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Enhancement of the activation energy due to coupling effects in $Cd_xZn_{1-x}Te/ZnTe$ double quantum dots

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Temperature-dependent photoluminescence measurements show that the activation energy of $Cd_{0.6}Zn_{0.4}Te/ZnTe$ double quantum dots (QDs) increases with decreasing ZnTe separation layer. At a separation-layer thickness of 6 nm, this behavior can be attributed to enhancement in the tunneling probability of carriers from the smaller $Cd_{0.6}Zn_{0.4}Te$ 1.5-monolayer (ML) QDs to the larger 3.0-ML QDs due to the coupling effect between the upper and the lower $Cd_{0.6}Zn_{0.4}Te$ QDs. The present results indicate that the activation energy in $Cd_{0.6}Zn_{0.4}Te/ZnTe$ double QDs is significantly affected by the ZnTe separation layer. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2374650]

I. INTRODUCTION

Semiconductor quantum dots (QDs) have been very attractive because of interest in both fundamental physical properties[1,2] and promising applications in electronic and optoelectronic devices, such as QD single-electron transistors,[3] QD lasers,[4] QD optical switches,[5] and QD infrared photodetectors.[6] Nanoscale devices utilizing QDs can be fabricated without an additional lithography process because QDs already maintain discrete atomlike energy levels with good optical properties.[7] Among the various kinds of QDs, III-V/III-V QDs are the most extensively studied systems. However, relatively little work has been performed on II-VI ternary/II-VI binary QDs in comparison with III-V ternary/III-V binary QDs (Refs. 8 and 9) because of the delicate problems encountered in the growth process. Among these II-VI ternary/II-VI binary QDs, $Cd_xZn_{1-x}Te/ZnTe$ QD systems have become particularly attractive because of their potential applications in optoelectronic devices operating in the green region of the spectrum.[10] II-VI QDs have been also particularly attractive because of the interest in the generation of single photons.[11,12] In particular, vertically stacked double QDs, consisting of smaller band gap QD arrays separated by a thin larger band gap barrier, are currently receiving considerable attention for application in next-generation optoelectronic and quantum information processing devices.[13,14] Even though some work on the optical properties of coupled CdTe/ZnTe QDs and quantum-well structures have been reported,[15] systematic studies concerning the dependence of the coupling effect and the activation energy on the thickness of the ZnTe separation layer in vertically stacked $Cd_xZn_{1-x}Te/ZnTe$ double QDs are very important for improving the efficiencies of optoelectronic devices.

This paper presents activation energy variations due to a coupling behavior in combined $Cd_xZn_{1-x}Te/ZnTe$ double QDs grown using molecular beam epitaxy (MBE). Atomic force microscopy (AFM) measurements were performed to characterize the surface microstructural properties of $Cd_{0.6}Zn_{0.4}Te$ layers of different thicknesses grown on ZnTe buffer layers. Photoluminescence (PL) measurements were carried out in order to investigate the coupling effect and to determine the activation energies in the vertically stacked $Cd_{0.6}Zn_{0.4}Te/ZnTe$ double QDs.

