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Temperature Dependence of Luminescence Intensity of CdTe/$Cd_{0.6}Mg_{0.4}$Te Heterostructure under Above-Barrier Excitation

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The temperature dependence of the luminescence of a CdTe/$Cd_{0.6}Mg_{0.4}$Te quantum well (QW) was investigated in the temperature range 5−200 K. It was found that under under-barrier excitation this dependence is characterized by two nonradiative recombination channels with activation energies of 0.01 and 0.037 eV. Under above-barrier excitation, a feature appears in the temperature dependence of the QW luminescence intensity, associated with exciton delocalization in the $Cd_{0.6}Mg_{0.4}$Te barrier. Nonradiative recombination in the barrier is characterized by two activation energies: 0.0065 and 0.046 eV. A model is proposed that describes the temperature effect on the luminescence intensity of the QW and barrier, taking into account exciton delocalization in the barrier and their trapping at nonradiative recombination centers.

Keywords: II−VI semiconductors, heterostructures, quantum wells, luminescence, excitation transfer.

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Introduction

Luminescence properties are among the key characteristics of heterostructures of various types, significantly determining their practical application potential [1–8]. The temperature dependence of heterostructure luminescence intensity is related to quenching channels such as thermally stimulated excitation transfer to other heterostructure elements and/or centers of nonradiative recombination. These centers become empty at a certain temperature and can capture excitons and free carriers. The depopulation of such centers is characterized by their activation energy, so the temperature dependence of quantum well (QW) luminescence quenching should be described by exponential functions. In this work, the temperature dependence of luminescence of a heterostructure with a single CdTe QW confined by $Cd_{0.6}Mg_{0.4}$Te barriers was investigated under different excitation regimes, and a model was developed to adequately describe the experimental data.

Experimental Details

The barrier layers of the CdTe/$Cd_{0.6}Mg_{0.4}$Te heterostructure were grown by MBE; the 9.5 nm thick QW was grown by atomic layer epitaxy; the substrate is (100) GaAs. Luminescence in the temperature range 5−200 K was excited by continuous lasers with photon energies of 1.96 eV 1 W/cm^2) and 2.41 eV (power density $W = 5$ and 95 W/cm^2).

Results and Discussion

With increasing temperature from 5 to 100 K, the luminescence intensity of the CdTe QW decreases by a factor of 2, whereas the luminescence of the $Cd_{0.6}Mg_{0.4}$Te barrier fully degrades (Figure 1).

Reference [9] showed that the integral intensity of QW luminescence can be described by an expression containing two exponential functions:

$$I_1(T) = \frac{I_0}{1 - a_1 e^{-E_1/kT} + a_2 e^{-E_2/kT}}. \quad (1)$$

This model implies the existence of two centers of nonradiative relaxation with activation energies E_1 and E_2, which differ significantly. Such an approach has previously been used in studies of II−VI and III−V-type heterostructures [10–13]. In our case, not only the parameters of nonradiative centers were determined, but also the effect of thermal exciton delocalization in the barrier was taken into account.

The temperature dependence of the QW luminescence intensity with under-barrier excitation by a continuous laser with photon energy 1.96 eV and power density $W = 1$ W/cm^2 is well approximated by a function of type (1) with parameters $E_{Q1} = 0.01$ eV, $E_{Q2} = 0.0037$ eV, $a_{Q1} = 9$, $a_{Q2} = 940$ (Fig. 2). The energies E_{Q1} and E_{Q2}characterize nonradiative recombination channels in the QW.

