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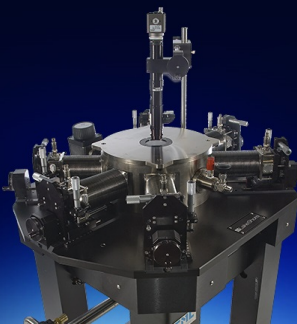
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Optical properties of CdTe/ZnTe quantum dots sandwiched between two quantum wells with ZnTe separation barriers

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Temperature-dependent photoluminescence (PL) measurements were performed to investigate the optical properties of CdTe/ZnTe nanostructures. The activation energy of the CdTe/ZnTe quantum dots (QDs) sandwiched between two quantum wells (QWs) with ZnTe separation barriers, as obtained from the temperature-dependent PL spectra, was much larger than the activation energies of the QDs alone and of the QDs combined with a single QW. This behavior can be attributed to a transfer of carriers from the QWs to the QDs through a separation layer due to a nonresonant multiphonon-assisted tunneling process resulting from carrier thermal emission. © 2006 American Institute of Physics. [DOI: 10.1063/1.2385114]

Semiconductor quantum dots (QDs) have attracted attention because of interest in investigations of fundamental physics¹⁻³ and because of application in potential nanoscale devices such as QD lasers,⁴ QD light-emitting diode,⁵ QD infrared photodetectors,⁶ and QD memories.⁷ Recently, a unique type of nanostructures, combining an auxiliary quantum well (QW) with the QDs via tunneling through a barrier, has been theoretically and experimentally investigated.^{8,9} These combined nanostructures provide many advantages, such as larger carrier collection, more lateral transport, and higher activation energy of the QDs, for high-efficiency electronic and optoelectronic devices. In spite of such interesting possibilities and significant potential applications, a complete investigation of the energy and the carrier transfer in CdTe/ZnTe combined nanostructures is still not available.¹⁰ Even though very few studies have addressed the optical properties of coupled CdTe/ZnTe QDs and QW structure with thin ZnTe thin separation barriers,⁸ work on the optical properties and the enhancement mechanism of the activation energy in CdTe/ZnTe QDs sandwiched between two QWs with separation barriers has not yet been performed.

This letter presents the optical properties and the enhancement mechanism of the activation energy in CdTe/ZnTe QDs sandwiched between two CdTe/ZnTe QWs with ZnTe separation barriers grown by using molecular beam epitaxy (MBE) and atomic layer epitaxy (ALE). Atomic force microscopy (AFM) measurements were performed to characterize the structural properties of the CdTe layers on the ZnTe buffer layers. Photoluminescence (PL) measurements were carried out in order to investigate the interband transitions and to determine the activation energies of the CdTe/ZnTe QDs and of the CdTe/ZnTe QDs combined with the QW structure. The PL intensities, the full width at half maxima (FWHM) of the interband transition peaks, and the activation energies of the CdTe/ZnTe QDs, the CdTe/ZnTe QDs combined with one side of the QW structure (QW/QDs), and the CdTe/ZnTe QDs sandwiched

between two CdTe/ZnTe QW structures (QW/QDs/QW) were compared.

The several kinds of samples used in this study were grown on Si-doped *n*-type (100) GaAs substrates by using MBE and ALE, and the CdTe/ZnTe QW/QDs/QW consisted of the following structures: a 100 nm ZnTe capping layer deposited by MBE, a 6 Å CdTe single QW layer deposited by ALE, a 20 nm ZnTe separation layer deposited by MBE, 2.5 ML (monolayer) CdTe QDs deposited by ALE, a 20 nm ZnTe separation layer deposited by MBE, a 6 Å CdTe single QW layer deposited by ALE, and a 900 nm ZnTe buffer layer deposited by MBE. All of the ZnTe and the CdTe layers were unintentionally doped. The depositions of the ZnTe and CdTe layers were done at a substrate temperature of 320 °C. The source temperatures of the Zn and Te sources for the ZnTe epilayers were 280 and 300 °C, respectively, and those of the Cd and Te sources for the CdTe epilayers were 195 and 300 °C, respectively. For comparison with the optical properties of the CdTe/ZnTe QW/QDs/QW, the CdTe/ZnTe QDs, the CdTe/ZnTe QW, and the CdTe/ZnTe QW/QDs were grown by MBE and ALE under the same growth conditions.