II. EXPERIMENTAL DETAILS

Several kinds of samples containing both $Cd_{0.6}Zn_{0.4}Te/ZnTe$ QDs with 1.5-monolayer (ML) deposition and $Cd_{0.6}Zn_{0.4}Te/ZnTe$ QDs with 3.0-ML deposition were used in this study. The samples were grown on semi-insulating (100)-oriented GaAs substrates by MBE and consisted of the following structures: a 100 nm undoped ZnTe capping layer deposited by MBE, 1.5-ML $Cd_{0.6}Zn_{0.4}Te$ QDs deposited by MBE, an undoped ZnTe separation layer (thickness $\cong$ 6, 18, or 30 nm) deposited by MBE, 3.0-ML $Cd_{0.6}Zn_{0.4}Te$ QDs deposited by MBE, and a 900 nm undoped ZnTe buffer layer deposited by MBE. Since the thickness of the ZnTe buffer layer was much larger than that of the ZnTe capping layer, when the $Cd_{0.6}Zn_{0.4}Te$ QDs were grown on the ZnTe buffer layer, the magnitude of the electron confinement in the 1.5-ML $Cd_{0.6}Zn_{0.4}Te$ QDs was significantly increased. Reference samples for the 1.5-ML and the 3.0-ML $Cd_{0.6}Zn_{0.4}Te$ QDs were independently grown for comparison. The depositions of the ZnTe layer and the $Cd_{0.6}Zn_{0.4}Te$ QDs were done at a substrate temperature of 320 °C. The source temperatures of the Cd, Zn, and Te sources for the $Cd_{0.6}Zn_{0.4}Te$ QDs and ZnTe layers were 220, 280, and 300 °C, respectively. AFM measurements were performed by using a multimode AFM from Digital Instruments operating in the tapping mode. The PL measurements were carried out using a 50 cm monochromator equipped with an RCA 31034 photomultiplier tube. The excitation source was the 4420 Å line of a He–Cd laser, and the laser power density was 10 mW/cm^2. The sample temperature was controlled between 20 and 130 K by using a He displex system.

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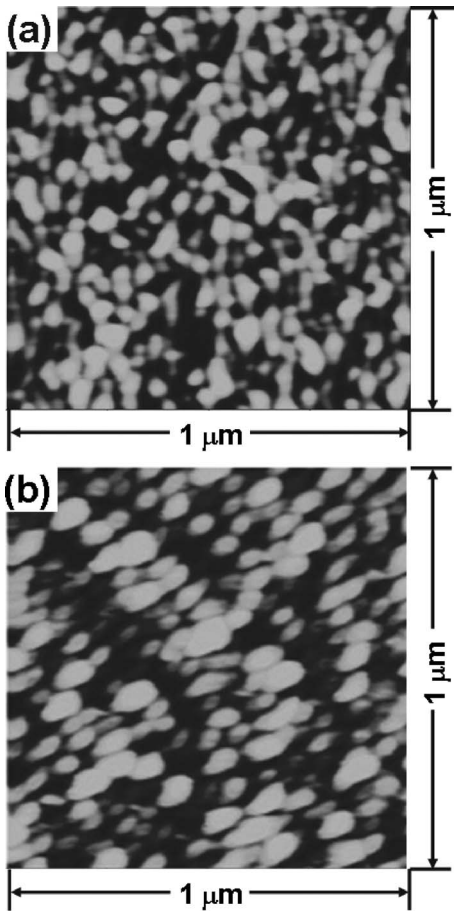

FIG. 1. Atomic force microscopy images of $Cd_{0.6}Zn_{0.4}Te/ZnTe$ quantum dots with thicknesses of (a) 1.5 and (b) 3.0 MLs grown on ZnTe buffer layers.

III. RESULTS AND DISCUSSION

Figure 1 shows AFM images of the uncapped surfaces of the $Cd_{0.6}Zn_{0.4}Te$ QDs deposited with thicknesses of (a) 1.5 and (b) 3.0 MLs on ZnTe buffer layers. The AFM images of the $Cd_{0.6}Zn_{0.4}Te$ QDs with thicknesses of 1.5 and 3.0 MLs on ZnTe buffer layers show that the $Cd_{0.6}Zn_{0.4}Te$ QDs are embedded in a ZnTe matrix. The diameters of the 1.5-ML $Cd_{0.6}Zn_{0.4}Te$ QDs are between 35 and 45 nm, and their average height and average density are 8 nm and 3×10^{10} cm^{-2}, respectively. The diameters of the 3.0-ML $Cd_{0.6}Zn_{0.4}Te$ QDs are between 45 and 55 nm, and their average height and average density are 10 nm and 2×10^{10} cm^{-2}, respectively. The height and the diameter of the $Cd_{0.6}Zn_{0.4}Te/ZnTe$ QDs increase with increasing $Cd_{0.6}Zn_{0.4}Te$ layer thickness, and the $Cd_{0.6}Zn_{0.4}Te/ZnTe$ QDs tend to stack.

