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Dependence of the exciton luminescence kinetics in the CdTe/$Cd_{0.6}Mg_{0.4}Te$ heterostructure on the thickness of quantum wells and temperature

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The luminescence of the CdTe/$Cd_{0.6}Mg_{0.4}Te$ heterostructure containing four quantum wells was studied in the temperature range of 5−140 K. Dependences of the luminescence decay time of CdTe quantum wells on their thickness and temperature were determined.

Keywords: CdTe quantum wells, exciton, time-resolved luminescence.

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Luminescence kinetics is one of the key characteristics of a quantum heterostructure, which substantially determines its practical applicability as a component of optoelectronic devices. Time-resolved luminescence has been studied on a wide range of heterostructures mainly related to groups III−V (see, e. g. [1–7]). The subject of this paper is studying the influence of the CdTe quantum well thickness and temperature on the exciton luminescence kinetics.

Dependence of the exciton luminescence decay time τ on the quantum well thickness and temperature was theoretically considered in [1]. It was shown that

$$\tau \propto E_B^{-1}\Delta(T)/r(T), \qquad (1)$$

where E_B is the electron and a hole binding energy in exciton, $\Delta(T)$ is homogeneous broadening of the exciton line, $r(T) = 1 - \exp[-(\Delta(T)/k_BT)]$ is the fraction of excitons within $\Delta(T)$ participating in radiative recombination, E_B depends on the quantum well thickness.

Properties of $\Delta(T)$ have been theoretically studied in [1,8]. Paper [8] considers various contributions to the homogeneous exciton line width in dependence on thickness of the CdTe/CdZnTe quantum well. It shows that exciton scattering by acoustic phonons significantly gets enhanced with decreasing quantum well thickness starting from 7 nm, while, on the contrary, the exciton-exciton scattering becomes weaker.

The test object is the CdTe/$Cd_{0.6}Mg_{0.4}Te$ heterostructure with quantum wells 1.3, 2.6, 5.2 and 10.4 nm thick (hereinafter QW1, QW2, QW3, QW4, respectively) grown on a GaAs(100) substrate. Barrier layers with 19.8 nm thickness were fabricated by molecular beam epitaxy; quantum wells were created by atomic layer deposition.

The samples were placed in a closed-cycle helium cryostat SHI-4-1 (Janis Research Co., Inc.). The heterostructures' continuous-wave luminescence was excited by helium-cadmium laser Plasma Lab HCL-49M with the photon energy of 2.82 eV; the spectra were recorded by monochromator MDR-204 (LOMO Photonics). To measure the luminescence kinetics, the samples were placed in closed-cycle helium cryostat Montana Instruments. Luminescence was excited by laser PicoQuant LDH-1B-450-B (photon energy of 2.75 eV, average power of 16 μW, pulse repetition rate of 1 MHz, pulse length of 50 ps). Diameter of the laser spot on the sample was 1.3 μm, peak power density in the pulse was $1.5 \cdot 10^7$ W/cm^2. Spectral separation of the signal was performed using monochromator MDR-41 (LOMO Photonics). The luminescence kinetics was measured by the time-correlated single-photon counting method using the ECOPRS-CCR-SW/TW-85 system (SCONTEL, Moscow, Russia). The system built around a closed-cycle cryostat with vibration damping (Montana Cryostation) detects photons with superconducting single-photon detectors combined with single-mode fiber optics. Time resolution of the detection module is 50 ps. The time-correlated single-photon counting method was realized by using stream digital time converter TimeTagger Ultra (Swabian Instruments, Stuttgart, Germany). The total response time of the system was about 100 ps.

Luminescence spectrum of the QW1−4 quantum wells and barrier is shown in Fig. 1. At low temperatures, the barrier free excitons either relax into quantum wells or get localized at random potentials of the $Cd_{0.6}Mg_{0.4}Te$ solid solution. In this case, the barrier luminescence intensity and kinetics are determined by the long lifetime of localized excitons. As the temperature increases, localization of the barrier excitons becomes weaker, which leads to quenching of the barrier luminescence and decrease in its decay time (Fig. 2, *a*). As for the luminescence of quantum wells, its

