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Anisotropic magneto-optical effects in $(CdTe)_{0.5}(Cd_{0.75}Mn_{0.25}Te)_{0.5}$ tilted superlattices

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We have studied anisotropic Zeeman shift of magneto-photoluminescence (PL) from $(CdTe)_{0.5}(Cd_{0.75}Mn_{0.25}Te)_{0.5}$ tilted superlattices fabricated by fractional monolayer growth onto a 1° off vicinal surface of $CdTe_{0.74}Mg_{0.26}Te(001)$. Compositionally modulated wire structures in the (001) plane have been confirmed by polarized PL. The Zeeman shift of the $(CdTe)_{0.5}(Cd_{0.75}Mn_{0.25}Te)_{0.5}$ tilted superlattices is about 150 times of that of a nonmagnetic system of $(CdTe)_{0.5}(Cd_{0.74}Mn_{0.26}Te)_{0.5}$ tilted superlattices in the Faraday configuration, which is caused by the exchange interaction between excitons and Mn ions. The magneto-PL depends on the direction of the external magnetic field in the (001) plane; the Zeeman shift in the perpendicular field to the wire direction is larger than that in the parallel field. Furthermore, we demonstrate a reorientation of hole spins in the magnetic field parallel to the wire. The observed anisotropic Zeeman shift is attributed to the one-dimensional spin quantization, with the total angular momentum being projected along the confinement axis in the wire structure.

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I. INTRODUCTION

Useful functions of most of existing semiconductor devices are produced by using the charge of electrons. On the other hand, magnetic recording for storage of mass information is achieved by using the spin of electrons in ferromagnetic materials. Recently, the possibility to control both the charge and spin of electrons has attracted a great attention for discovery of new functional devices. Diluted magnetic semiconductors (DMS's), which contain a high concentration of magnetic ions in host semiconductors, especially II-VI (Refs. 1–6) and III-V (Refs. 7–13) semiconductors, look promising to realize them. Ohno *et al.* discovered ferromagnetism in *p*-type (Ga,Mn)As grown on GaAs.[9] They demonstrated that holes play a key role in ferromagnetism.[11] Photogenerated holes behave by themselves like holes in the *p*-type DMS; photogenerated holes in (In,Mn)As/GaSb heterostructures cause ferromagnetism,[10] which suggests a possibility of controlling the exchange interaction by light.

Low-dimensional DMS heterostructures are expected to realize further new magneto-optical phenomena by the quantum confined excitonic states.[14] Oka *et al.* have demonstrated a large Zeeman shift and exciton magnetic polaron (EMP) formation induced by the magnetic ions in (Cd,Mn)Te quantum well (QW),[14,15] (Cd,Mn)Se quantum wire (QWR),[15,16] and (Cd,Mn)Se quantum dot.[14–16] On the other hand, the Zeeman shift and EMP formation in the nonmagnetic QW interacting with magnetic ions in the DMS barrier have been reported for an asymmetric (Cd,Mn)Te/CdTe/(Cd,Mg)Te QW.[17–19] Optical and spin properties of the excitons separated spatially from the magnetic ions are expected to be controlled by controlling the wave function of the exciton. Especially, excitons in lower-dimensional quantum structures can interact sensitively with the DMS surrounding them. In this paper, we have studied magneto-photoluminescence (PL) from $(CdTe)_{0.5}(Cd_{0.75}Mn_{0.25}Te)_{0.5}$ tilted superlattices (TSL's) grown on a vicinal surface of $Cd_{0.74}Mg_{0.26}Te(001)$. The exciton PL of the TSL's shows a clear linear-polarization anisotropy demonstrating the one-dimensional (1 D) structure, i.e., compositionally modulated QWR's. In the magnetic field, PL peak shifts remarkably because of the exchange interaction between excitons and Mn ions. The exchange interaction shows a clear anisotropy depending on the direction of the magnetic field in the growth plane. We have investigated the origin of the anisotropy by measuring polarized magneto-PL.