The temperature dependence of barrier luminescence intensity can also be described by an exponential function of type (1). Calculations for the barrier yield $E_{B1} = 0.0065$ eV, $E_{B2} = 0.046$ eV, $a_{B1} = 3$ and $a_{B2} = 12\,000$. (Fig. 3). These activation energies can be considered unrelated to exciton

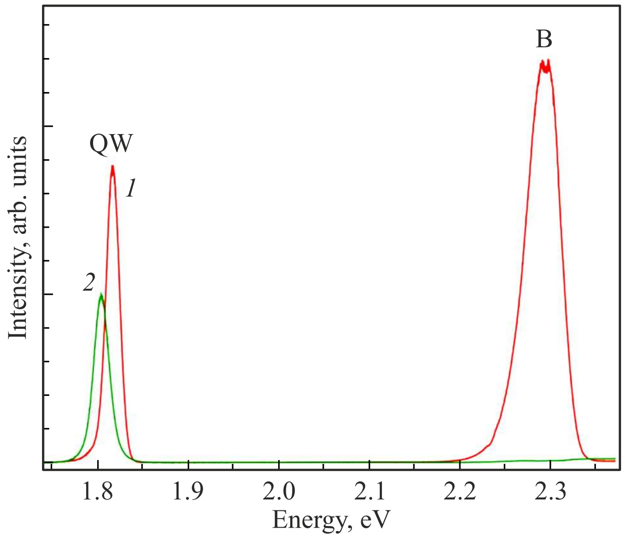

Figure 1. Luminescence spectra of the QW (QW) and barrier (B) of the CdTe/$Cd_{0.6}Mg_{0.4}$Te heterostructure at temperatures $T = 5$ K (*1*) and $T = 100$ K (*2*).

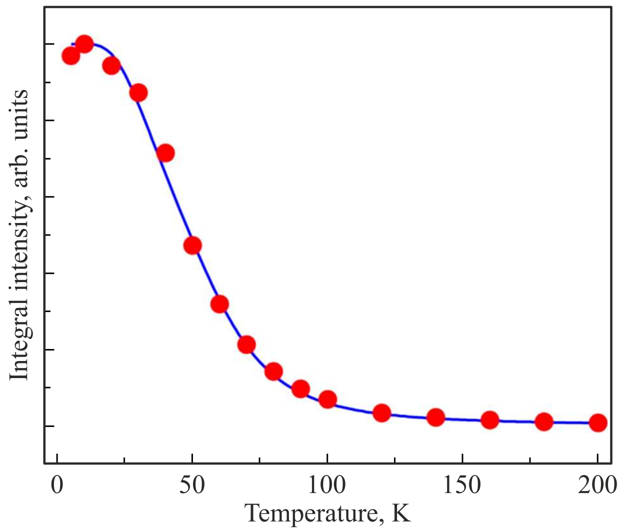

Figure 2. Temperature dependence of the integral luminescence intensity of the CdTe/$Cd_{0.6}Mg_{0.4}$Te QW with under-barrier excitation and photon energy 1.96 eV. Dots — experiment, solid curve — approximation by formula (1) with activation energies $E_{Q1} = 0.01$ eV, $E_{Q2} = 0.0037$ eV, $a_{Q1} = 9$, $a_{Q2} = 940$.

transfer from the barrier to the QW, since the QW volume is much smaller than the barrier volume. They characterize exciton delocalization in the barrier.

The temperature dependence of the QW luminescence intensity under above-barrier excitation significantly differs from that with under-barrier excitation. It exhibits a maximum near $T = 50$ K, which cannot be described by a model containing two exponentials. To adequately describe this dependence under above-barrier excitation, one should consider not only two nonradiative recombination channels in the QW but also the effect of temperature on the

