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# Experimental Study of Optical Transitions in Be-Doped GaAs/AlAs Multiple Quantum Wells

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We present a photoluminescence study of optical transitions in Be acceptor-doped GaAs/AlAs multiple quantum wells at room and liquid nitrogen temperatures. We investigate excitonic spectra and reveal acceptor-impurity induced effects in multiple quantum wells having different width.

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## 1. Introduction

The development of THz detectors and emitters is one of the key-topics in modern solid-state physics [1–3]. As impurity states have transitions within this range and their energy levels can be engineered by varying quantum wells (QW) widths [4–6], these structures could be used as active components of THz devices. Therefore, the understanding of the optical properties and impurity features are of particular importance for designers.

In this work we investigate the properties of photoluminescence (PL) spectra of GaAs/AlAs multiple quantum wells (MQWs) at both liquid nitrogen and room temperatures. We study excitonic states and reveal acceptor-impurity induced effects in QWs having different widths and doping levels.

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## 2. Samples and experimental details

The samples were grown by the MBE technique on semi-insulating GaAs substrates and contained  $N = 200, 50, 40$  wells having width  $L_W$  of 10, 15, and 20 nm separated by a 5 nm wide AlAs barriers. Each GaAs well was moderately ( $5 \times 10^{10} \text{ cm}^{-2}$  for  $L_W = 10$  nm,  $2.5 \times 10^{12} \text{ cm}^{-2}$  for  $L_W = 15$  nm and  $L_W = 20$  nm)  $\delta$ -doped with Be acceptors at the center of the well. The PL was excited by a continuous wave argon-ion laser, the PL signal was then dispersed by a monochromator and detected by a cooled GaAs photomultiplier operating in the photon counting regime.

## 3. Photoluminescence spectra and discussion

The PL spectra for three MQWs samples at room and nitrogen temperatures are shown in Fig. 1 and Fig. 2. One can see a series of clearly resolved peaks at both temperatures. The main intensity PL bands are associated with the MQWs heavy- and light-hole excitonic PL transitions denoted as  $X_{e1-hh1}$  and  $X_{e1-lh1}$ , respectively. For MQWs  $L_W = 15$  and 20 nm, both  $X_{e1-hh1}$  and  $X_{e1-lh1}$  peaks are merged together, here also the line  $E_{e2-hh1}$ , associated with second excited electronic level can be resolved. All these transitions are indicated by arrows in Fig. 1 and commented in the figure caption. It is worth noting that the difference from marked energy to the maximum of the peak is the exciton binding energy for narrow quantum wells is bigger than for wide quantum wells. This fact correlates nicely with theoretical predictions [7].

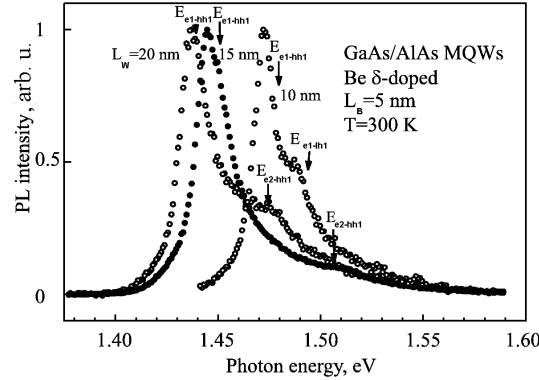


Fig. 1. The PL spectra of the Be  $\delta$ -doped GaAs/AlAs samples for three different  $L_W = 10, 15,$  and  $20$  nm MQWs at room temperature. Arrows indicate calculated energy  $E_{e1-hh1}$ ,  $E_{e2-hh1}$ ,  $E_{e1-lh1}$  differences from first heavy hole to first electron, first heavy hole to second electron, and first light hole to first electron energy levels, respectively.

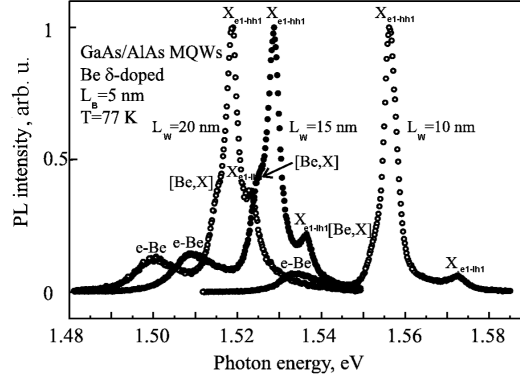


Fig. 2. The PL spectra of the Be  $\delta$ -doped GaAs/AlAs samples for three different  $L_W = 10, 15,$  and  $20$  nm MQWs at liquid nitrogen temperature.  $X_{e1-hh1}$  and  $X_{e1-lh1}$  indicate heavy hole and light hole excitonic transitions,  $[Be, X]$  — to Be acceptor bound exciton, e-Be — free electron–neutral Be acceptor transitions.

