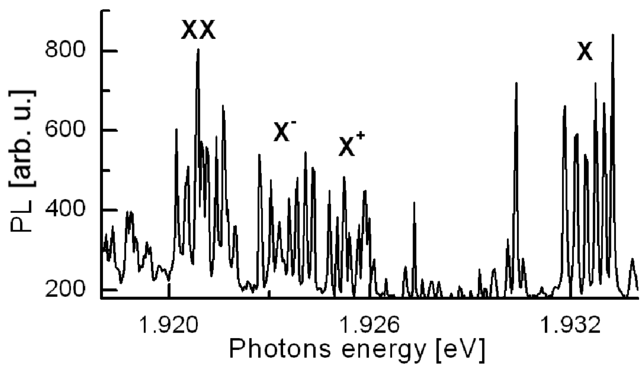

Fig. 1. The spectrum of the QD with a single manganese ion chosen for measurements.

Figure 2 shows the intensity-scale plots of neutral exciton and negative trion PL spectra versus magnetic field. The six lines of the exciton evolve with increasing magnetic field to form a symmetrical pattern of three groups. The middle one is the most intense.

In the negative trion spectrum, seven lines can be distinguished in the absence of magnetic field. Their evo-

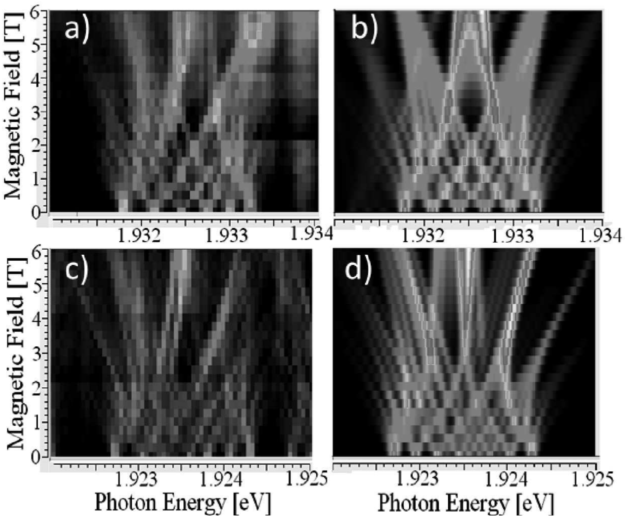

Fig. 2. Experimental magnetophotoluminescence and theoretical model for exciton ((a) and (b) respectively) and negative trion ((c) and (d) respectively).

lution with the field is more complicated. However in higher field three main groups of lines are clearly visible.

4. Theoretical model

We follow the model described in Ref. [9], supplemented by introduction of the Mn ion. The initial state of the exciton (before recombination) includes manganese ion, an electron and a hole interacting with each other and with the magnetic field $\boldsymbol{B} = (B_x, 0, 0)$:

$$H_{\mathrm{i}} = \mu_{\mathrm{B}} \left(g_{\mathrm{Mn}} \boldsymbol{SB} + g_{\mathrm{e}} \boldsymbol{\sigma B} + g_{\mathrm{h}} \boldsymbol{jB} \right) - I_{\mathrm{e}} \boldsymbol{S\sigma} - I_{\mathrm{h}} \boldsymbol{Sj} + \left(\frac{3}{2}\delta_2 - \frac{2}{3}\delta_0 \right) \sigma_z j_z - \frac{2}{3}\delta_2 \sum_{i=x,y,z} j_i^3 \sigma_i - \frac{1}{2}\Delta_{lh} j_z^2 \,,$$

where S, σ and j are manganese, electron and hole spins (5/2, 1/2 and 3/2 respectively). Their g-factors are g_{Mn}, g_{e}, g_{h} and μ_{B} stands for the Bohr magneton. The electron– manganese and hole-manganese exchange integrals are denoted by I_{e} and I_{h}, respectively. The energy distance between bright and dark exciton is δ_0 and dark exciton splitting is δ_2. Δ_{lh} governs the splitting between light and heavy holes.

After recombination only the manganese ion is left in the QD, therefore its Hamiltonian is

$$H_{\mathrm{f}} = \mu_{\mathrm{B}} g_{\mathrm{Mn}} \boldsymbol{SB} \,.$$

We must take the Pauli exclusion principle in consideration to write negative trion Hamiltonians. The two electrons in initial state form a spin singlet, therefore their interactions in the Hamiltonian sum up to 0:

$$H_{\mathrm{i}} = \mu_{\mathrm{B}} \left(g_{\mathrm{Mn}} \boldsymbol{SB} + g_{\mathrm{h}} \boldsymbol{jB} \right) - I_{\mathrm{h}} \boldsymbol{Sj} - \frac{1}{2}\Delta_{lh} j_z^2 \,.$$

In the final state the QD contains a manganese ion and an electron

$$H_{\mathrm{f}} = \mu_{\mathrm{B}} \left(g_{\mathrm{Mn}} \boldsymbol{SB} + g_{\mathrm{e}} \boldsymbol{\sigma B} \right) - I_{\mathrm{e}} \boldsymbol{S\sigma} \,.$$

For convenience we use the base of pure-spin states to carry out computations.

We use the optical transitions matrix to simulate the spectra. According to the optical selection rules a transition between pure-spin states of the system is possible only if the difference between final and initial total angular momentum equals ± 1. We assume that the manganese spin is conserved during the exciton recombination.

Then we compute the probabilities of transitions between eigenstates of initial and final Hamiltonians for exciton and negative trion. We use the expression $|\langle f|M|i\rangle|^2$, where f and i are final and initial eigenstates and M is the transition matrix. This probability is taken as a measure of the line intensity. The photon energy is equal to the difference of respective eigenvalues of states f and i.

5. Discussion

The introduced model reproduces experimental results quantitatively. The positions of lines in the absence of magnetic field and their evolution agree with a good accuracy.

This was obtained by fitting all parameters of Hamiltonians, except for the manganese g-factor assumed to be equal to 2 and δ_0 and δ_2 set to their typical values of 1 meV and 10 μeV, respectively, because they could not be determined in our experiment. Δ_{lh} was set to 40 meV to get the light and dark holes splitting around 40 meV. We also assumed the $I_{\mathrm{e}}/I_{\mathrm{h}}$ ratio to be -0.75, same as the bulk materials. This means assuming the same wave function density for electrons and heavy holes.

The fitting of the experimental spectra allowed us to obtain the value of the electron g-factor equal to -0.2. The fitting procedure was insensitive to the hole g-factor. Therefore measurements in the Voigt configuration may help to determine the values of electron and hole g-factors separately, when combined with measurements in the Faraday configuration, which supply the value of the excitonic g-factor.

6. Summary

The used theoretical model allowed us to reproduce experimental measurements of exciton and negative trion spectra in magnetic field in the Voigt configuration. Analysis of results allowed us to determine separately the electron g-factor equal to -0.2, unavailable from the bright exciton measurements in the Faraday configuration.

Acknowledgments

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