Proceedings of the 42th "Jaszowiec" International School and Conference on the Physics of Semiconductors, Wisła 2013

Time Resolved Photoluminescence Study of the Wide (Cd,Mn)Te/(Cd,Mg)Te Quantum Well

J. Kutrowska[a], P. Bugajny[a], M. Baranowski[a], L. Bryja[a], M. Syperek[a,*], A. Wójs[a], J. Misiewicz[a], M. Wiater[b], G. Karczewski[b] and T. Wojtowicz[c]

[a]Institute of Physics, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

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

The static and dynamic properties of excitons and trions in a 80 nm wide $Cd_{1-x}Mn_xTe/Cd_{0.7}Mg_{0.3}Te$ quantum well with extremely small Mn content ($x = 0.00027$) have been studied by means of time-integrated and time-resolved photoluminescence experiment at low and elevated temperatures. The trion binding energy has been estimated to be 2.6 ± 0.8 meV. The exciton and trion lifetimes have been measured to be ≈ 150 ps, and ≈ 200 ps, respectively. The temperature dependence of both lifetimes together with the multicomponent character of the PL decay process suggest a spatial localization of excitons and trions in the investigated quantum well.

DOI: 10.12693/APhysPolA.124.895

PACS: 78.55.Et, 78.47.D−, 78.67.De

1. Introduction

Magnetic semiconductors and their low-dimensional structures are very interesting for application in future optically-controlled spintronic devices. A special place is dedicated to the II–VI semiconductor compounds, for which the introduction of a magnetic component such as Mn ions is relatively easy. In the so-called diluted magnetic or semimagnetic semiconductors, e.g. (Cd,Mn)Te, a strong *sp–d* exchange interaction between the electrons or holes and the magnetic ions is responsible for exceptional spin-related phenomena like the giant Zeeman splitting of the band states and/or formation of magnetic polaron state [1–3]. The wide energy band-gap, strong electron confinement, high exciton binding energy (higher than in III–V counterparts), and high optical quality make the spin dependent phenomena easily controlled and tested by means of existing optical methods, even at elevated temperatures.

Since the control and manipulation of the spin dependent processes in such quantum systems are governed by the electron and hole or exciton (the Coulomb bound electron and hole) dynamics, therefore it is of great importance to provide information about the particle or quasiparticle state evolution.

In this work, we report on the investigation of exciton recombination dynamics in a wide $Cd_{1-x}Mn_xTe/Cd_{0.7}Mg_{0.3}Te$ quantum well grown by molecular beam epitaxy on a GaAs substrate. Such a quantum well system is characterized by a relatively deep confining potential, weak two-dimensional quantization along the growth direction, and an extremely small Mn mole fraction. All of these key parameters distinguish the quantum well system from those studied so far. The structure has been investigated by photoluminescence and time-resolved photoluminescence experiments.

*corresponding author; e-mail: marcin.syperek@pwr.wroc.pl

2. Investigated structures and experimental details

The $Cd_{1-x}Mn_xTe$ quantum well sample was grown in a molecular beam epitaxy process on a GaAs substrate. The quantum well width is equal to 80 nm and manganese atoms concentration within the well is extremely low: $x = 0.00027$. The manganese molar fraction was determined from low temperature ($T = 1.4$ K) reflectivity experiments [4]. The quantum well barrier is made of $Cd_{0.7}Mg_{0.3}Te$, which in consequence leads to a high confinement potential for electrons and holes in the well. The quantum well system is nominally undoped, however, quantum wells with (Cd,Mg)Te barrier are often *p*-type because of surface states which act as acceptor centers [5].

For photoluminescence and time-resolved photoluminescence experiments the sample was held in a closed-cycle helium refrigerator which allows changing the sample temperature in the range of 10–300 K. In the case of photoluminescence and time resolved photoluminescence experiments with the streak camera detection, the quantum well structure was excited by the train of pulses from a mode-locked Ti:sapphire laser after frequency doubling of its output. The laser pulse duration was ≈ 160 fs, at a repetition frequency of ≈ 76 MHz, with a photon energy of 3.1 eV (400 nm). The photoluminescence signal was detected by a liquid nitrogen cooled Si charge coupled device camera combined with a 0.3 m focal length single grating monochromator. The streak camera system based on an S20 photocathode was attached to a monochromator, allowing spectral and temporal analysis of the photoluminescence signal. The effective time

resolution of the setup was ≈ 20 ps, whereas spectral resolution was around 0.8 meV.