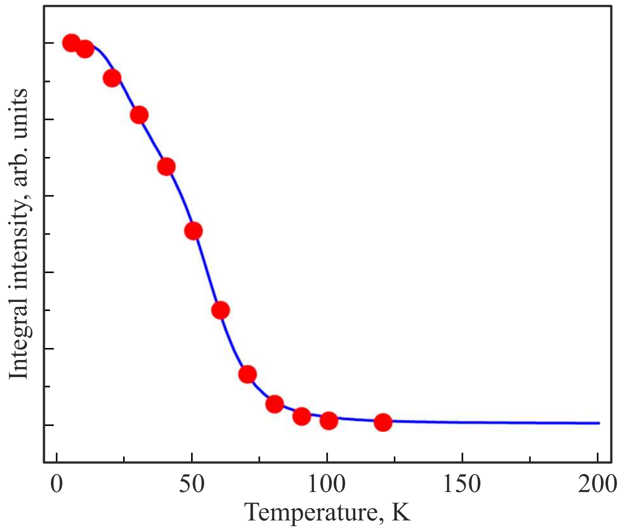

Figure 3. Temperature dependence of the luminescence intensity of the $Cd_{0.6}Mg_{0.4}$Te barrier under excitation with photon energy 2.41 eV at excitation power density $W = 5\,W/cm^2$. Dots represent experimental data, solid curve is the approximation by a formula of type (1) with parameters $E_{B1} = 0.0065$ eV, $E_{B2} = 0.046$ eV, $a_{B1} = 3$ and $a_{B2} = 12\,000$.

excitation transfer rate from the barrier to the QW. At low temperatures, due to exciton localization in the barrier, which is a solid solution, exciton relaxation from barrier layers to the QW is limited. Temperature increase initiates formation of free excitons in the barrier and accelerates their transfer to the QW. This process, in our opinion, is determined by the energies E_{B1} and E_{B2}measured from the temperature quenching of barrier luminescence. Additionally, with temperature increase, the concentration of free excitons in the barrier rises, increasing the probability of their capture by nonradiative recombination centers.

Thus, the model adequately describing the temperature dependence of QW luminescence takes into account:

1) The influence of nonradiative recombination centers on QW luminescence, characterized by activation energies E_{Q1} and E_{Q2}, obtained experimentally with under-barrier excitation (Fig. 2),

2) Exciton delocalization in the barrier, determined by activation energies E_{B1} and E_{B2} obtained from temperature quenching data of barrier luminescence (Fig. 3),

Temperature-driven increase of free exciton concentration in the barrier layer, which relax both into the QW and onto nonradiative recombination centers in the barrier. These processes are characterized by an activation energy E_3 (a fitting parameter) and a constant a_3.

Therefore, the temperature dependence of CdTe/$Cd_{0.6}Mg_{0.4}$Te QW luminescence intensity under above-barrier excitation (Fig. 4) is described by the

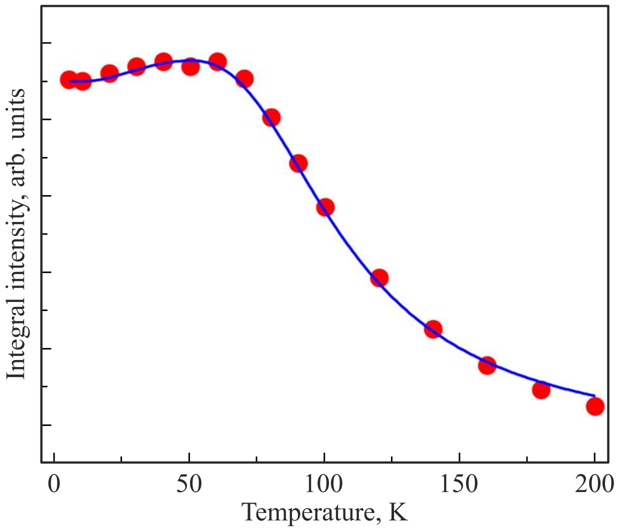

Figure 4. Temperature dependence of the integral luminescence intensity of the CdTe/$Cd_{0.6}Mg_{0.4}Te$ QW under above-barrier excitation with photon energy 2.4 eV at power density 5 W/cm^2. Dots are experimental data, solid curve is approximation by formula (2). $E_{Q1} = 0.01$ eV, $E_{Q2} = 0.0037$ eV, $a_{Q1*} = 0.5$, $a_{Q2*} = 60$, $E_{B1} = 0.0065$ eV, $E_{B2} = 0.046$ eV, $a_{B1} = 3$ and $a_{B2} = 12\,000$, $E_3 = 0.039$ eV, $a_5 = 3000$.