II. EXPERIMENTS

$CdTe/Cd_{0.75}Mn_{0.25}Te$ wire structures have been fabricated by a self-regulated method for the growth of TSL's using molecular beam epitaxy. $Cd_{0.96}Zn_{0.04}Te(001)$ substrate misoriented 1° toward the [110] direction was used in this study. This substrate has steps aligned along the $[1\bar{1}0]$ direction. The growth temperature was 310 °C. Before growing the TSL's, we grew 200 ML (monolayer) of $Cd_{0.74}Mn_{0.26}Te$ as a buffer layer. $(CdTe)_{0.5}(Cd_{0.75}Mn_{0.25}Te)_{0.5}$ TSL's were fabricated by repeated deposition of 0.5 ML of CdTe followed by 0.5 ML of $Cd_{0.75}Mn_{0.25}Te$ on the vicinal surface of $Cd_{0.74}Mg_{0.26}Te(001)$. This cycle was repeated 30 times. As a consequence, the 1° vicinal surface is expected to fabricate square wires with a cross section of 9.3×9.7 nm^2.[20] This size is comparable with the bulk Bohr radius (6.5 nm) of CdTe. A 50 ML $Cd_{0.74}Mg_{0.26}Te$ was deposited after the TSL growth. We have confirmed the wire structure using cross-

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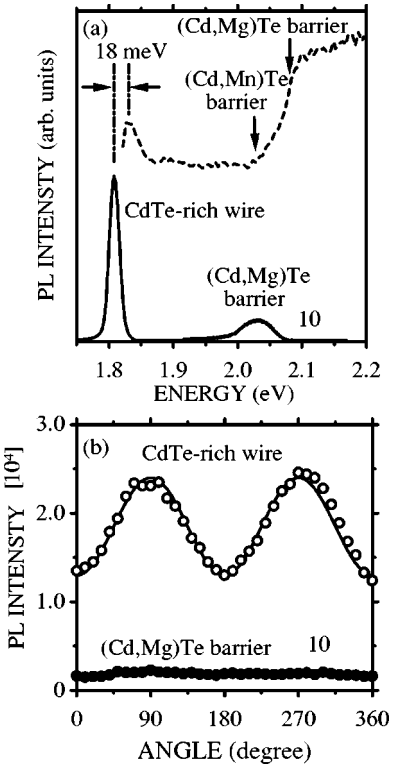


FIG. 1. (a) PL (solid line) and PLE (dashed line) spectra of the $(CdTe)_{0.5}(Cd_{0.75}Mn_{0.25}Te)_{0.5}$ TSL's. The sample temperature was 3.8 K. (b) PL intensity as a function of polarization angle. Here, the angle is defined from the [110] direction. Open and solid circles are the results for the CdTe-rich wire and $Cd_{0.74}Mg_{0.26}Te$ barrier, respectively. Solid line shows the sine curve.

sectional transmission electron microscopy of the $(CdTe)_{0.5}(Cd_{1-x}Mn_xTe)_{0.5}$ TSL's.[21] The chemical contrast between CdTe and $Cd_{1-x}Mn_xTe$ layers is not strong, indicating some intermixing between the layers. Therefore, the $(CdTe)_{0.5}(Cd_{0.75}Mn_{0.25}Te)_{0.5}$ TSL's are considered to be equivalent to compositionally modulated QWR's consisting of CdTe-rich and $Cd_{0.75}Mn_{0.25}Te$-rich wires.

PL and PL excitation (PLE) experiments were carried out under the excitation of the 488 nm line of an Ar-ion laser and monochromatic light of a tungsten lamp, respectively. Magneto-PL was measured at 1.5 K in an optical cryostat with a superconducting split-coil magnet up to 5 T. The second harmonic light pulses (387 nm, 200 fs) of a Ti:sapphire laser excited by an Ar-ion laser were used as the excitation. The excitation density is 0.27 $\mu J/cm^2$.

III. RESULTS AND DISCUSSION

Figure 1(a) shows PL and PLE spectra of the $(CdTe)_{0.5}(Cd_{0.75}Mn_{0.25}Te)_{0.5}$ TSL's. The sample temperature was 3.8 K. The solid line indicates the PL spectrum. The PL from the CdTe-rich wire and $Cd_{0.74}Mg_{0.26}Te$ barrier are clearly observed at 1.81 eV and 2.03 eV, respectively. We investigated linear polarization properties of these PL signals. Figure 1(b) shows linearly polarized PL intensities of the CdTe-rich wire and $Cd_{0.74}Mg_{0.26}Te$ barrier as a function of the polarization angle. Here, the angle is defined from the [110] direction. Open and solid circles are the results for the CdTe-rich wire and $Cd_{0.74}Mg_{0.26}Te$ barrier, respectively. The PL intensity of the $Cd_{0.74}Mg_{0.26}Te$ barrier is independent of the polarization angle. Nevertheless, a clear sinusoidal structure is found in the PL intensity of the CdTe-rich wire. The PL intensity of the CdTe-rich wire shows maxima at 90° and 270°, at which the polarization is parallel to the wire. This result demonstrates the quantum confinement with the quantization direction perpendicular to the wire. On the other hand, the PL intensity polarized perpendicular to the wire, which correspond to the angles of 0° and 180° in Fig. 1(b), is not zero. This result can be explained by the compositionally modulated wire structure and lateral coupling of exciton wave functions between the CdTe-rich wires separated by the narrow $Cd_{0.75}Mn_{0.25}Te$-rich wires. A dashed line in Fig. 1(a) shows PLE spectrum detected at 1.81 eV. The PLE spectrum shows a strong absorption resonance at 1.828 eV. The Stokes shift is about 18 meV, which is remarkable at less than 10 K. The large Stokes shift is due to the EMP formation and a nonmagnetic localization such as alloy potential fluctuation. The EMP formation is a result of the exchange interaction between excitons and Mn ions.