At liquid nitrogen temperature (Fig. 2), some additional lines appear in the spectrum: we attribute the lower energy transitions, labeled as e-Be, to the recombination between an electron to Be acceptor levels. Other line, marked as  $[Be, X]$  originates from excitons bound to the acceptor impurity.

The acceptor binding energy  $E_A$  can be determined from the relation [8]  $E_A = E(X_{e1-hh1}) + E(X_{hh}) - E(e\text{-Be})$ , where  $E(X_{e1-hh1})$  and  $E(e\text{-Be})$  are the energies of the  $X_{e1-hh1}$  and e-Be lines, and  $E(X_{hh})$  is the binding energy of the heavy hole exciton and can be deduced from theoretical calculations [7]. Our estimates from the PL spectrum show that acceptor binding energy increases with the decrease in QW width as predicted in [9]. For example, for  $L_W = 10$  nm, it is  $E_A \approx 33$  meV, and while for a QW with  $L_W = 20$  nm it is  $E_A \approx 28.5$  meV.

In Fig. 3 we show the PL spectra at 77 K over a wider energetic range and at higher sensitivity. One can resolve here two additional lines that were masked in the previous spectra. We bear in mind the transitions at 1.4726 and 1.4364 eV which we ascribe to the e-Be one longitudinal optical (1LO) phonon and 2LO phonon replica, respectively. We found that the same spectral features were observed in all the studied MQW structures. The energy difference is  $E_{e\text{-Be}} - E_{1LO} \approx E_{1LO} - E_{2LO} \approx 36.2$  meV, i.e. equals to GaAs longitudinal optical phonon energy. A similar effect was observed in carbon-doped bulk GaAs [10].

To get an understanding of the PL spectra, we have analyzed the QW having 15 nm width (Fig. 3). The excitonic PL spectra consist of a series of lines:  $[Be, X]$ ,  $X_{e1-hh1}$  and  $X_{e1-lh1}$ . The binding energy of bound exciton  $E(X_{e1-hh1}) - E[Be, X] \approx 3.85$  meV nicely coincides with other experimental findings for GaAs/AlAs (3.7 meV) [9], and for GaAs/Al<sub>0.33</sub>Ga<sub>0.67</sub>As (3.8 meV) [11] quantum wells, which is larger than for GaAs (2.9 meV) [12]. Modeling the lineshape  $I$  we assumed that the excitonic PL line width broaden-

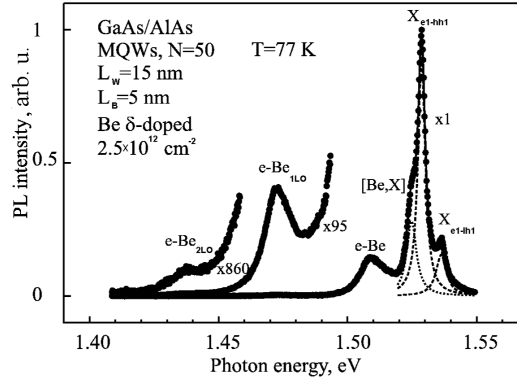


Fig. 3. The PL spectra of the Be  $\delta$ -doped GaAs/AlAs  $L_W = 15$  nm at liquid nitrogen temperature.  $X_{e1-hh1}$  and  $X_{e1-lh1}$  indicate heavy-hole and light-hole excitonic transitions,  $[Be, X]$  — to Be acceptor bound exciton, e-Be — free electron–neutral Be acceptor transitions, e-Be $_{1LO}$ , e-Be $_{2LO}$  are its one and two phonon replicas. Curves (dotted points and continuous line) are Lorentzian excitonic band approximation.