3. Experimental results and discussion

Figure 1a shows temperature evolution of photoluminescence spectra registered for the investigated (Cd,Mn)Te/$Cd_{0.7}Mg_{0.3}Te$ quantum well after non-resonant excitation by the train of laser pulses. At temperature $T = 10$ K, two photoluminescence features are clearly resolved, and are spectrally located at 1.6106 eV and 1.6080 eV. With increasing temperature, both photoluminescence lines shift parallel toward low energy (Fig. 1b), which is accompanied by a drop of the peak intensity (Fig. 1c). One can see in Fig. 1c that the lower energy transition diminishes in intensity with the temperature growth much faster than the high energy one, and finally disappears in temperatures above $T = 30$ K ($k_BT \approx 2.6$ meV). This temperature corresponds to the energy distance $\Delta E = 2.6 \pm 0.8$ meV between observed photoluminescence peaks. These data suggest the existence of some correlation between both optical transitions.

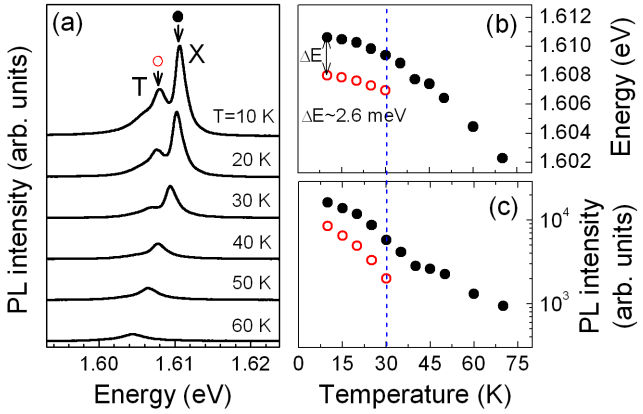

Fig. 1. (a) Photoluminescence spectra as a function of temperature for 80 nm wide (Cd,Mn)Te/$Cd_{0.7}Mg_{0.3}Te$ quantum well. X (full circle) and T (open circle) denote the exciton and trion transition in the well. (b) Temperature dependence of the exciton (full circles) and trion (open circles) photoluminescence peak positions, and (c) intensities. The photoluminescence spectra measured under non-resonant excitation $E = 3.1$ eV by the pulse laser source.

Tentatively, we can assume that the high energy transition corresponds to the radiative recombination of neutral exciton (X), whereas the low energy transition is related to the charged exciton recombination — trion (T), both confined to the quantum well. The energy distance between both transitions *cannot be straightforwardly assigned* to the binding energy of an additional electron (or hole) to the neutral exciton (to form the trion state) [6]; ΔE is rather dissociation energy [7]. In the literature, there is no available experimental data concerning the trion binding energy for CdTe quantum wells wider than 60 nm [8]. However, by simple extrapolation of existing experimental and theoretical data to the studied structure we obtained binding energy of ≈ 1.5 meV [7, 9], much lower than measured one. The apparent discrepancy between both values can be explained by taking into account the above barrier illumination process, which would possibly create excess carrier concentration in the well and thus increase the trion binding energy. This effect can be very pronounced in CdTe quantum wells [9]. Another possible explanation is related to exciton localization in the quantum well which can increase the trion binding energy as well.

Figure 2a and c presents time-resolved photoluminescence traces obtained for the exciton and the trion emission at various temperatures up to 30 K. All the traces reveal a setup-resolution limited rise time and a complex decay process which is assumed to be bi-exponential, with a slow and fast decay component. The characteristic decay times of the fast components are ≈ 150 ps and ≈ 200 ps for the X and T emission, respectively. Both values vary a little with temperature. The decay time of the slow component is ≈ 600 ps for X and 650 ps for T emission processes and both decrease with increasing temperature.

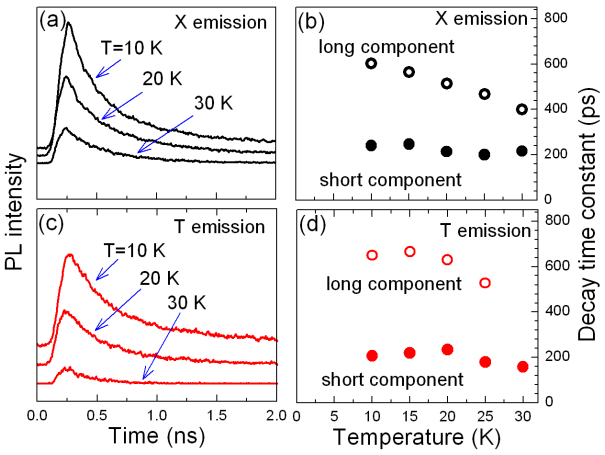

Fig. 2. (a) and (c) the time-resolved photoluminescence traces for the exciton and the trion emission, respectively. Temperature dependence of the long (open circles) and short (full circles) photoluminescence decay time constants obtained for the exciton (b) and the trion (d) emissions. Time resolved photoluminescence traces measured under non-resonant excitation at ≈ 3.1 eV by the pulse laser source.

