Vol. 88 (1995) *ACTA PHYSICA POLONICA A* No. 5

Proceedings of the XXIV International School of Semiconducting Compounds, Jaszowiec 1995

# $\delta$-DOPED $CdTe/Cd_{1-x}Mn_xTe$ MULTIPLE QUANTUM WELLS INVESTIGATED BY PHOTOREFLECTANCE SPECTROSCOPY*

P. SITAREK, J. MISIEWICZ

Institute of Physics, Technical University of Wrocław
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

G. KARCZEWSKI, T. WOJTOWICZ AND J. KOSSUT

Institute of Physics, Polish Academy of Sciences
Al. Lotników 32/46, 02-668 Warszawa, Poland

Room temperature photoreflectance spectroscopy was used to investigate $CdTe/Cd_{1-x}Mn_xTe$ multiple quantum wells grown by MBE. Structures were indium $\delta$-doped into the well or into the barrier. The value of heavy and light hole subbands splitting was measured and compared to the calculated ones. The influence of the position of $\delta$-doping on the measured spectra was shown.

PACS numbers: 61.72.Vv, 78.66.Hf

## 1. Introduction

Magneto-optical properties of bulk cadmium manganese telluride (CMT) have been widely investigated [1, 2]. The aim of this contribution is to present an application of photoreflectance (PR) spectroscopy [3, 4] to determine parameters of $CdTe/Cd_{1-x}Mn_xTe$ multiple quantum well (MQW) as well as an influence of indium $\delta$-doping on these structures.

## 2. Calculation of the influence of strains

The lattice mismatch present in CdTe–$Cd_{1-x}Mn_xTe$ QW leads to: the heavy and the light holes splitting — the shear part (S), and band gap shift — hydrostatic part (H) [5] as described below

$$E_{k,j} = E_j^0 + \sum_{i=c,v} \Delta E_{i,j}^{H} + \sum_{i=c,v} \Delta E_{i,j,k}^{S}, \tag{1}$$

*This work is partly supported by the State Committee for Scientific Research (Republic of Poland) under the contract PBZ-Z011/P4/93/01 and Technical University of Wrocław.

where $E_j^0$ is the band gap energy of unstrained structure, $i$ refers either to the conduction band (c) or the valence band (v), $j$ refers to the well or the barrier material and $k$ distinguishes between hh or lh. If the shear component is perpendicular to the interface the values of $\Delta E_{i,j}^{\mathrm{H}}$ and $\Delta E_{i,j,k}^{\mathrm{S}}$ may be defined as

$$\Delta E_{i,j}^{\mathrm{H}} = -2a^{i,j}\left(1 - \frac{C_{12}^j}{C_{11}^j}\right)\varepsilon_j, \tag{2}$$

$$\Delta E_{i,j,k}^{\mathrm{S}} = 2b^{j,k}\left(1 + 2\frac{C_{12}^j}{C_{11}^j}\right)\varepsilon_j, \tag{3}$$

where $C_{n,m}$ are the elastic stiffness constants, $a^{i,j}$ and $b^{j,k}$ are the hydrostatic and tetragonal shear deformation potentials, respectively, and $\varepsilon_j = \frac{a_\perp - a_0^j}{a_0^j}$ where $a_0^j$ is the lattice constant of the well or barrier material in interface plane of the unstrained structure, and $a_\perp = \sum_{n=1}^{N} \frac{d_n \xi_n}{a_0^n} / \sum_{n=1}^{N} \frac{d_n \xi_n}{(a_0^n)^2}$, where $N$ is the number of layers in structure, $d_n$ is thickness of the layer and $\xi_j = C_{11}^j + C_{12}^j - 2(C_{12}^j)^2 (C_{11}^j)^{-1}$.

After calculation of strain related components (2), (3) the obtained energy differences $E_{k,j}$ were used to determine the effective depth of quantum wells. The Schrödinger equation for the finite, rectangular well was used to find the interband transition energies [6, 7]. No excitonic correlations were introduced at this preliminary stage.

In the above calculations the following values of parameters were used:
— the valence band offset was taken as 30% of total energy band gap [8],
— the band gap energy of CMT was taken from formula [9]

$$E_{\mathrm{Cd}_{1-x}\mathrm{Mn}_x\mathrm{Te}}\ [\mathrm{eV}] = 1.517 + 1.4x, \tag{4}$$

— the lattice constant was taken from $a_0^{\mathrm{Cd}_{1-x}\mathrm{Mn}_x\mathrm{Te}}\ [\mathrm{\AA}] = 6.4807 - 0.1459x$,
— the deformation potentials in eV: $a = -3.43, b = -0.8$,
— the elastic stiffness constants in $10^{10}$ N/m$^2$: $C_{11} = 5.6$, $C_{12} = 3.87$,
— and the effective masses of bulk CdTe in terms of $m_e$ (the free electron mass): 0.11 for electrons, 0.45 for heavy holes and 0.11 for light holes [10].

## 3. Experiment and discussion

The photoreflectance spectra were measured at 295 K in a setup similar to described in [11] with the coherent Ar laser (514.5 nm) as the pumping beam source.

The heterostructures used in this investigation were grown by MBE technique on GaAs substrate. First, a buffer layer of CdTe was deposited followed by an additional CdTe layer with thickness of 3.5 $\mu$m and 50 periods of CdTe/$\mathrm{Cd}_{1-x}\mathrm{Mn}_x\mathrm{Te}$ with thickness of 70 Å and 130 Å, respectively. Samples were $\delta$-doped with In in the center of the wells or of the barriers using different amount of the dopants.

