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EXCITON MAGNETO-OPTICAL STUDY ON SINGLE QUANTUM WELLS, $Cd_{1-x}Zn_xTe/Cd_{1-x'-y}Zn_{x'}Mn_yTe$*

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Four-single quantum wells composed of the ternary non-magnetic compounds $Cd_{0.93}Zn_{0.07}Te$ (well width = 13, 19, 40, 90 Å), separated by the quaternary magnetic-compound $Cd_{0.48}Zn_{0.04}Mn_{0.48}Te$ on (100)GaAs substrate were grown by MBE, and exhibited clear and distinctive photoluminescence lines corresponding to each quantum well. Double luminescence peaks with closely spaced within one well were observed from 90 Å and 40 Å quantum wells. Temperature and magnetic-field study revealed characteristic luminescence features associated with a bound exciton near the interface rather than with one monolayer fluctuation.

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Diluted magnetic semiconductors (DMSs) are known as "spin functional material", characterized by their novel magneto-optical properties. Quantum wells (QWs) and superlattices consisting of non-magnetic and DMS layers offer unique opportunities not only for band gap but also for spin engineering. The MBE was used to grow four-single QWs composed of the ternary non-magnetic compounds $Cd_{1-x}Zn_xTe$ (with nominal well width 13, 19, 40, 90 Å, respectively, and $x = 0.07$), separated by the quaternary DMS-compound $Cd_{1-x'-y}Zn_{x'}Mn_yTe$ barrier (with nominal 450 Å thick, $x' = 0.04$, $y = 0.48$) on (100)GaAs substrate. These ternary and quaternary structures allow us to have a possible independent control of the energy band offset and magnetic properties of the system.

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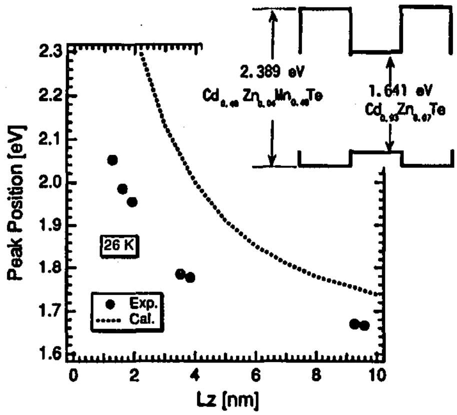

Fig. 1. The PL peak positions as a function of the QW widths L_z in $Cd_{0.93}Zn_{0.07}Te$ (well width = 13, 19, 40, 90 Å)/$Cd_{0.48}Zn_{0.04}Mn_{0.48}Te$ single quantum wells. The dotted line shows the results of a simple square-well potential calculation.

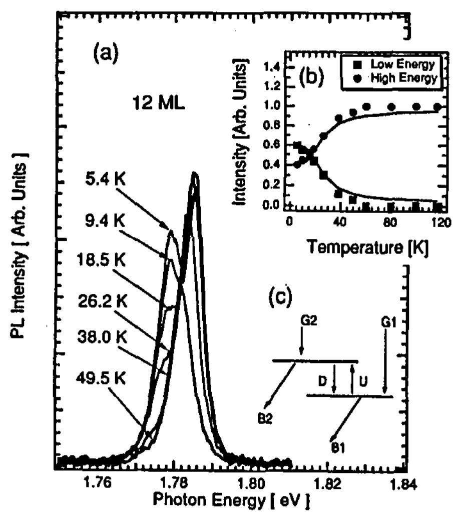

Fig. 2. (a) The temperature evolution of the PL lines in a 12 ML QW, (b) relative change of the integrated intensity of the two PL lines with temperatures, and (c) a two-level model to interpret the intensity variation.

