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Contribution of excitons and free carriers to energy transfer in $CdTe/Cd_{0.6}Mg_{0.4}Te$ quantum wells of different thickness

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Luminescence excitation spectra of barrier layers and quantum wells in $CdTe/Cd_{0.6}Mg_{0.4}Te$ heterostructure containing four quantum wells with thicknesses of 1.3, 2.6, 5.2, and 10.4 nm have been investigated. The contributions of free carriers and excitons to excitation transfer within the barrier layers and from the barrier layers to the quantum wells, depending on the quantum well thickness and temperature, are discussed.

Keywords: CdTe quantum wells, luminescence, luminescence excitation spectra, excitation transfer, exciton.

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Introduction

The properties of heterostructures containing quantum wells and quantum dots are largely determined by the processes of energy transfer between the elements of the heterostructure [1–9]. Information about the relaxation of optical excitation in crystalline systems can be obtained from the excitation luminescence spectra (ELS). Unlike luminescence spectra, ELS provide information about the excited levels of quantum structures, which is why ELS are sometimes called pseudo-absorption spectra. ELS are usually studied in the below-barrier energy range of the heterostructure [1,2]. We have studied ELS of heterostructures with CdTe QW in the energy range above the exciton level of the barrier. This allows obtaining information about the mechanisms of excitation relaxation in the barrier and the transfer of excitation from the barrier to the QW at different temperatures. In this paper, the ELS of heterostructure of $CdTe/Cd_{0.6}Mg_{0.4}Te$ is studied in the temperature range of $5-100$ K.

Experiment details

The $CdTe/Cd_{0.6}Mg_{0.4}Te$ heterostructure was grown on an $\langle 100 \rangle$ GaAs substrate with a $Cd_{0.6}Mg_{0.4}Te$ buffer layer with a thickness $0.7\,\mu$m, it contains four QWs with a thickness of 1.3, 2.6, 5.2, and 10.4 nm (QW1, QW2, QW3, and QW4, respectively) (Fig. 1). The barrier layers with a thickness of 31 nm were grown by the MBE method, the QW were grown by the atomic layer deposition (ALD). A halogen lamp emission passed through a monochromator was used to obtain the ELS. The spectral width of the excitation region did not exceed 0.03 eV, and when measuring the signal, the spectral width did not exceed 0.018 eV. The luminescence spectra of a sample that was excited by a laser with a wavelength of 455 nm (2.73 eV) are shown in Fig. 2.

Experimental results and discussion

Barrier ELS

When luminescence is detected in the center of the emission band of the barrier, the ELS has a maximum at the energy of the free exciton, which is determined by the absorption and reflection spectra, the intensity of the spectrum decreases with distance from the exciton level of the barrier (Fig. 3, *a*). According to the mathematical model developed and applied in [9,10], the ELS shape can be represented as

$$\exp(-E/E_0) + C, \qquad (1)$$

where the energy E is calculated from the maximum of the spectrum, E_0 is a fitting parameter. In accordance with the $\exp(-E/E_0)$ and C models, the contributions of photo-generated hot excitons and carriers to the population of emitting states are determined, respectively. Previously, we studied the ELS of manganese ions in the $CdTe/Cd_{0.6}Mn_{0.4}Te$ heterostructure. The optical properties of a dilute CdMnTe magnetic semiconductor have been

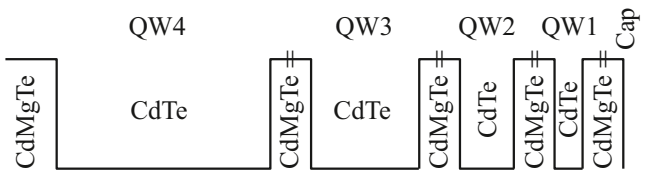


Figure 1. The structure diagram of the $CdTe/Cd_{0.6}Mg_{0.4}Te$ heterostructure.