Figure 1 shows a three-dimensional AFM image of the uncapped surface of the 2.5 ML CdTe QDs grown on ZnTe buffer layers. The AFM image reveals that uniformly sized CdTe QDs are formed on the ZnTe buffer layer. The average density and the average diameter of the QDs are approximately $4 \times 10^{10} \text{ cm}^{-2}$ and 40 nm, respectively.

Figure 2 shows PL spectra at 14 K for (a) the CdTe/ZnTe QW with a 6 Å CdTe well, (b) the 2.5 ML CdTe/ZnTe QDs, (c) the 2.5 ML CdTe/ZnTe QW/QDs, and (d) the 2.5 ML CdTe/ZnTe QW/QDs/QW. The dominant peaks at 2.307 eV for the CdTe/ZnTe QW with a 6 Å CdTe well and 2.242 eV for the 2.5 ML CdTe/ZnTe QDs shown in Figs. 2(a) and 2(b), respectively, correspond to the interband transition from the ground electronic subband to the ground heavy hole (E_1 -HH₁).¹¹⁻¹⁵ The peaks corresponding to the E_1 -HH₁ transitions of the CdTe/ZnTe QDs and QW for the CdTe/ZnTe QW/QDs with a 6 Å CdTe well and a ZnTe separation layer of 20 nm appear at 2.222 and 2.305 eV,

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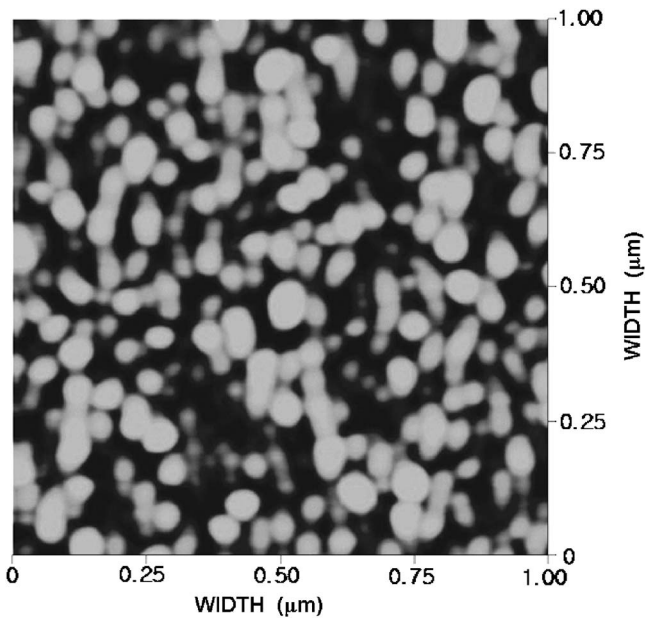


FIG. 1. Three-dimensional atomic force microscopy image of uncapped CdTe quantum dots with a thickness of 2.5 ML grown on ZnTe buffer layers.

respectively,⁹ as shown in Fig. 2(c). The dominant peaks at 2.225 and 2.300 eV for the 2.5 ML CdTe/ZnTe QW/QDs/QW, each with a 6 Å CdTe well and a 20 nm ZnTe separation layer, correspond to the E_1 -HH₁ transitions related to the CdTe/ZnTe QDs and the CdTe/ZnTe QWs, respectively, as shown in Fig. 2(d). The error deviation of the PL peaks corresponding to the E_1 -HH₁ transitions is ± 0.005 eV. The values of the FWHM for the E_1 -HH₁ transitions of the CdTe/ZnTe QDs, the CdTe/ZnTe QW/QDs, and the CdTe/ZnTe QW/QDs/QW are 34.31, 29.01, and 25.53 meV, respectively. Therefore, the value of the FWHM for the E_1 -HH₁ transitions of the CdTe/ZnTe QW/QDs/QW is the smallest among the three kinds of samples. This behavior might be attributed to an improvement in the uniformity of the QDs resulting from the strain induced by the two sides of the QW structures. The red shift of the E_1 -HH₁ transition

