High Magnetic Field Photoluminescence Study of Pressure Effect on Spin Exchange Interaction in a CdTe/Cd_{1-x}Mn_xTe Single Quantum Well Structure

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Photoluminescence (PL) measurements in CdTe/Cd_{1-x}Mn_xTe ($x=0.24$) single quantum well (SQW) structure with different quantum well (QW) widths and bulk Cd_{1-x}Mn_xTe ($x=0.15$) under high hydrostatic pressures up to 2.68 GPa and DC magnetic fields up to 30 T are reported. We analyze the Zeeman shift of the band-edge exciton PL peaks, taking into account a linear magnetization term, and obtain pressure dependence of spin exchange parameters. Negative pressure dependence of the p - d hybridization is found for the barrier of the SQW structure and the bulk sample. A possibility that the hybridization is weakened due to the pressure induced relaxation of the distortion around Te atoms is proposed.

[CdMnTe, single quantum well structure, exciton, sp - d hybridization, pressure effect]

1. Introduction

The spins of extended electrons and those of local magnetic ions are coupled strongly through sp - d hybridization in diluted magnetic semiconductors (DMS's). This coupling underlies harmonization of electronics engineering and spin engineering. Various techniques such as alloying and quantum structure forming have been applied to synthesis of DMS's in order to improve their spin-related functions. In a single quantum well (SQW) structure with non-magnetic wells and magnetic barrier layers, for example, we can adjust the amount of magnetic ions included in the exciton Bohr radius by means of changing well width or magnetic ion concentration in the barriers. Systematic investigation of the sp - d hybridization and of the d - d exchange among magnetic ions in thus synthesized materials is desired.

Simultaneous application of high pressure and high magnetic fields has enabled us to investigate material properties more in detail. For example, the high magnetic field is a powerful tool to study magnetic properties of materials and the pressure can modify the bond length, which leads to a continuous change of interaction length. As for DMS's such as Cd_{1-x}Mn_xSe ($x=0.05$), Cd_{1-x}Co_xSe ($x=0.12$) [1], and a CdTe/Cd_{1-x}Mn_xTe ($x=0.09$) SQW structure [2], PL studies under both pressure and magnetic fields have revealed enhancement of the p - d hybridization by pressure. We are interested in pressure effect on the sp - d hybridization in DMS quantum structures with higher magnetic ion content, where the number of isolated spins is very small. Heiman *et al.* reported that the magnetic field dependence of the magnetization of bulk Cd_{1-x}Mn_xTe with $x>0.1$ become linear above 15 T owing to small isolated clusters and the random network of Mn ions [3]. The pressure effect of the spin exchanges in such materials have not been studied precisely and will be reported in this paper.

2. Experimental

Our sample was a CdTe/Cd_{1-x}Mn_xTe ($x=0.24$) SQW structure which consisted of 13, 19 and 38 Å thick CdTe wells sandwiched by 480 Å thick Cd_{1-x}Mn_xTe ($x=0.24$) barriers. Hybrid buffer layers between the SQW's and (100) GaAs were constructed. The hydrostatic pressures of 0.08, 0.43, 0.85, 2.08 and 2.68 GPa were generated in a diamond-anvil cell made of BeCu 17200. Its diameter and diagonal length was 8.9 mm and 11.9 mm, respectively. Methanol-ethanol (4:1) mixed liquid was used as pressure fluid. The R₁ fluorescence line of ruby was used to calibrate the pressure. Excitation light (488.0 nm) from an Ar ion laser and photoluminescence signal were transferred through a

Fig.1. Measurement system for magneto-PL.

single optical fiber. DC magnetic fields up to 30 T were generated by a water cooled resistive magnet with a 32 mm bore. We also made similar experiments for a bulk Cd_{1-x}Mn_xTe ($x=0.15$) at 0.02,

1.06 and 1.99 GPa. The experimental system is shown in Fig. 1.