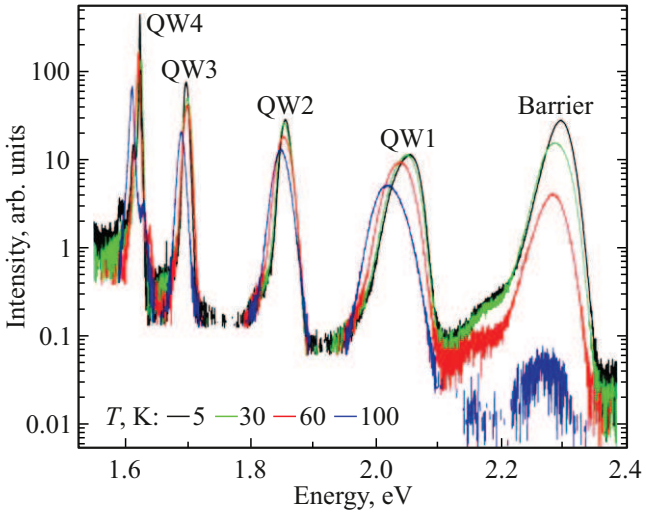


Figure 2. Photoluminescence spectra of the CdTe/$Cd_{0.6}Mg_{0.4}Te$ heterostructure at various temperatures.

studied in detail, and it has been established that the 3*d*-shell of manganese is excited only by energy transfer from excitons. It turned out that the ELS of manganese ions is identical to the ELS of the CdTe/$Cd_{0.6}Mg_{0.4}Te$ barrier and the spectra shown in Fig. 3, *a*. This is additional evidence in favor of the fact that the exponential shape of the ELS reflects the exciton contribution to the population of the emitting object.

It should be noted that according [11,12], where the luminescence of excitons in cadmium sulfide was studied, ELS in crystals with a short lifetime of the emitting state has a saw-tooth shape reflecting the relaxation process of hot excitons with scattering by LO-phonons. In the case when the lifetime is long, the teeth are not observed, this corresponds to our case.

The maximum of the emission band of the barrier, which is a solid solution, corresponds to excitons localized at shallow random potentials. There is a high probability that an electron localized at such a potential will relax to another random potential without waiting for a hole. For this reason, the channel of populating such states by individual carriers turns out to be ineffective in relation to their contribution to light emission. It should be emphasized that the low level of optical excitation used in the present experiment contributes to this separation of electrons and holes.

When the ELS is detected on the low-energy side of the luminescence band of the barrier, the maximum of the spectrum at a temperature of 5 K is significantly higher than the resonance energy of the free exciton (Fig. 3, *b*). This form of ELS corresponds to a large value in (1) of the term C, which determines the contribution of free carriers to the population of emission states. Excitons localized on deep fluctuations contribute to the low-energy side of the luminescence band of the barrier. The probability of an electron localized in a deep fluctuation going to an even deeper fluctuation is small, a hole manages to join it, and a localized exciton is formed. In such a situation, the generation of hot carriers should make a significant contribution to luminescence. As the temperature increases, the probability of carrier transition to other potentials and nonradiative recombination centers increases, as a result of which the contribution of individual carriers to the formation of localized excitons decreases.

The sharp change in the ELS shape of the low-energy side in a narrow temperature range is noteworthy (Fig. 3, *b*). Even at $T > 20$ K, the contribution of free carriers is insignificant, while the large depth of the localization potential implies the stability of localized excitons to an increase in temperature. Excitons bound on shallow impurities can contribute to the luminescence of the low-energy side of the barrier emission band. The sequential capture of an electron and a hole is an effective channel for the formation of such exciton-impurity complexes. As the temperature increases, the formation of such complexes stops, and the contribution of free carriers to luminescence decreases accordingly.

QW excitation luminescence spectra

QW ELS were recorded in the maxima of their luminescence bands. The temperature behavior of the ELS of the narrow QW1 is similar to the behavior of the ELS of the low-energy side of the luminescence band of the barrier (Fig. 4, *a*). The maximum of the spectrum at $T = 5$ K is about 2.65 eV, i.e. significantly higher than the exciton resonance of the barrier. At $T > 30$ K, the contribution that we attribute to free carriers is already insignificant, and the maximum of the ELS coincides with the exciton of the barrier. The temperature transformation of QW1 ELS can be explained by the fact that the simultaneous presence of an electron and a hole is required for the formation of an exciton inside the QW. For narrow QW levels, the height of the barriers is small, therefore, as the temperature increases, the release of carriers into the barrier increases, and this reduces the probability of exciton formation from individual carriers. At the same time, the propagation of the exciton wave function of the narrow QW1 into the barrier promotes the relaxation of barrier excitons into this QW with the increasing temperature.