Figure 2 shows PL spectra at 32 K for the $Cd_{0.6}Zn_{0.4}Te/ZnTe$ QDs with thicknesses of (a) 1.5 and (b) 3.0 MLs and for the double QD structures of 1.5-ML $Cd_{0.6}Zn_{0.4}Te/ZnTe$ QDs and 3.0-ML $Cd_{0.6}Zn_{0.4}Te/ZnTe$ QDs for ZnTe separation layers of (c) 30, (d) 18, and (e) 6 nm. The dominant peaks, one at 2.145 eV for the 3.0-ML $Cd_{0.6}Zn_{0.4}Te/ZnTe$ QDs and the other at 2.312 eV for the 1.5-ML $Cd_{0.6}Zn_{0.4}Te/ZnTe$ QDs, which correspond to the interband transitions from the ground electronic subband to the ground heavy hole (E_1-HH_1), are seen for ZnTe separation layers of 30 and 18 nm. Only one dominant peak appears for the $Cd_{0.6}Zn_{0.4}Te/ZnTe$ double QDs with a ZnTe separation thickness of 6 nm, as shown in Fig. 2(e). This behavior is attributed to a superposition of two spectra, one originating from the upper 3.0-ML $Cd_{0.6}Zn_{0.4}Te/ZnTe$ QDs and the other originating from the lower 1.5-ML $Cd_{0.6}Zn_{0.4}Te/ZnTe$ QDs, due to the coupling effect between two QDs.[16] As the thickness of the ZnTe separation layer decreases while the PL intensity corresponding to the 3.0-ML $Cd_{0.6}Zn_{0.4}Te/ZnTe$ QDs increases, the PL intensity related to the 1.5-ML $Cd_{0.6}Zn_{0.4}Te$ QDs decreases. This behavior originates from an increase in the carriers in the 3.0-ML $Cd_{0.6}Zn_{0.4}Te$ QDs due to carrier transfer from the smaller 1.5-ML QDs to the larger 3.0-ML QDs by means of a nonresonant multiphonon-assisted tunneling process[17] or to tunneling of carriers from the 1.5-ML $Cd_{0.6}Zn_{0.4}Te$ QDs to the 3.0-ML QDs with decreasing thickness of the ZnTe separation layer.[18] The peak position corresponding to the 3.0-ML $Cd_{0.6}Zn_{0.4}Te$ QDs shifts to higher energy with decreasing ZnTe separation-layer thickness due to the intermixing caused by strain in the coupled $Cd_{0.6}Zn_{0.4}Te/ZnTe$ QDs.[16,19,20]

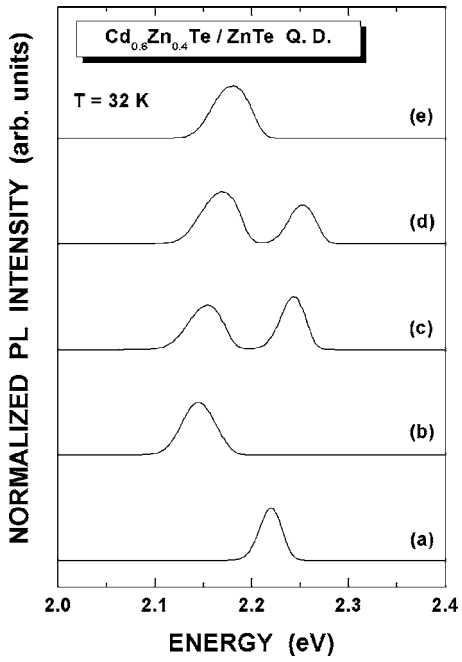

FIG. 2. Photoluminescence spectra at 32 K for $Cd_{0.6}Zn_{0.4}Te/ZnTe$ quantum dots with thicknesses of (a) 1.5 and (b) 3.0 MLs and for 3.0-ML $Cd_{0.6}Zn_{0.4}Te/ZnTe$ quantum dots combined with 1.5-ML $Cd_{0.6}Zn_{0.4}Te/ZnTe$ quantum dots with ZnTe separation layers of (c) 30, (d) 18, and (e) 6 nm.

