40th "Jaszowiec" International School and Conference on the Physics of Semiconductors, Krynica-Zdrój 2011

Signatures of *p*-Shell Electron *g*-Factor in *s*-Shell Emission of CdTe/ZnTe Quantum Dots

T. Kazimierczuk[a,*], M. Goryca[a], P. Wojnar[b], A. Golnik[a], M. Nawrocki[a] and P. Kossacki[a]

[a]Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Hoża 69, 00-681 Warsaw, Poland

[b]Institute of Physics, Polish Academy of Sciences, al. Lotników 32/46, 02-668 Warsaw, Poland

We analyze the photoluminescence of excitonic complexes containing *p*-shell electron in the magnetic field in the Faraday configuration. We demonstrate that despite the *p*-shell electron is not involved directly in the recombination process, its *g*-factor influences the emission spectrum. We found that in the case of CdTe/ZnTe quantum dots the *p*-shell electron is significantly less affected by the magnetic field than *s*-shell electron in the same dot.

PACS: 78.55.Et, 78.67.Hc

1. Introduction

Photoluminescence (PL) measurements are a convenient experimental technique to study properties of self-assembled quantum dots (QDs). Due to fast energy relaxation [1] the observed photoluminescence is usually related to the recombination of electrons and holes residing on the lowest (*s*-shell) orbitals. Emission from the higher shells (*p*-shell, ...) is observed only under excitation intensities strong enough to saturate the lower levels. Typically, the *p*-shell emission takes place in energies higher than *s*-shell emission of the same dot by tens of meV. Emission lines related to *p*-shell emission are therefore often overwhelmed by *s*-shell emission of other QDs in the area. Fortunately, some properties of the excited orbitals can be inferred also from the *s*-shell emission.

In this work we focus on magnetic properties of *p*-shell electron studied via *s*-shell emission of CdTe/ZnTe QDs. In particular, we will analyze the Zeeman effect of two transitions related to excitonic complexes containing *p*-shell electron: X^{2-} and XX^{-}.

2. Experimental setup

We performed PL experiments on samples containing self-assembled CdTe QDs with ZnTe barriers. The samples were grown using molecular beam epitaxy (MBE) technique with intermediate layer of amorphous tellurium to induce QD formation [2]. A surface density of obtained QDs was 10^9–10^{10} cm^{-2}. Details of the growth procedure are described in Ref. [3].

The measurements were performed at $T \approx 1.7$ K in He-bath cryostat. QDs were excited non-resonantly using frequency-doubled Ti:sapphire femtosecond laser. Reflective microscope objective immersed in the liquid He together with the sample enabled focusing on a spot of a diameter below 0.5 μm. Such spatial resolution allowed us to resolve individual emission lines related to single QDs in the low-energy tail of QD band in the PL spectrum. The PL signal was recorded using 0.5 m spectrograph with a CCD camera. Linear polarizer and wave-plates (a $\lambda/2$ and $\lambda/4$ retarder) were used in polarization-resolved measurements. Superconducting coil allowed us to apply magnetic field up to 7 T in the Faraday configuration.

3. Results

Examplary PL spectra of single dots measured in the experiment are presented in Fig. 1. The emission lines form typical pattern studied in detail previously [4, 5]. This enabled us to identify the lines related to recombination of neutral and charged excitons (X, X^{+}, X^{-}, X^{2-}) and biexcitons (XX and XX^{-}). Two of these transitions — X^{2-} and XX^{-} — include a *p*-shell electron. This electron does not directly participate in the recombination process, nevertheless it influences the emission energy through exchange interaction [5, 6]. One of the consequences of this interaction is a fine structure of these transitions as shown in Fig. 1c,d.

We will now focus on the behavior of X^{2-} and XX^{-} transitions in the magnetic field along the growth direction. It was demonstrated that in both cases the behavior observed in the experiment can be satisfactorily modelled simply assuming the same *g*-factor for electrons irrespective of the shell [5]. In general, the *g*-factors for *s*- and