The ELS of QW4 and QW3 transform in the opposite way with increasing temperature (Fig. 4, *a, b*). At low temperatures, the excitonic mechanism of excitation relaxation makes a significant contribution to the formation of their ELS. However, the contribution of exciton relaxation becomes insignificant at $T > 40$ K; excitons in QW4 and QW3 are formed by sequentially capturing of carriers of different signs at temperatures above 40 K. The reason for the temperature weakening of the exciton contribution to the relaxation of excitation in QW4 and QW3 is probably the barrier exciton relaxation to nonradiative centers, which is manifested in the rapid temperature quenching of the luminescence of the barrier.

As for the QW2 ELS, only minor changes are observed in its ELS over the entire temperature range 5–100 K

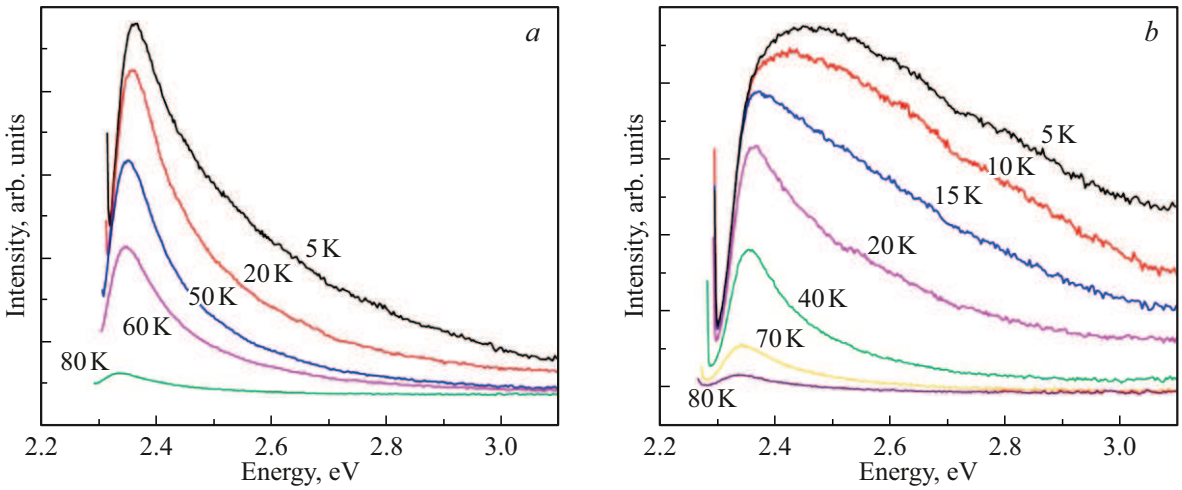


Figure 3. ELS exciton of the barrier layer of the CdTe/$Cd_{0.6}Mg_{0.4}Te$ heterostructure at various temperatures. (*a*) measurement of the signal at the maximum of the luminescence band; (*b*) measurement of the signal on the low-energy side of the luminescence band (1/2 of maximum).