In order to determine and to compare the activation energies of the electrons in the $Cd_{0.6}Zn_{0.4}Te/ZnTe$ QDs in the 1.5 and 3.0 MLs and the double QD structure consisting of 1.5- and 3.0-ML $Cd_{0.6}Zn_{0.4}Te/ZnTe$ QDs with separation layers of 30, 18, and 6 nm, we carried out temperature-dependent PL measurements. Because the quantum confinement of the heavy hole in the $Cd_{0.6}Zn_{0.4}Te/ZnTe$ QDs is very weak due to the very small valence-band offset between $Cd_{0.6}Zn_{0.4}Te$ and ZnTe, a large portion of the heavy hole wave function leaks into ZnTe barriers, reducing the overlap

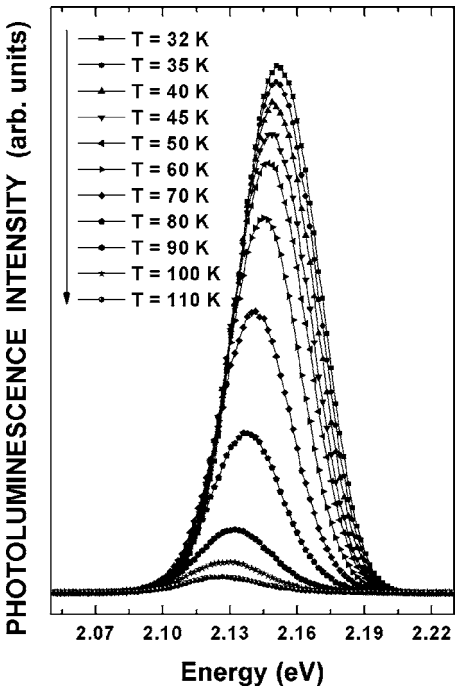

FIG. 3. Photoluminescence spectra measured at several temperatures for 3.0-ML $Cd_{0.6}Zn_{0.4}Te/ZnTe$ quantum dots combined with 1.5-ML $Cd_{0.6}Zn_{0.4}Te/ZnTe$ quantum dots with a ZnTe separation layer of 30 nm.

with the electron wave function, resulting in a significant decrease in the activation energy.[21] The PL results of the 1.5– and 3.0-ML $Cd_{0.6}Zn_{0.4}Te/ZnTe$ QDs with a separation layer of 30 and 6 nm measured at several temperatures are shown in Figs. 3 and 4 because they had the minimum and the maximum activation energies among the double QD structures. The PL quenching at higher temperatures is attributed

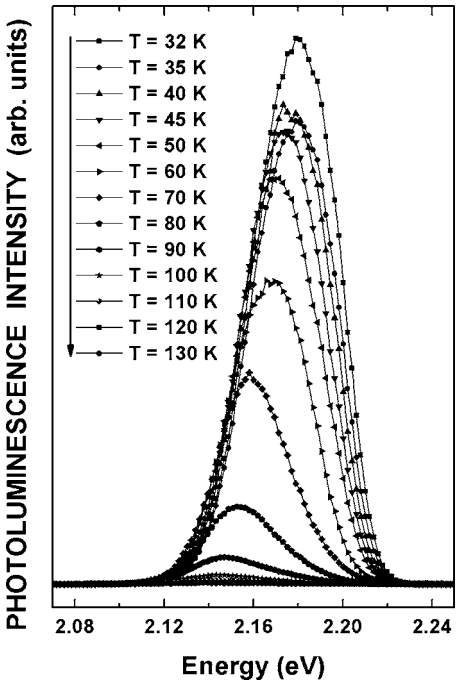

FIG. 4. Photoluminescence spectra measured at several temperatures for 3.0-ML $Cd_{0.6}Zn_{0.4}Te/ZnTe$ quantum dots combined with 1.5-ML $Cd_{0.6}Zn_{0.4}Te/ZnTe$ quantum dots with a ZnTe separation layer of 6 nm.