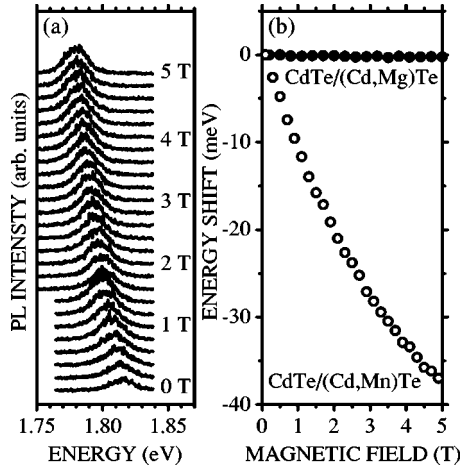


FIG. 2. (a) PL spectra of the $(CdTe)_{0.5}(Cd_{0.75}Mn_{0.25}Te)_{0.5}$ TSL's measured at the $\boldsymbol{W} \perp \boldsymbol{B} \| \boldsymbol{k}$ configuration. The sample temperature was 1.5 K. (b) The magnetic-field dependence of PL-peak shift. Open and solid circles are the results of the $(CdTe)_{0.5}(Cd_{0.75}Mn_{0.25}Te)_{0.5}$ TSL's and $(CdTe)_{0.5}(Cd_{0.74}Mg_{0.26}Te)_{0.5}$ TSL's, respectively.

Figure 2(a) shows unpolarized magneto-PL spectra of the $(CdTe)_{0.5}(Cd_{0.75}Mn_{0.25}Te)_{0.5}$ TSL's measured in various magnetic fields. The measurement configuration is $\boldsymbol{W} \perp \boldsymbol{B} \| \boldsymbol{k}$, where $\boldsymbol{W}$, $\boldsymbol{B}$, and $\boldsymbol{k}$ are vectors of the wire, the applied magnetic field, and the wave number of the PL, respectively. $\boldsymbol{k}$ is perpendicular to the (001) sample surface. The PL coincides with results of the right circular polarized magneto-PL. The magnetic-field dependence of the PL-peak shift of the $(CdTe)_{0.5}(Cd_{0.75}Mn_{0.25}Te)_{0.5}$ TSL's is plotted by open circle in Fig. 2(b). For comparison, we show results (solid circles) of a nonmagnetic system of $(CdTe)_{0.5}(Cd_{0.74}Mg_{0.26}Te)_{0.5}$ TSL's fabricated by the same method.[22] The PL peak of the $(CdTe)_{0.5}(Cd_{0.75}Mn_{0.25}Te)_{0.5}$ TSL's shifts remarkably toward the lower energy side with increasing magnitude of the mag-

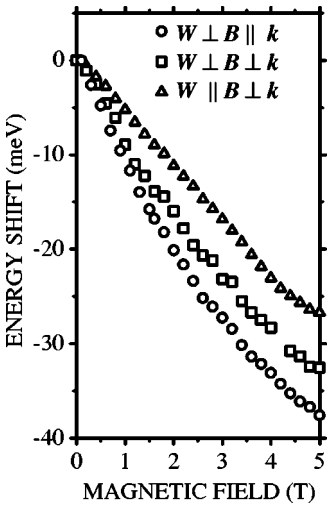


FIG. 3. The magnetic-field dependence of PL-peak shift. The sample temperature was 1.5 K. Circles, squares, and triangles indicate the results at $\boldsymbol{W}\perp\boldsymbol{B}\|\boldsymbol{k}$, $\boldsymbol{W}\perp\boldsymbol{B}\perp\boldsymbol{k}$, and $\boldsymbol{W}\|\boldsymbol{B}\perp\boldsymbol{k}$, respectively.