ing consists of two components: a homogeneous and an inhomogeneous part [13], i.e.  $\Gamma = \Gamma_0 + aT + b/[\exp(\hbar\omega_{LO}/kT) - 1]$ , where  $\Gamma_0$  is the temperature  $T$  independent inhomogeneous width, the second and the third terms arise because of the increase in the exciton scattering with acoustic and optical phonons with temperature, respectively; coefficients  $a$  and  $b$  represent corresponding scattering strengths. The  $\Gamma$  value may be obtained from the measured PL spectra using Gaussian or Lorentzian convolution procedures. It is expected that at very low temperatures, where the exciton–phonon scattering is not very efficient, the exciton PL spectra are mostly inhomogeneously broadened and have Gaussian convolution, while the line shape becomes more like a Lorentzian at higher temperatures. The exciton–acoustic-phonon interaction coefficient used are  $a \approx 2\text{--}10 \mu\text{eV/K}$  [14–17] and the exciton–LO-phonon interaction coefficient is taken to be  $b \approx 10\text{--}15 \text{ meV}$  [15–18]. Values obtained for our samples are the following:  $\Gamma_0 \approx 2 \text{ meV}$ ,  $\Gamma(T = 77 \text{ K}) \approx 3 \text{ meV}$ ,  $\Gamma(T = 300 \text{ K}) \approx 9 \text{ meV}$ , which agrees well with the results of the above-mentioned authors and theoretical predictions. It is worth noting that when the lines of heavy- and light-hole are merged at 300 K, the excitonic PL band is twice wide in comparison with separated bands. It can be seen evaluating the PL band width for the wells of  $L_W = 15$  and 20 nm with  $L_W = 10$  nm in Fig. 1.

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### References

- [1] F. Szmulowicz, T. Oogarah, J. Ehret, K. Mahalingam, H.C. Liu, S.M. Hegde, J. Solomon, D. Tomich, G. Landis, G.J. Brown, *Phys. Rev. B* **68**, 085305 (2003).
- [2] M. Rochat, J. Faist, M. Beck, U. Oesterle, M. Illegems, *Appl. Phys. Lett.* **73**, 3724 (1998).
- [3] P.-C. Lv, R.T. Troeger, T.N. Adam, S. Kim, J. Kolodzey, I.N. Yassievich, M.A. Odnoblyudov, M.S. Kagan, *Appl. Phys. Lett.* **85**, 22 (2004).
- [4] Q.X. Zhao, S. Wongmanerod, M. Willander, P.O. Holtz, S.M. Wang, M. Sadeghi, *Phys. Rev. B* **63**, 195317 (2001).
- [5] W.M. Zheng, M.P. Halsall, P. Harmer, P. Harrison, M.J. Steer, *Appl. Phys. Lett.* **84**, 735 (2004).
- [6] W.T. Masselink, Yia-Chung Chang, H. Morkoç, *Phys. Rev. B* **32**, 5190 (1985).
- [7] L.C. Andreani, A. Pasquarello, *Phys. Rev. B* **42**, 8928 (1990).
- [8] R.C. Miller, A.C. Gossard, W.T. Tsang, O. Munteanu, *Phys. Rev. B* **25**, 3871 (1982).
- [9] W.M. Zheng, M.P. Halsall, P. Harmer, P. Harrison, M.J. Steer, *J. Appl. Phys.* **92**, 6039 (2002).
- [10] Q. Huang, R.G. Ulbrich, *J. Lumin.* **99**, 19 (2002).
- [11] D. Boffety, A. Vasson, A.-M. Vasson, J. Leymarie, T.S. Cheng, C.A. Bates, J.M. Chamberlain, *Semicond. Sci. Technol.* **11**, 340 (1996).
- [12] W. Bludau, E. Wagner, *Phys. Rev. B* **13**, 5410 (1976).
- [13] S. Rudin, T.L. Reinecke, B. Segall, *Phys. Rev. B* **42**, 11218 (1990).
- [14] S. Rudin, T.L. Reinecke, *Phys. Rev. B* **66**, 085314 (2002).
- [15] A. Thränhardt, C. Ell, S. Mosor, G. Rupper, G. Khitrova, H.M. Gibbs, S.W. Koch, *Phys. Rev. B* **68**, 035316 (2003).
- [16] H. Zhao, S. Wächter, H. Kalt, *Phys. Rev. B* **66**, 085337 (2002).
- [17] A. Venu Gopal, R. Kumar, A.S. Vengurlekar, A. Bosacchi, S. Franchi, L.N. Pfeiffer, *J. Appl. Phys.* **87**, 1858 (2000).
- [18] D. Gammon, S. Rudin, T.L. Reinecke, D.S. Katzer, C.S. Kyono, *Phys. Rev. B* **51**, 16785 (1995).