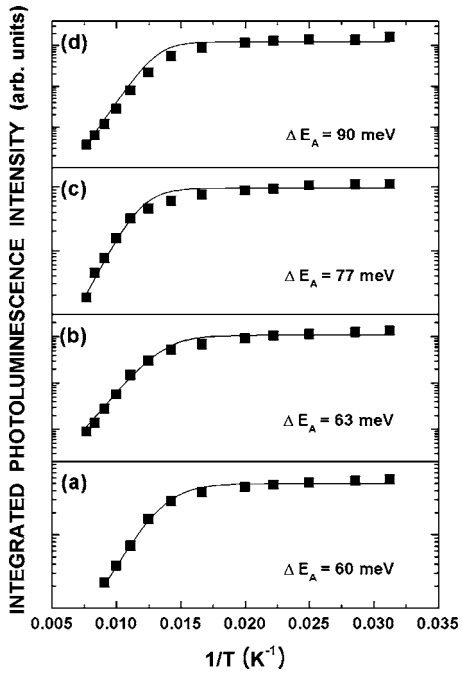

FIG. 5. Integrated photoluminescence intensities as a function of the reciprocal temperature for (a) 3.0 ML $Cd_{0.6}Zn_{0.4}Te/ZnTe$ quantum dots and for 3.0-ML $Cd_{0.6}Zn_{0.4}Te/ZnTe$ quantum dots combined with 1.5-ML $Cd_{0.6}Zn_{0.4}Te/ZnTe$ quantum dots with ZnTe separation layers of (b) 30, (c) 18, and (d) 6 nm.

to an escape of carriers via a nonradiative recombination path. If the equation $I=I_0/\{1+C[\exp(-E_A/k_BT)]\}$ is used, where I_0 and C are constants and E_A is an activation energy that corresponds to the barrier height for the nonradiative recombination path, the temperature dependence of the intensity can be fitted.[22] The activation energies of the electrons confined in the double QD structures of the $Cd_{0.6}Zn_{0.4}Te/ZnTe$ QDs in 1.5 and 3.0 MLs with ZnTe separation layers of 30, 18, and 6 nm, determined from the integrated PL intensities as a function of the reciprocal temperature,[23] are 63, 77, and 90 meV, respectively, as shown in Fig. 5. The activation energy of the sample with a ZnTe separation layer of 6 nm is much larger than that with a layer of 30 nm, and the enhancement of the activation energy in coupled $Cd_{0.6}Zn_{0.4}Te/ZnTe$ double QDs can be attributed to an additional confinement of carriers in the larger energy gap of the 3.0-ML QDs. The increase in the activation energy in the coupled $Cd_{0.6}Zn_{0.4}Te/ZnTe$ double QDs might be related to tunneling of carriers with short lifetimes in the smaller QDs to electronic states with longer lifetimes in the larger QDs, resulting in a higher equilibrium density of excited QDs.[16]

IV. SUMMARY AND CONCLUSIONS

The results of AFM measurements showed that 1.5- and 3.0-ML $Cd_{0.6}Zn_{0.4}Te$ QDs were grown on the ZnTe buffer layers, and the results of temperature-dependent PL measurements showed that the activation energy of the vertically stacked $Cd_{0.6}Zn_{0.4}Te/ZnTe$ double QDs increased with decreasing ZnTe separation layer. At a separation-layer thickness of 6 nm, this behavior could be attributed to enhancement in the tunneling probability of carriers from the smaller

$Cd_{0.6}Zn_{0.4}Te$ 1.5-ML QDs to the larger 3.0-ML QDs due to the coupling effect between the upper and the lower $Cd_{0.6}Zn_{0.4}Te$ QDs. These results suggest that coupled $Cd_{0.6}Zn_{0.4}Te/ZnTe$ double QDs hold potential for applications in optoelectronic devices operating in the green spectral range.

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