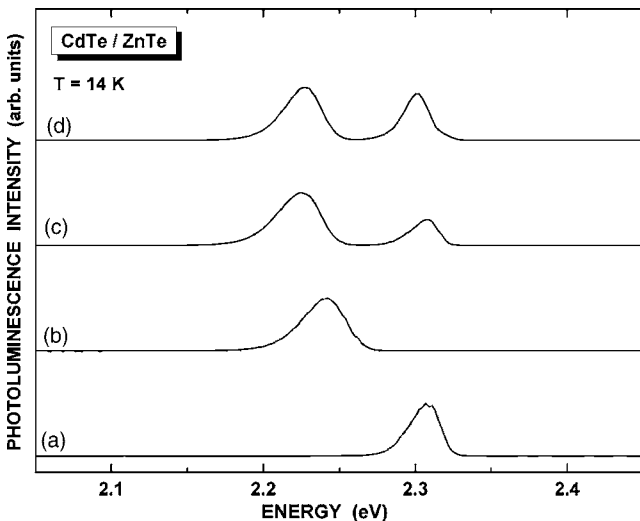


FIG. 2. Photoluminescence spectra for (a) the CdTe/ZnTe quantum well with a 6 Å CdTe well without QDs, (b) the 2.5 ML CdTe/ZnTe QDs, (c) the CdTe/ZnTe QDs combined with one side of the QW structure, and (d) the CdTe/ZnTe QDs sandwiched between two QW structures.

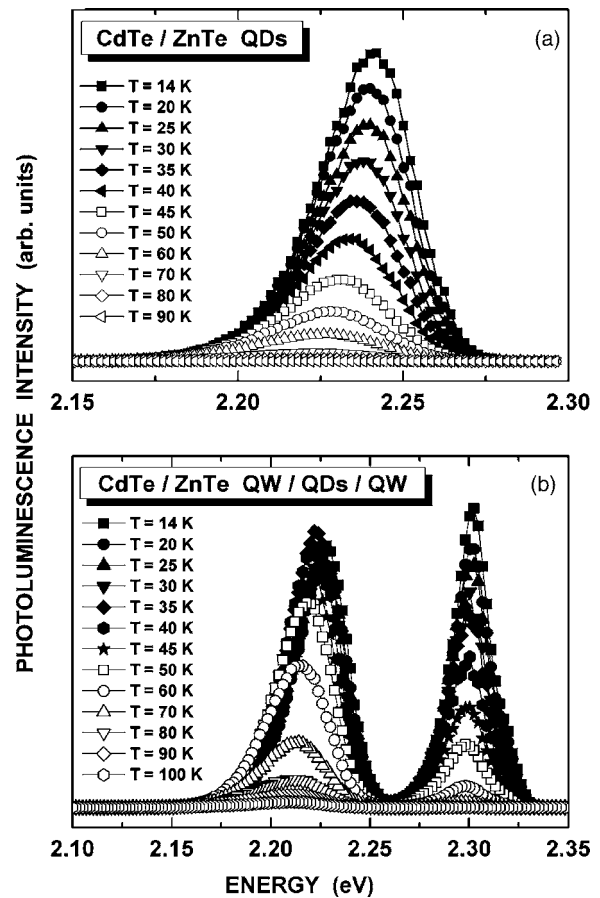


FIG. 3. Photoluminescence spectra measured at several temperatures for (a) the 2.5 ML CdTe/ZnTe QDs and (b) the CdTe/ZnTe QDs sandwiched between two QW structures.

peak corresponding to the CdTe/ZnTe QW/QDs/QW, in comparison with the CdTe/ZnTe QDs alone, originates from an increase in the QD size due to intermixing between the ZnTe barrier and the CdTe QW active layer caused by the strain induced in the combined CdTe/ZnTe QW.¹⁶

In order to determine the activation energies of the electrons in CdTe/ZnTe confined nanostructures, we performed temperature-dependent PL measurements. The PL spectra measured at several temperatures for the CdTe/ZnTe QDs and the CdTe/ZnTe QW/QDs/QW are shown in Fig. 3. While the integrated PL intensity corresponding to the E_1 -HH₁ transitions for the CdTe/ZnTe QW dramatically decreases with increasing temperature, that for the CdTe/ZnTe QDs slightly decreases between 14 and 50 K, indicative of the strong localization of the excitons by the potential energy of the QDs, which is in reasonable agreement with the results reported by Terai *et al.*¹¹ and Karczewski *et al.*¹² The PL quenching at higher temperatures is attributed to an escape of carriers via a nonradiative recombination path. If the equation $I=I_0/[1+C \exp(-\Delta E_A/k_B T)]$ is used, where I_0 is the integrated PL intensity at 0 K, C is the ratio of the thermal escape rate to the radiation recombination rate, ΔE_A is the activation energy which corresponds to a barrier height to the nonradiative recombination path, and k_B is the Boltzmann constant, the temperature dependence of the intensity can be fitted.¹⁵ The activation energies of the electrons confined in the CdTe/ZnTe QDs, the CdTe/ZnTe QW/QDs, and the CdTe/ZnTe QW/QDs/QW, as determined from the integrated PL intensities as a function of the reciprocal