3. Results and Discussion

We observed four luminescence signals assigned to band-edge exciton PL's from three wells and a barrier of the SQW sample, respectively, at low temperatures without magnetic fields. Figure 2(a) shows pressure dependence of energies (E_0) of the PL peaks at 4.2 K. The experimental data are described very well by the following function,

$$E_0(P) = E_0 + a \cdot P + b \cdot P^2, \quad (1)$$

where P is pressure in GPa. The fitting results are shown in Fig. 2(b) together with the data of Meyer *et al.* [2] for CdTe/Cd_{1-x}Mn_xTe ($x=0.09$) SQW structure. In our results, the

Fig. 2(a). Pressure dependence of the PL peak energies in the CdTe/Cd_{1-x}Mn_xTe ($x=0.24$) SQW structure. Lines are least-squares fits of Eq. (1). (b). The pressure coefficients vs. well width together with the results of Meyer *et al.* Data for the barrier are shown at the well width of zero because barriers can be regarded as QW's without width. Lines are guides for the eyes.

coefficient b is much smaller for all the wells than that of Meyer *et al.* They reported that no well width dependence was observed in the a , whereas we find that it became larger with increasing the well width. These results could be explained by much larger effect of pressure on the exciton binding energy due to the barrier height variation in our higher Mn concentration system.

Zeeman shifts of PL peaks at the lowest pressure and the highest pressure, 2.08 GPa for the barrier and 2.68 GPa for the others of the SQW sample, are as shown in Fig. 3. Field dependence of the shift was almost linear above 15 T for all layers

Fig. 3. The Zeeman shifts vs. magnetic fields of the band-edge excitons at the lowest and the highest pressures in the CdTe/Cd_{1-x}Mn_xTe ($x=0.24$) SQW structure. The lines are least-squares fits of Eq. (2) and (3).

except for the 38 Å thick well. This linear dependence can be attributed to the linear field dependence of the magnetization reported by Heiman *et al.* [3] In the 38 Å thick QW, we suppose the Bohr radius is almost comparable to the half of the well width and the exciton feels only the spins at the interface. Zeeman shifts (ΔE) of the exciton PL peak energies could be described very well as shown in Fig. 3 by the following expression including a linear magnetization term,

$$E = (1/2)(\beta - \alpha)N_0(\chi \langle S_z \rangle_{Mn} + M_l H), \quad (2)$$

$$\langle S_z \rangle_{Mn} = S_0 B_{5/2}(H, T + T_0), \quad (3)$$

where $B_{5/2}$, x , H , α , β , N_0 , S_0 , T_0 and M_l are the modified Brillouin function for a spin of 5/2, Mn content, an external field, s - d , p - d

interaction constants, cation site density, two phenomenological fitting parameters for spin saturation, and a linear magnetization factor, respectively.

Fig.4. Pressure dependence of (a) $N_0(\alpha-\beta)$, (b) T_0 and (c) M_f in $\text{CdTe}/\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ ($x=0.24^*$ and $0.09^{**}[2]$) SQW structures. Lines are guides for the eyes.

Pressure dependence of $N_0(\alpha-\beta)$, T_0 and M_f was obtained after careful fitting as shown in Fig. 4(a), (b) and (c), respectively. T_0 increased and M_f decreased for all layers of the SQW sample and the bulk sample with increasing pressure, which reflects the enhancement of the $d-d$ coupling among the Mn ions. $N_0(\alpha-\beta)$ increased for all the wells with increasing pressure, which agrees quantitatively with the previous experimental reports and also

theoretical prediction[4,5] taking into the bond length dependence of the $p-d$ hybridization. However, its pressure dependence for the barrier and the bulk sample was negative, which is not explicable by the simple model. This dependence seems to be peculiar to those materials with larger Mn content, in which there is distortion around Te atoms. The σ -bond between an Mn- d -orbit and a Te- p -orbit becomes stronger when distorted according to a simple calculation following Harrison's treatment [5]. The distortion would be expected to be relaxed by hydrostatic pressure. We propose a possibility that pressure induced relaxation of the distortion might weaken the $p-d$ hybridization.

4. Conclusion

We have obtained linear and quadratic pressure coefficients of band-edge exciton PL peak energies for QW's and the barrier in the $\text{CdTe}/\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ ($x=0.24$) SQW structure. The linear coefficient increased with increasing the QW width. The quadratic one is much smaller in all layers than the previous reports.

The PL peaks shift almost linearly with respect to magnetic fields above 15 T for all layers except for the 38 Å thick well. Those Zeeman shift can be described very well by Eq. (2) including a linear magnetization term. Negative pressure dependence of $N_0(\alpha-\beta)$ in the bulk $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ ($x=0.15$) and the barrier of the $\text{CdTe}/\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ ($x=0.24$) SQW structure can not be explained by the conventional theoretical model. We propose a possibility that the $p-d$ hybridization is enhanced by the distortion around Te atoms and that the distortion is relaxed by pressure.

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