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Cd_{1-x}Mn_xTe PARABOLIC QUANTUM WELLS*

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We report on the growth and optical studies of II-VI semiconductor parabolic quantum wells made of $Cd_{1-x}Mn_x$ Te for a broad range of quantum well widths and Mn molar fractions x. Photoluminescence excitation spectra revealed several series of peaks equidistant in energy associated with interband optical transitions between harmonic oscillator levels. From the analysis of the spectra the valence band offset $Q_{hh} = 0.44 \pm 0.1$ was determined for the CdTe/Cd_{1-x}Mn_xTe system.

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Quantum structures with graded confining potential are interesting both from the point of view of their unique physical properties as well as from the point of view of their potential applications [1]. This was recognized already many years ago and has been used successfully in III-V semiconductor family. For instance, one of the characteristics of quantum wells (QW) with parabolically shaped confining potential is their strong sensitivity of the energy level positions [1,2] (as well as of the probabilities of interband optical transitions between these levels) to the actual value of the valence band offset.

Here, we report on the growth and the optical study of II-VI semiconductor parabolic quantum wells (PQW) that are particularly interesting because of the stronger, as compared to III-Vs, excitonic effects. We have chosen the diluted magnetic semiconductor $Cd_{1-x}Mn_xTe$ for constructing these structures because of its extreme sensitivity to the presence of a magnetic field. This allows, e.g., an observation of field-induced changes of the QW shape as seen by carriers with opposite spins — a feature that is impossible to achieve with the use of nonmagnetic semiconductors. In this paper we concentrate on the photoluminescence excitation

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studies performed at zero magnetic field and aimed at determination of the valence band offset in CdTe/CdMnTe system.

We produced a set of eleven QW structures each containing a single PQW with x = 0 at the center of the well. Molecular beam epitaxy and digital growth method [1], described below, were employed for this purpose. All our growth processes were performed on (001) GaAs substrates with 4 μ m thick CdTe buffers. The growth of entire structures was performed in metal rich conditions with Cd and CdTe cells continuously opened. Mn cell shutter was continuously opened for the growth of the barriers and pulsed during the growth of the PQW. The growth rates of CdTe and $Cd_{1-x}Mn_xTe$, limited by a constant Te flux, were nearly the same if expressed in Å/s. These rates were measured by RHEED intensity oscillations. The growth of each PQWs was divided into 41 steps. For each step the Mn cell was opened for the time needed to obtain a given (required by the assumed composition profile) value of Mn mole fraction x. For example, if an average x over a particular step with a size 6.48 Å was to be equal to 1/2 of the molar fraction of the barrier then the Mn cell was opened for the time required to grow a 3.24 Å wide $Cd_{1-x}Mn_xTe$ layer in the center of this step (to a good approximation half of the time required to grow this step). In order to achieve an accurate control of the composition the growth rate was reduced from a typical value of 0.6 ML/s down to 0.1-0.14 ML/s. The precision of the profile control was limited mainly by the reaction time of the effusion cell shutters, which in the MBE system used (EPI 620 with pneumatic shutters) is of the order of 0.1 sec.

A wide range of different curvatures of the parabolic confining potential, that is necessary for a precise valence band offset determination, was obtained with the use of two methods. In the first, the curvature was varied by changing the QW width for a nominally constant composition of the barrier material and in the second, the barrier composition for different structures was varied while keeping QW width constant. PQWs with the barrier composition x from 0.13 to 0.95, as determined by an analysis of the post grow X-ray diffractograms, and with a nominal width between 40 and 120 ML (130 and 390 Å) were produced.

PQW structures were studied by means of low temperature photoluminescence (PL) and photoluminescence excitation spectroscopy (PLE). Circularly polarized exciting light with the beam perpendicular to the sample surface and with a typical power of the order of 20 W/cm² was used. The detection energy for PLE was set at the peak of the PL and the polarization of emitted light was not analyzed. For all samples a series of peaks equidistant in energy, associated with $\Delta n = 0$ (*n* being the level index) excitonic transitions from the heavy hole (hh_n) to electron (e_n) levels, were observed in PLE spectra. Typical results are presented on the left hand side of Fig. 1, showing data for three samples with the same 80 ML width and different compositions of the barrier material. The identification of the peaks is given in the figure and explained in the caption.

In order to determine the valence band offset we can use an infinite barrier approximation. We checked by a direct comparison with a calculation suitable for finite PQWs [3] that such a simple description is very accurate in the case of our relatively deep and wide QWs. The differences between the energy values of various levels involved in the observed optical transitions obtained in the infinite barrier



Fig. 1. PLE spectra of three 80 ML wide PQWs with different barrier compositions (left). All data were taken at T = 1.7 K. The identification of the lines is given in the figure with the labels Hnm (Lnm), where n is the hh (lh) state index and m is the level index in the conduction band. The right hand side of the figure shows the average energy distance between the peaks in the hh series plotted vs. square root of the curvature of the confining potential. The straight line is the least square fit to the data and yields the valence band offset value $Q_{\rm hh} = 0.44$.

approximation and those resulting from a solution of an exact analytic equation obtained in the case a finite PQW [3] are much smaller than experimental errors.

Quantized energies of carrier with the mass m_i^* from the *i*-th band (*i* = e, lh, hh) bounded by the infinitely high parabolic potential $V_i = \frac{K_i}{2}z^2$ are given by

$$E_{ni} = \left(n - \frac{1}{2}\right) \hbar \sqrt{\frac{K_i}{m_i^*}}, \qquad K_i = Q_i K, \qquad K = \frac{8\Delta E_g}{L_z^2}$$

where $Q_i = \Delta E_i / \Delta E_g$ with ΔE_i being the discontinuities of the band edges, ΔE_g being the energy gap discontinuity at the distance $\pm L_z/2$ from the center of the QW, and n = 1, 2, 3... being the harmonic oscillator quantum number. Therefore, plotting experimental values of the energetic distance between two successive transitions in heavy hole series: $\Delta E = E_{(n+1)hh} + E_{(n+1)e} - E_{nhh} - E_{ne}$ versus square root of the total curvature K, one should obtain a straight line. The slope of this line is determined by the value of the valence band offset $Q_{\rm hh}$ ($Q_{\rm hh} + Q_{\rm e} = 1$). The experimental linear dependence of ΔE vs. \sqrt{K} is clearly visible on the right hand side of Fig. 1, where the data for all our samples are collected. The curvatures of PQWs, used to produce this plot, were calculated taking nominal QW widths and experimental values of composition x. From the least squares fit of the data of Fig. 1 to the straight line and using the values of the effective masses $m_e = 0.095$ for the electrons and $m_{\rm hh} = 0.65$ for the heavy holes we obtained the valence band offset $Q_{\rm hh} = 0.44 \pm 0.1$. This value agrees within experimental error with our previous estimation based on experiments done with much more limited number of PQW structures [4], as well as with recent determinations by other authors [5, 6]. The precision of the determination of the valence band offset from the studies of PQWs can be further increased if $\Delta n \neq 0$ transitions are observed and correctly identified [1]. Experiments in the presence of an external magnetic field should be very useful in this respect.

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