* corresponding author; e-mail: Tomasz.Kazimierczuk@fuw.edu.pl

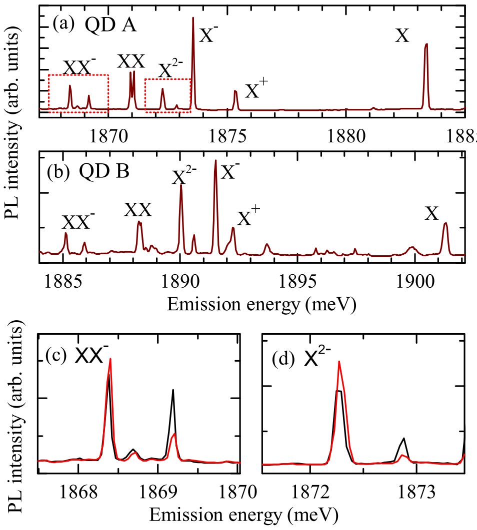

Fig. 1. (a), (b) PL spectra of single CdTe/ZnTe dots measured without polarization resolution. (c), (d) PL spectra measured in two perpendicular polarizations demonstrating fine structure of X^{2-} and XX^-.

p-shell electrons are different but in the discussed case the Zeeman effect of the hole dominates over the Zeeman effect of the electron and therefore the splittings are relatively well reproduced within the simple assumption of equal g-factors. The verification of this assumption requires precise comparison between (similar) splitting values of different emission lines of X^{2-} or XX^-.

3.1. Zeeman effect in XX^-

The difference between g-factors of electrons on different shells can be accessed by comparison of the Zeeman effect on two emission lines of XX^- recombination (Fig. 2a). In the initial state of this transition only the p-electron is affected by the magnetic field (other carriers are paired on the s-shells). The transition leads to two possible final configurations of the remaining carriers: (1) electrons in triplet $S_z = 0$ state or (2) electrons in triplet $|S_z| = 1$ state antiparallel to the hole spin. Thus, in the first case the spectral g-factor (in convention where g-factor of the neutral exciton is $g_\mathrm{h} - g_\mathrm{e}$) is given by $g_\mathrm{h} - g_{\mathrm{e}_p}$ and in the latter case the g-factor is given by $g_\mathrm{h} - g_{\mathrm{e}_s}$. These expressions are more complicated after including in-plane anisotropy but the difference between them is still given by $g_{\mathrm{e}_s} - g_{\mathrm{e}_p}$ [7].

Analysis of both splittings shown in Fig. 2b clearly evidences a difference between spectral g-factors and thus a difference between g-factors of s- and p-shell electrons. The spectral g-factors yielded, respectively, 1.43 and 1.68 for QD A and 1.38 and 1.80 for QD B. In both cases the difference is significant: 0.25 for QD A and 0.42 for QD B. The difference is striking when compared with typical value of s-shell electron g-factor $g_{\mathrm{e}_s} \approx -0.45$ [8]. For both analyzed dots the g-factor p-shell electron is thus much closer to 0 (i.e. less negative).

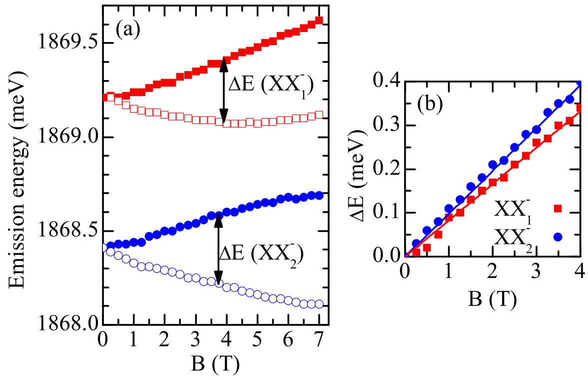

Fig. 2. (a) XX^- transition energy and (b) related splittings as a function of magnetic field for QD A.

3.2. Zeeman effect in X^{2-}

The difference between values of g-factors for s- and p-shell electrons can be studied also in magnetophotoluminescence data of X^{2-} shown in Fig. 3a. The recombi-

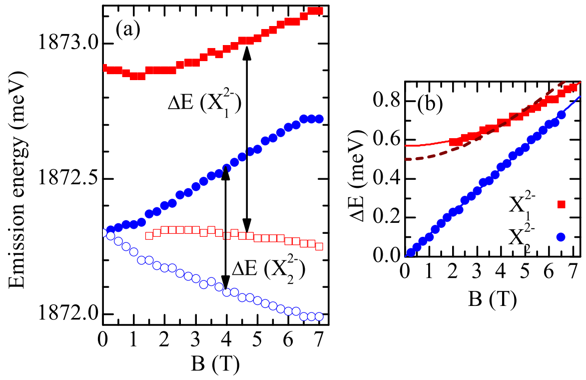

Fig. 3. (a) X^{2-} transition energy and (b) related splittings as a function of magnetic field for QD A. Solid lines present fits of linear and $\sqrt{\delta^2 + (g\mu_\mathrm{B}B)^2}$ functions to the experimental data. Dashed line presents a fit with g-factor value fixed to the value obtained from linear fit of splitting denoted by $\Delta E(X_2^{2-})$.