following expressions:

$$I_2(T) = \frac{I_0 + A\left(a_{B1}e^{-\frac{E_{B1}}{kT}} + a_{B2}e^{-\frac{E_{B2}}{kT}}\right)I_3(T)}{1 + a_{Q1*}e^{-\frac{E_{Q1}}{kT}} + a_{Q2*}e^{-\frac{E_{Q2}}{kT}}}, \quad (2)$$

where $A = 0.18$, $I_0 = 1$, $E_{Q1} = 0.01$ eV, $E_{Q2} = 0.0037$ eV, $a_{Q1*} = 0.5$, $a_{Q2*} = 60$, $E_{B1} = 0.0065$ eV, $E_{B2} = 0.046$ eV, $a_{B1} = 3$, $a_{B2} = 12\,000$, $E_3 = 0.039$ eV, $a_3 = 3000$.

It should be noted that in expression (2), values of a_{Q1*} and a_{Q2*}decreased as expected. This is caused by saturation of nonradiative recombination centers with increasing transfer of excitons and carriers in the QW. To confirm this assumption, the above-barrier excitation power density was increased to $W = 95$ W/cm^2 and the temperature dependence of integral luminescence intensity of the CdTe/$Cd_{0.6}Mg_{0.4}Te$ QW was measured and is shown in Fig. 5.

As expected, parameter are decreased while values a remained unchanged. The new set of parameters in expression (2) is: $E_{Q1} = 0.01$ eV, E eV, $E_{Q2} = 0, 0037$, $a_{Q1*} = 0.3$, $E_{B1} = 0.0065$ eV, $E_{B2} = 0.046$ eV, $a_{Q2*} = 40$ and $a_{B1} = 0.51$. $E_3 = 0.039$ eV, $a_{B2} = 4000$, $a_3 = 1100$.

Thus, the influence of temperature and excitation level on the luminescence intensity of the CdTe/$Cd_{0.6}Mg_{0.4}Te$ QW was studied and a model was proposed that adequately describes the experimental results.

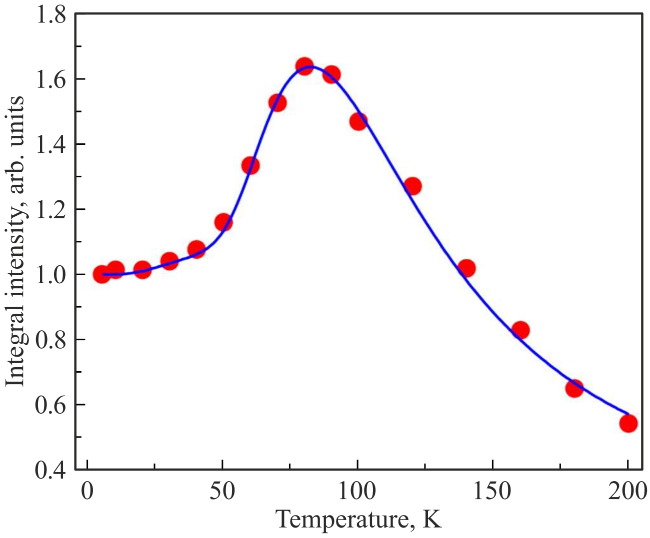

Figure 5. Temperature dependence of integral luminescence intensity of the CdTe/$Cd_{0.6}Mg_{0.4}Te$ QW under above-barrier excitation with photon energy 2.41 eV at power density 95 W/cm^2. Dots represent experimental data, solid curve is approximation by formula (2) with parameters specified in the text.

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Conflict of interest

The authors declare no conflict of interest.

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