Examples of the spectra are shown in Fig. 1. The upper one is from sample 07114-b strongly $\delta$-doped in the barriers. Spectra were analysed in term of fitting

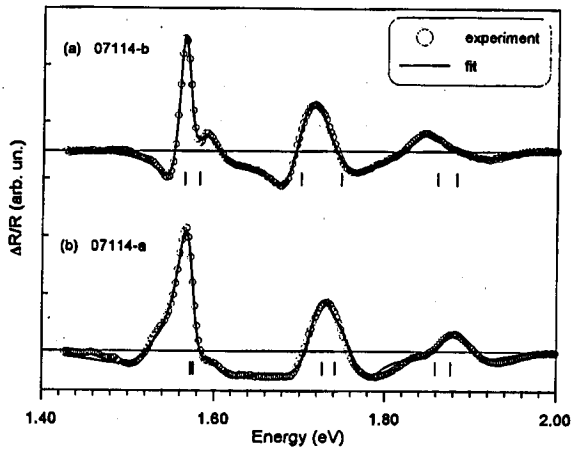


Fig. 1. The PR spectra at 300 K of samples: (a) 07114-b — In doped in barriers, (b) 07114-a — In doped in wells. Vertical lines show energies obtained from fitting procedure, see Table.

TABLE

Best fit parameters in Eq. (5) obtained by using the fitting procedure to the experimental data of samples 07114-a and 07114-b.

| Transition | 07114-b | | | | 07114-a | | | |
|---|---|---|---|---|---|---|---|---|
| | $E_n$ [eV] | $\Gamma_n$ [meV] | $C_n$ [arb.un.] | $\phi_n$ [rad] | $E_n$ [eV] | $\Gamma_n$ [meV] | $C_n$ [arb.un.] | $\phi_n$ [rad] |
| 1hh | 1.567 | 18 | 1.7 | 5.3 | 1.575 | 24 | 1.6 | 5.9 |
| 1lh | 1.585 | 43 | 4.4 | 4.9 | 1.576 | 29 | 3.7 | 5.2 |
| 2hh | 1.699 | 43 | 5.0 | 3.5 | 1.727 | 33 | 4.3 | 6.3 |
| 2lh | 1.747 | 42 | 4.4 | 4.2 | 1.742 | 34 | 3.8 | 4.3 |
| barrier lh | 1.857 | 48 | 2.4 | 4.0 | 1.859 | 38 | 1.1 | 5.7 |
| barrier hh | 1.885 | 46 | 1.1 | 3.0 | 1.877 | 39 | 2.8 | 4.3 |

of the Aspnes line shape functions

$$\frac{\Delta R}{R} = \mathrm{Re}\sum_{n}^{P} C_n e^{i\phi_n}(E - E_n + i\Gamma_n)^{-m}, \tag{5}$$

where $P$ is the number of transitions, $E$ is the photon energy of a reflected light, $\phi_n$, $C_n$, $E_n$, $\Gamma_n$ are the phase factor, the amplitude, the transition energy and the broadening parameter, respectively, for the $n$-th transition. For the 2D systems at room temperature $m = 3$ [3]. Successful fit was obtained for a set of six Aspnes lines attributed to 1hh, 1lh, 2hh, 2lh in the well and lh and hh in the barrier. From the position of the hh peak related to the barrier and using the formula (4), the concentration of Mn was estimated as 24.5%. For the case of barrier doped structure the theoretically calculated, including strains, transition energies in eV

are as follows: 1.565 (1hh), 1.582 (1lh), 1.701 (2hh), 1.748 (2lh), 1.861 (barrier lh) and 1.883 (barrier hh).

The lower spectrum in Fig. 1 is from the sample 07114-a equally strongly $\delta$-doped in each well. In this case good agreement with calculated values for the same quantum well parameters was not possible to obtain. The best fit gives the energies shown in Table.

Differences between the transition energies in both structures, particularly for hh transitions indicates that strong $\delta$-doping in the wells affects the effective well potential more efectively than the doping in the barriers.

## References

[1] For a review, see J.K. Furdyna, J. Kossut, in: *Diluted Magnetic Semiconductors*, in *Semiconductors and Semimetals*, Vol. 25, Eds. R.K. Willardson, A.C. Beer, Academic Press, New York 1988, p. 1.

[2] K. Nakamura, H. Nakano, *Jpn. Phys. Soc.* **59**, 1154 (1990).

[3] F.H. Pollak, O.I. Glembocki, *Proc. SPIE* **946**, 2 (1988).

[4] F.H. Pollak, H. Shen, *Mater. Sci. Eng. R* **10**, 275 (1993).

[5] J.H. Chen, W.S. Chi, Y.S. Huang, Y. Yin, F.H. Pollak, D.G. Pettit, J.M. Woodall, *Semicond. Sci. Technol.* **8**, 1420 (1993).

[6] C. Weisbuch, B. Vinter, *Quantum Semiconductor Structures*, Academic Press, Boston 1991, p. 11.

[7] G. Bastard, *Phys. Rev. B* **25**, 7584 (1982).

[8] J.A. Gaj, W. Grieshaber, C. Bodin-Deshayes, J. Ciebert, G. Feuillet, Y. Merle d'Aubigné, A. Wasiela, *Phys. Rev. B* **50**, 5512 (1994).

[9] J. Misiewicz, X.-L. Zheng, P. Becla, D. Heiman, *Solid State Commun.* **66**, 351 (1988).

[10] R.L. Harper, Jr., R.N. Bicknell, D.K. Blanks, N.C. Giles, J.F. Schetzina, Y.R. Lee, A.K. Ramdas, *J. Appl. Phys.* **65**, 624 (1989).

[11] J. Misiewicz, P. Markiewicz, J. Rebisz, Z. Gumienny, M. Panek, B. Ściana, M. Tłaczała, *Phys. Status Solidi B* **183**, K43 (1994).