nation of X^{2-} splits into four lines in the magnetic field. They are organized in two pairs. One pair originates from the configuration of X^{2-} where the p-shell electron and the hole have parallel spins. These transitions lead to two electrons in $|S_z| = 1$ triplet state. In such a case the spectral g-factor is given by $g_\mathrm{h} - g_{\mathrm{e}_s}$ as p-shell g-factor affects the initial and the final state identically. The second pair of lines originates from the configuration of X^{2-} where the p-shell electron and a hole have antiparallel spins. Such configurations are mixed with in-plane anisotropy leading to pronounced zero-field splitting. The Zeeman effect can additionally increase this splitting according to relation $\Delta E = \sqrt{\delta^2 + (g\mu_\mathrm{B}B)^2}$ where δ is the value of the anisotropic splitting and $g = g_\mathrm{h} - g_{\mathrm{e}_p}$. The same expression holds for the spectral splitting as the electrons in the final state are in $S_z = 0$ triplet configuration which is not affected by magnetic field.

Figure 3 shows that splittings of both pairs exhibit different g-factor values. The fitted values yielded, respectively, 1.95 and 1.64 for QD A and 2.00 and 1.54 for QD B. The difference between s- and p-shell electron g-factors yielded 0.31 for QD A and 0.46 for QD B. In both cases the values are comparable to the differences inferred earlier from the XX^- transition.

4. Conclusions

Our results clearly evidence the difference between g-factor values of s- and p-shell electron. This demonstration bases solely on the emission from the s-shell. Such a difference was previously observed in CdSe/ZnSe system [7], however in that case the relation of s- and p-shell electron g-factors was reversed (i.e., $g_{e_s} > g_{e_p}$). This difference is due to different relation of bulk g-factors in Se- and Te-based systems. Unlike in selenide system, in our case the conduction band g-factor of ZnTe barrier is lower (more negative) than CdTe dot material. Therefore, our results provide a strong argument supporting the interpretation introduced in Ref. [7] that the crucial factor responsible for observed g-factor variation is the difference in the barrier penetration for s- and p-orbital.

Acknowledgments

This work was supported by the Polish Ministry of Science and Higher Education as research grants in years 2009–2011, by the EuromagNetII, by the sixth Research Framework Programme of EU (contract No. MTKD-CT--2005-029671) and by the Foundation for Polish Science.

References

[1] R. Heitz, M. Veit, N.N. Ledentsov, A. Hoffmann, D. Bimberg, V.M. Ustinov, P.S. Kop'ev, Z.I. Alferov, *Phys. Rev. B* **56**, 10435 (1997).

[2] F. Tinjod, B. Gilles, S. Moehl, K. Kheng, H. Mariette, *Appl. Phys. Lett.* **82**, 4340 (2003).

[3] P. Wojnar, J. Suffczyński, K. Kowalik, A. Golnik, M. Aleszkiewicz, G. Karczewski, J. Kossut, *Nanotechnology* **19**, 235403 (2008).

[4] T. Kazimierczuk, J. Suffczynski, A. Golnik, J.A. Gaj, P. Kossacki, P. Wojnar, *Phys. Rev. B* **79**, 153301 (2009).

[5] T. Kazimierczuk, T. Smolenski, M. Goryca, L. Klopotowski, P. Wojnar, K. Fronc, A. Golnik, M. Nawrocki, J.A. Gaj, P. Kossacki, *Phys. Rev. B* **84**, 165319 (2011).

[6] T. Kazimierczuk, A. Golnik, M. Goryca, P. Wojnar, J. Gaj, P. Kossacki, *Acta Phys. Pol. A* **116**, 882 (2009).

[7] I.A. Akimov, K.V. Kavokin, A. Hundt, F. Henneberger, *Phys. Rev. B* **71**, 075326 (2005).

[8] Y. Léger, L. Besombes, L. Maingault, H. Mariette, *Phys. Rev. B* **76**, 045331 (2007).