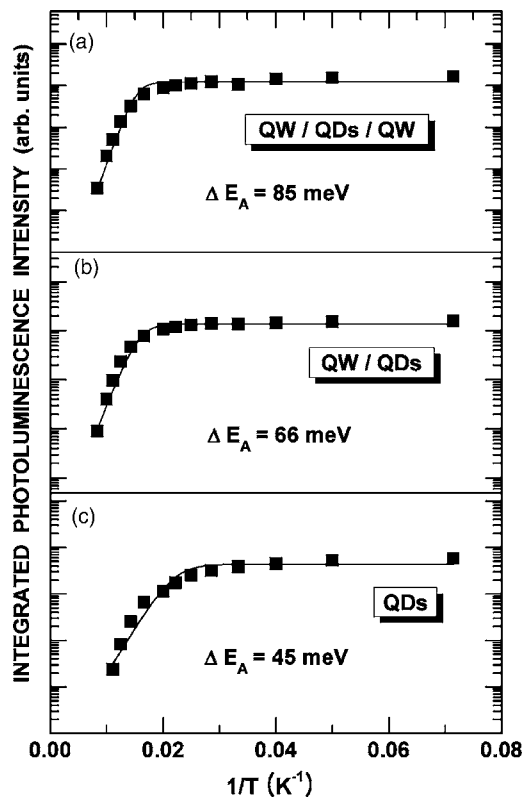


FIG. 4. Integrated photoluminescence intensities as functions of the reciprocal temperature for (a) the 2.5 ML CdTe/ZnTe QDs, (b) the CdTe/ZnTe QDs combined with one side of the QW structure, and (c) the CdTe/ZnTe QDs sandwiched between two QW structures.

temperature,¹⁷ are 45, 66, and 85 meV, as shown in Fig. 4. The activation energy obtained for the electrons confined in the CdTe/ZnTe QW/QDs/QW is larger than those of the electrons confined in the CdTe/ZnTe QDs alone and in the CdTe/ZnTe QW/QDs. The higher activation energy for CdTe/ZnTe QW/QDs/QW, in comparison with the other two cases, originates from an enhancement of the carrier confinement resulting from the transfer of carriers from the QWs to the QDs through the barrier due to the increase in thermal energy with increasing temperature.

While the PL intensity of the E_1 -HH₁ transition in the CdTe/ZnTe QW/QDs/QW increases with increasing temperature up to 35 K, that in CdTe/ZnTe QW/QDs increases with increasing temperature up to 30 K. This behavior might be attributed to the strong localization of the excitons by the potential energy of the CdTe/ZnTe QDs between the QWs (Refs. 11 and 12) due to carrier thermionic emission¹⁸ and carrier transfer.¹⁹ The slight increase in the peak intensity in the temperature range between 30 and 35 K can be attributed to a transfer of carriers with a short lifetime from the CdTe/ZnTe QW to states with a long lifetime in the CdTe/ZnTe QDs,²⁰ resulting in a higher equilibrium density of excited CdTe/ZnTe QDs. Since the quantum-confinement effect of the electrons occupying the CdTe/ZnTe QW is smaller than that in the QDs, a carrier transfer behavior appears at a relatively low temperature for the CdTe/ZnTe QW/QDs/QW. The intensities of the E_1 -HH₁ transitions in the CdTe/ZnTe QW/QDs/QW and in the CdTe/ZnTe QW/QDs decrease with increasing temperature above 30 and 35 K, respectively. Furthermore, above 30 K, the integrated intensity of the E_1 -HH₁ transition in the CdTe/ZnTe QW/

QDs/QW is higher than that in CdTe/ZnTe QW/QDs, and this behavior can be attributed to an enhanced trap density in QDs resulting from the transfer of carriers from the QW to the QDs due to a nonresonant multiphonon-assisted tunneling process.¹⁹

In summary, the results of the PL measurements showed that the FWHM of the E_1 -HH₁ transitions in the CdTe/ZnTe QW/QDs/QW was much smaller than those in the QDs and in the QW/QDs, and the results of the temperature-dependent PL measurements showed that the activation energy of the CdTe/ZnTe QW/QDs/QW was much larger than those of the QDs and the QW/QDs. This behavior can be attributed to a transfer of carriers from the QW to the QDs due to a nonresonant multiphonon-assisted tunneling processes resulting from the thermal energy. The present observations can help improve the understanding of the enhancement mechanism of the activation energy in CdTe/ZnTe combined nanostructures.

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