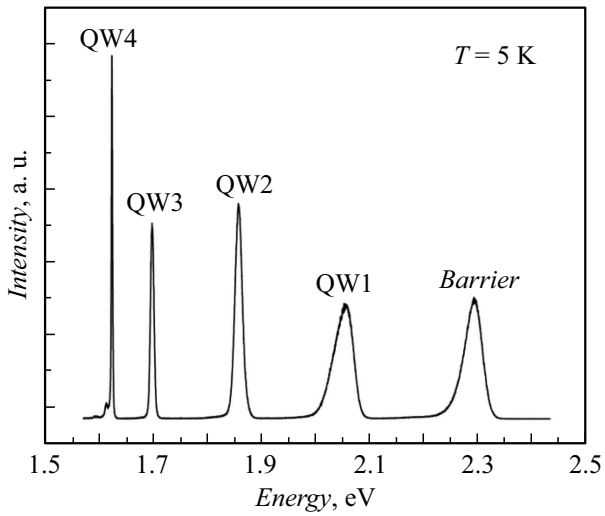

Figure 1. Luminescence spectrum of the $CdTe/Cd_{0.6}Mg_{0.4}Te$ heterostructure quantum wells and barrier measured under continuous excitation.

attenuation with increasing temperature has a significantly different character. Fig. 2, *b* illustrates variations in the luminescence kinetics of quantum well QW3. At the temperatures of up to 40 K, the kinetic curves exhibit two exponential components. When $T = 5$ K, corresponding decay times τ_1 and τ_2 are 400 and 1150 ps, while intensity of the slow component is two orders of magnitude lower than that of the fast one. A possible contribution to slow component τ_2 is associated with emission of excitons localized on shallow impurities. Along with this, another possible reason for the increase in the QW3 luminescence lifetime is the tunnel radiative recombination of electrons and holes localized in the quantum well expanded regions. In this case, the luminescence kinetics is determined by how far apart these regions are. As the temperature increases, the slow component contribution decreases because localization becomes weaker; as a result, the luminescence decay at temperatures above 40 K is described by a single exponent.

Figs. 3 and 4 present the dependences of luminescence decay time τ_1 of quantum wells QW1–4 on their thickness and temperature, which are in agreement with theoretical concepts. The shortest luminescence decay time τ_1 at the temperatures below 30 K is observed for QW2. This may be explained by that this quantum well exhibits the highest exciton binding energy.

What is noteworthy is a weak τ_1 dependence on thickness of quantum wells QW1–3 at $T < 40$ K and strengthening of this dependence at $T > 40$ K. In our opinion, this is due to the effect of the QW1–3 heteroboundaries near which the presence of defects affecting the luminescence decay time is most probable. This effect is more pronounced in thin wells; due to this, τ_1 varies slightly for QW1 and QW2 at the temperatures below 60 and 40 K, respectively. At higher temperatures, there occurs an increase in τ_1, which is determined by ratio $\Delta(T)/r(T)$ in equation (1).

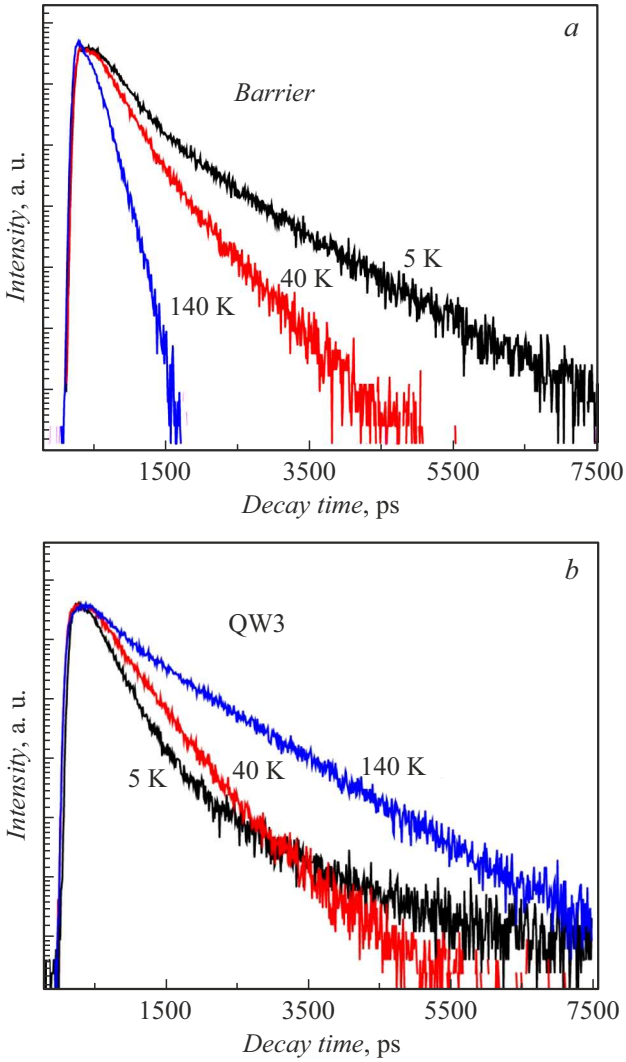

Figure 2. Luminescence decay kinetics of the barrier quantum well (*a*) and QW3 (*b*).