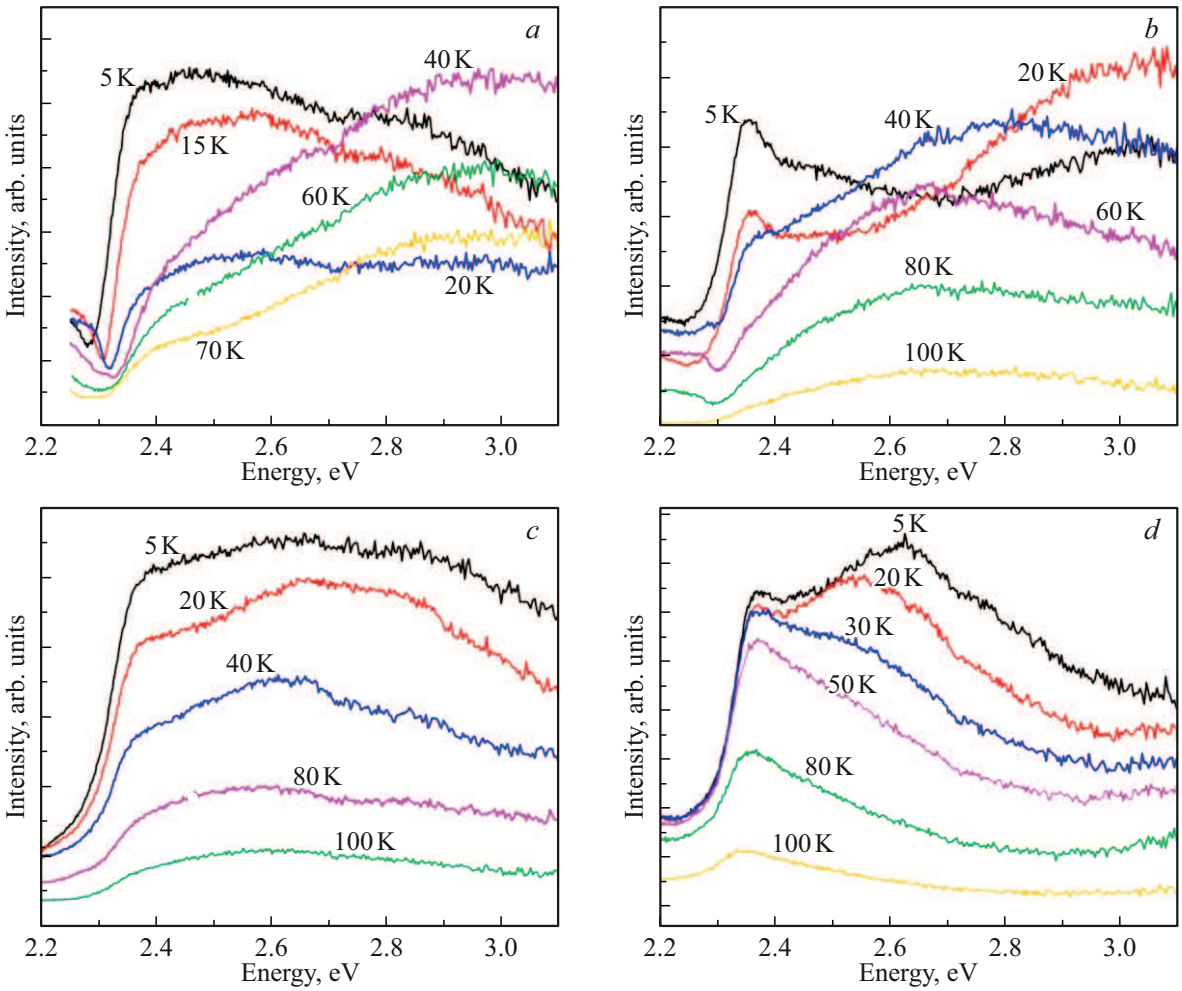


Figure 4. ELS of QW4 (*a*), QW3 (*b*), QW2 (*c*) and QW1 (*d*) of CdTe/$Cd_{0.6}Mg_{0.4}Te$ heterostructure at various temperatures.

(Fig. 4, *c*). The contributions of excitons and carriers change in a similar way with increasing temperature, so there are no radical changes in the ELS of QW2. It can be said that the temperature behavior of the QW8 ELS is intermediate in comparison with the ELS of narrow and thick layers.

Conclusions

The shape of the ELS barrier of the CdTe/$Cd_{0.6}Mg_{0.4}$Te heterostructure, which is recorded at the maximum of the luminescence band, is described by an exponent over the entire temperature range studied, and the relaxation of hot excitons makes the main contribution to the population of light-emitting states. At low temperatures, hot free carriers greatly contribute to the population of states corresponding to the low-energy side of the barrier band emission, while their contribution decreases rapidly with increasing temperature.

The contributions of hot excitons and carriers to ELS of QW of various thicknesses at low temperatures are comparable in magnitude. At high temperatures, the luminescence of thick QW is determined by the relaxation of hot free carriers, whereas hot excitons make the main contribution to the luminescence of narrow QW.

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Conflict of interest

The authors declare no conflict of interest.

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