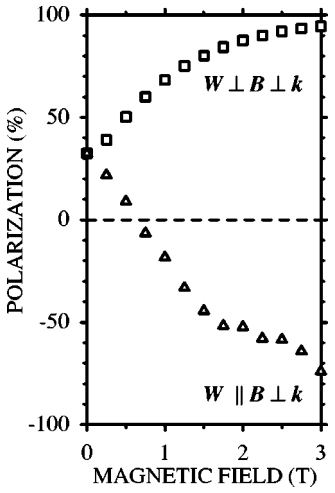


FIG. 4. The magnetic-field dependence of PL polarization. The PL polarization is defined by $(I_{E\|wire}-I_{E\perp wire})/(I_{E\|wire}+I_{E\perp wire})$, where $I_{E\|wire}$ and $I_{E\perp wire}$ are the intensities of PL polarized parallel and perpendicular to the wire, respectively. The sample temperature was 1.5 K. Triangles and squares indicate the results at $\boldsymbol{W}\|\boldsymbol{B}\perp\boldsymbol{k}$ and $\boldsymbol{W}\perp\boldsymbol{B}\perp\boldsymbol{k}$, respectively.

netic field. The PL-peak shift in 5 T of the $(CdTe)_{0.5}(Cd_{0.75}Mn_{0.25}Te)_{0.5}$ TSL's is about 150 times larger than that of the $(CdTe)_{0.5}(Cd_{0.74}Mg_{0.26}Te)_{0.5}$ TSL's; 0.24 meV for the $(CdTe)_{0.5}(Cd_{0.74}Mg_{0.26}Te)_{0.5}$ TSL's and 37 meV for the $(CdTe)_{0.5}(Cd_{0.75}Mn_{0.25}Te)_{0.5}$ TSL's in 5 T, respectively. It is noted that the significant PL-peak shift of the CdTe-rich wire almost coincides with one of a homogeneously diluted bulk of $Cd_{0.8}Mn_{0.2}Te$, 45 meV in 7 T.[23] On the other hand, it has been reported that PL-peak shift for the asymmetric $Cd_{0.86}Mn_{0.14}Te/CdTe(4.9\ nm)/Cd_{0.78}Mg_{0.22}Te$ QW is 3 meV in 3 T,[18] which is about ten times smaller than the present PL-peak shift. Although the Mn concentration in the CdTe-rich wire is not clear, it is considered that diffused Mn ions into the CdTe-rich wire results in the remarkable PL-peak shift. Furthermore, the shift is enhanced by overlapping of the exciton wave function in the wire with the Mn ions in the barrier ($Cd_{0.75}Mn_{0.25}Te$-rich wires). The Zeeman effects also reduce the DMS barrier height. Then, the weakened carrier confinement causes deep penetration of the exciton wave function into the DMS barrier with increasing magnitude of the magnetic field, which enhance the exchange interactions.

Figure 3 shows the magnetic-field dependence of the PL-peak shift measured at three kinds of configurations. Circles, squares, and triangles show results at $(\boldsymbol{W}\perp\boldsymbol{B}\|\boldsymbol{k})$, $\boldsymbol{W}\perp\boldsymbol{B}\perp\boldsymbol{k}$, and $\boldsymbol{W}\|\boldsymbol{B}\perp\boldsymbol{k}$, respectively. The PL-peak shift for the CdTe-rich wire clearly depends on the configuration. The effective Zeeman effects including the exchange interaction can be described by the Hamiltonian[1]

$$\mathcal{H}_{Zeeman}=\sum_i J(\boldsymbol{r}-\boldsymbol{R}_i)\boldsymbol{S}_i\cdot s+g\mu_B\boldsymbol{B}\cdot\boldsymbol{s}, \qquad (1)$$