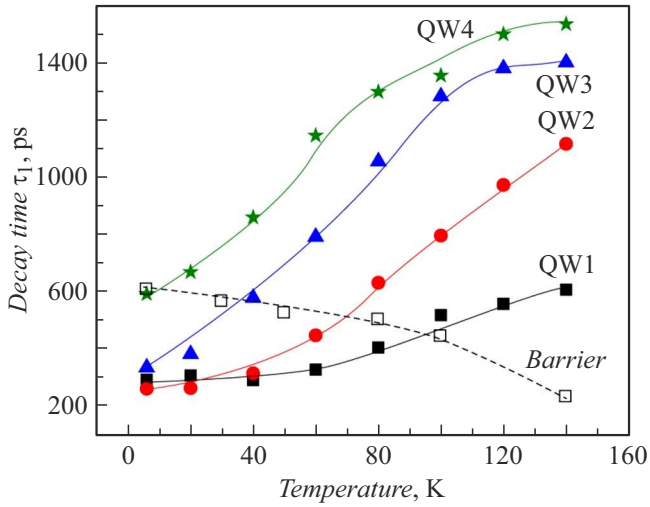

Figure 3. Temperature dependences of decay times of the barrier luminescence and luminescence fast component τ_1 of the QW1–4 quantum wells.

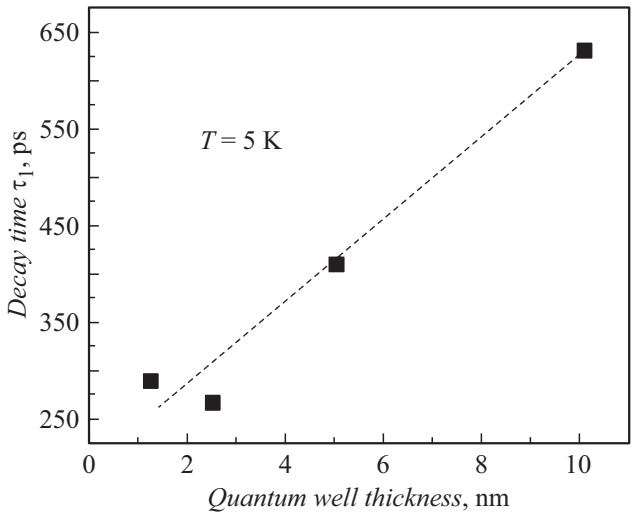

Figure 4. Dependence of luminescence decay time τ_1 on the quantum well thickness at the temperature of 5 K.

Noteworthy is variation in the derivative of the τ_1 dependence on temperature for QW3 and QW4 at $T > 100$ K. To our mind, this is due to an increase in exciton mobilities, which leads to enhancement of their quenching on nonradiative recombination centers and, hence, makes the increase in τ_1 slower. The exciton mobility depends on the quantum well thickness; this may explain the absence of the τ_1 increase slowdown in QW1 and QW2 in the same temperature range.

In [9], luminescence kinetics of the $CdTe/Cd_{0.75}Mn_{0.25}Te$ quantum wells was investigated. Data of that study showed that, as the quantum well thickness decreased from 30 to 3.4 nm, the luminescence decay time varied only slightly (from 170 to 140 ps) and weakly depended on temperature. These data disagree with our results concerning both the decay times in general and their variations with quantum well thickness. This discrepancy is apparently caused by that in our case the pulsed-excitation power density is orders of magnitude higher than that in [9]. At low excitation levels, the luminescence kinetics is to a high extent determined by the energy transfer to nonradiative recombination centers. This is evidenced, e. g., by a drastic decrease in the luminescence decay time of the 5 nm thick quantum well, which was observed in [9] at temperatures above 50 K. Under strong excitation, nonradiative centers get saturated, and this energy-dissipation channel stops affecting the decay kinetics of exciton luminescence.

Comparison of our results with the data obtained in [1,2] shows that characteristic values of luminescence decay times in CdTe and GaAs quantum wells, as well as their variation with quantum well thickness and temperature, are close to each other.

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Conflict of interests

The authors declare that they have no conflict of interests.

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