The short decay time constants are close to the expected free exciton and trion lifetimes in a quantum well which are in the range of tens up to one hundred picoseconds [9–13]. The existing discrepancy between the measured values and the literature data can be related to the excitation conditions. Under non-resonant excitation the incomplete exciton/trion thermalization process can lead to the observation of a slightly longer lifetimes [9–13]. However, the lack of typical linear increase

in the free exciton and trion lifetimes with temperature (see decay time values related to the fast component of TRPL signal in Fig. 2b and d) suggests the presence of an additional interwell localization for both species. When the spatial confinement of exciton/trion is reduced in the QW, it is expected that the exciton/trion lifetime will increase according to theory presented in Ref. [12]. For the weak localization scenario the exciton/trion can be confined to mean well-width fluctuations spatially extended over distance larger than the exciton diameter. In this case we would only expect a small increase of the localized exciton/trion lifetime in respect of the free one. However, when the spatial extent of some localized centers decreases, it can lead to observation of much longer decay time constant related to an exciton and trion radiative decay process. Possibly, this effect is responsible for presence of long decay time components of measured TRPL signal.

4. Conclusions

The static and dynamic optical properties of an 80 nm wide $Cd_{1-x}Mn_xTe/Cd_{0.7}Mg_{0.3}Te$ quantum well of extremely small Mn content in the well have been studied by means of time-integrated and time-resolved photoluminescence techniques. The photoluminescence experiment at $T = 10$ K reveals two distinctive emission lines attributed to the exciton and trion emission located in the well. Based on the energy difference between both photoluminescence lines the trion binding energy has been determined to be equal to 2.6 ± 0.8 meV. The photoluminescence experiment allowed evaluation of the exciton and trion lifetimes to be ≈ 150 ps and ≈ 200 ps, respectively. The temperature dependence of both lifetimes together with the multicomponent character of the photoluminescence decay process suggest a spatial localization of excitons and trions in the investigated quantum well.

Acknowledgments

Authors acknowledge the financial support from the Foundation for Polish Science through a Subsidy "Mistrz" No. 10/2012.

References

[1] J.K. Furdyna, *J. Appl. Phys.* **64**, R29 (1988).

[2] J. Kossut, W. Dobrowolski, in: *Handbook of Magnetic Materials*, Ed. K.H.J. Buschow, Elsevier, Amsterdam 1993.

[3] D.R. Yakovlev, K.V. Kavokin, *Comments Condens. Matter Phys.* **18**, 51 (1996).

[4] C. Rice, L.C. Smith, J.J. Davies, D. Wolverson, M. Wiater, G. Karczewski, T. Wojtowicz, *Phys. Rev. B* **86**, 155318 (2012).

[5] W. Maślana, P. Kossacki, M. Bertolini, H. Boukari, D. Ferrand, S. Tatarenko, J. Cibert, J.A. Gaj, *Appl. Phys. Lett.* **82**, 1875 (2003).

[6] M.A. Lampert, *Phys. Rev. Lett.* **1**, 450 (1958).

[7] P. Kossacki, *J. Phys., Condens. Matter* **15**, R471 (2003).

[8] K. Kheng, K. Saminadayar, N. Magnea, *J. Cryst. Growth* **184/185**, 849 (1998).

[9] R.A. Sergeev, R.A. Suris, G.V. Astakhov, W. Ossau, D.R. Yakovlev, *Eur. Phys. J. B* **47**, 541 (2005).

[10] V. Ciulin, P. Kossacki, S. Haacke, J.-D. Ganiere, B. Deveaud, A. Esser, M. Kutrowski, T. Wojtowicz, *Phys. Rev. B* **62**, R16310 (2000).

[11] L.C. Andreani, F. Tassone, F. Bassani, *Solid State Commun.* **77**, 641 (1991).

[12] M. Sugawara, *Phys. Rev. B* **51**, 10743 (1995).

[13] B. Deveaud, F. Clerot, N. Roy, K. Satzke, B. Sermage, D.S. Katzer, *Phys. Rev. Lett.* **67**, 2355 (1991).