where $\boldsymbol{S}_i$ and $\boldsymbol{s}$ is the spin operators for the Mn ion at $\boldsymbol{R}_i$ and for the exciton at r, respectively, $J(\boldsymbol{r}-\boldsymbol{R}_i)$ an exchange integral, g the g factor, and μ_B the Bohr magneton. Because of the scalar product relations of $\boldsymbol{S}_i\cdot\boldsymbol{s}$ and $\boldsymbol{B}\cdot\boldsymbol{s}$, the Faraday configuration $(\boldsymbol{W}\perp\boldsymbol{B}\|\boldsymbol{k})$ results in the largest Zeeman shift. On the other hand, an anisotropic Zeeman shift is observed at the Voigt configurations ($\boldsymbol{W}\perp\boldsymbol{B}\perp\boldsymbol{k}$ and $\boldsymbol{W}\|\boldsymbol{B}\perp\boldsymbol{k}$). The PL-peak shift at $\boldsymbol{W}\perp\boldsymbol{B}\perp\boldsymbol{k}$ is larger than that at $\boldsymbol{W}\|\boldsymbol{B}\perp\boldsymbol{k}$. Such anisotropic behavior never appears in the bulk material and QW. The anisotropic PL-peak shift corresponds to an anisotropic exchange interaction. We consider that this can be attributed to the electronic structures of the compositionally modulated QWR structures. In $CdTe/Cd_{0.95}Mn_{0.05}Te$ QW (Ref. 24) and $Cd_{0.9}Mn_{0.1}Te/Cd_{0.6}Mg_{0.4}Te$ QW,[25] similar anisotropic Zeeman splitting has been observed between in-plane and perpendicular magnetic fields. In the in-plane magnetic field, rotation of the hole spins from the confinement direction to the external field direction occurs, and a complex Zeeman splitting caused by the valence-band mixing results in a small Zeeman shift as compared with that in the perpendicular field. In the case of the compositionally modulated QWR structure, the initial quantization direction of the hole spins is perpendicular to the wire. Therefore, it is expected to be reoriented the hole spins into the external field direction when applying the field parallel to the wire. To demonstrate the reorientation of the hole spins in our sample, we have measured linear polarized PL. Figure 4 shows the magnetic-field dependence of the PL polarization. Here, the PL polarization is defined by $(I_{E\|wire}-I_{E\perp wire})/(I_{E\|wire}+I_{E\perp wire})$, where $I_{E\|wire}$ and $I_{E\perp wire}$ are the PL intensities polarized parallel and perpendicular to the wire, respectively. Squares and triangles indicate results at $\boldsymbol{W}\perp\boldsymbol{B}\perp\boldsymbol{k}$ and $\boldsymbol{W}\|\boldsymbol{B}\perp\boldsymbol{k}$, respectively. As shown in Fig. 1(b), the PL polarization in 0 T is about 28%. At the $\boldsymbol{W}\perp\boldsymbol{B}\perp\boldsymbol{k}$ configuration, the PL polarization increases with the magnetic field. On the other hand, the PL polarization at the $\boldsymbol{W}\|\boldsymbol{B}\perp\boldsymbol{k}$ configuration decreases with the magnetic field. Moreover, the PL polarization becomes negative above $\sim$0.5 T. This result reveals a reorientation of the hole spins from the initial quantization direction toward the external field parallel to the wire. According to the discussions for QW's,[24,25] the small Zeeman shift observed at $\boldsymbol{W}\|\boldsymbol{B}\perp\boldsymbol{k}$ can

be attributed to the valence-band mixing caused by the reorientation of the hole spins. The anisotropic orientation of the hole spins in the (001) plane is a characteristic feature expected in the 1D structure.

IV. CONCLUSION

Anisotropic large Zeeman shift was found in the $(CdTe)_{0.5}(Cd_{0.75}Mn_{0.25}Te)_{0.5}$ TSL's grown on a vicinal surface of $Cd_{0.74}Mg_{0.26}Te(001)$. From linear polarized PL measurements, the $(CdTe)_{0.5}(Cd_{0.75}Mn_{0.25}Te)_{0.5}$ TSL's is confirmed to be equivalent to the compositionally modulated QWR structures. The Zeeman shift of the $(CdTe)_{0.5}(Cd_{0.75}Mn_{0.25}Te)_{0.5}$ TSL's is found to be about 150 times of that of a nonmagnetic system of $(CdTe)_{0.5}(Cd_{0.74}Mg_{0.26}Te)_{0.5}$ TSL's. Furthermore, the Zeeman shifts of the $(CdTe)_{0.5}(Cd_{0.75}Mn_{0.25}Te)_{0.5}$ TSL's shows anisotropic behavior in the Voigt configurations; the Zeeman shift at $\boldsymbol{W}\|\boldsymbol{B}\perp\boldsymbol{k}$ is smaller than that at $\boldsymbol{W}\perp\boldsymbol{B}\perp\boldsymbol{k}$. We have demonstrated a reorientation of the hole spins from the initial quantization direction toward the external field parallel to the wire at the $\boldsymbol{W}\|\boldsymbol{B}\perp\boldsymbol{k}$ configuration. The reorientation of the hole spins mixes the valence bands, and, therefore, the Zeeman shift becomes small.

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