Strong and clear exciton photoluminescence (PL) lines were observed at low temperatures, consisting of 4 main peaks and associated weak lines. Peak positions of these lines measured at 26 K were attempted to plot as a function of the well-thickness as shown in Fig. 1, where an assumption was made that the closely spaced lines were originated from the one monolayer (ML = 0.32 nm) difference. As for the purpose of a guide for the comparison, results of a simple envelope-function calculation assuming a square-well potential were presented in the same figure. Here the nonparabolicity of the conduction band was taken into account, but the effects caused by the strain and exciton binding energy were neglected. The valence band offset was set equal to 0. The Zn alloy dependence of E_g for $Cd_{1-x}Zn_xTe$ was taken from the data by Meyer et al. [1], and Mn alloy dependences of E_g for $Cd_{1-x}Mn_xTe$ and $Zn_{1-x}Mn_xTe$ were referred from the data by Lee et al. [2, 3]. Finally, E_g of $Cd_{1-x'-y}Zn_{x'}Mn_yTe$ was determined following the conventional method employed by Williams et al. [4]. The model calculation was done assuming the nominal values of the alloy components estimated from the growth conditions. The deviations from the experimental points are, therefore, caused dominantly by the possible errors in the estimation of the energy band gap E_g of $Cd_{1-x}Zn_xTe$ and $Cd_{1-x'-y}Zn_{x'}Mn_yTe$, respectively, since the actual values of the alloy compositions are not known.

Figure 2 demonstrates the temperature evolution of the PL spectra in a 12 ML (40 Å) quantum well. With increasing temperatures the peak at the higher energy side becomes strong relative to the one at the lower energy side. Relative variation of the integrated intensity of the two peaks with temperatures is presented in Fig. 2b.

A simple two-state model shown in Fig. 2c was used to analyze the PL intensity variations in Fig. 2b. Two states are separated by the energy ΔE, and the rate equation for the exciton concentrations n_1 and n_2 are given by

$$\frac{\mathrm{d}n_1}{\mathrm{d}t} = -(B_1 + U)n_1 + Dn_2 + G_1, \tag{1}$$

$$\frac{\mathrm{d}n_2}{\mathrm{d}t} = Un_1 - (B_2 + D)n_2 + G_2, \tag{2}$$

where $G_{1,2}$ are the exciton generation rates, and $B_{1,2}$ are the exciton radiative recombination rates at each level. In the equilibrium conditions, one can set $\mathrm{d}n_1/\mathrm{d}t = \mathrm{d}n_2/\mathrm{d}t = 0$. Here the relation for the exciton up and down migration rates, U and D, are given by $U/D = \exp(-\Delta E/kT)$, where k is the Boltzman constant. The PL intensities are proportional to n_1B_1 and n_2B_2, respectively at each level. The solid curves in Fig. 2b are the results of the calculation after adjusting the values to $B_1 = 0.02$, $B_2 = 0.98$, $G_1 = 0.3$, $G_2 = 0.7$, and $D = 0.7$. The large difference of the radiative recombination rate $B_1 \ll B_2$ suggests that the lower energy level 1 is related rather to a bound state than to a free state. In case when both of the two levels are free states emerged from the QWs with 1 ML difference, one should obtain the result $B_1 \approx B_2$. The similar tendency was obtained from the double PL lines in the 30 ML (90 Å) QW.

Finally, we describe briefly the results of magneto-photoluminescence measured up to 3.5 T. The detection of the σ^+-component of the PL lines exhibited low energy shifts reflecting the large Zeeman splitting of the exciton. The narrower the QW-width is, the larger is the Zeeman shift, mainly due to a larger extent of the exciton wave function penetration into the magnetic barrier. What is to be noticed is the comparison of the two PL lines in the 12 ML QW as shown in Fig. 3. The peaks of the two PLs showed similar Zeeman shifts, however, PL at the lower energy side (the level 1 in Fig. 2c) exhibited a slightly larger shift than that of the higher energy level, which is in conflict with the tendency in case of the QWs with 1 ML difference. These results together with the discussion above lead to a

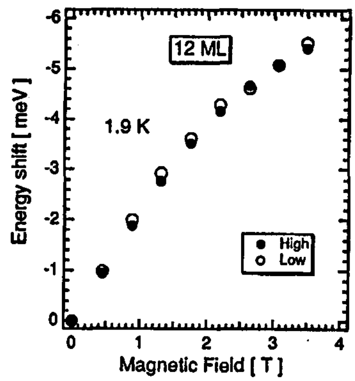

Fig. 3. Zeeman shifts of the high energy (solid circle) and low energy (open circle) PL lines from the 12 ML QW at 1.9 K.

conclusion that the observed bound-exciton state is localized more likely to the interface where the exciton wave function can capture a greater number of Mn localized spins. The small difference of the Zeeman shifts of the two PLs suggests that the bound state (level 1) is related to D^0X rather than A^0X, since the effect of Mn spins for the conduction electrons is weaker than that of holes. The similar PL line related to D^0X have been reported in CdTe/$Cd_{1-x}Mn_xTe$ multi quantum wells [5].

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