03

Energy transfer in heterostructure GaAs/AlGaAs with quantum wells of different thicknesses separated by thick barriers

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Temperature dependence of luminescence of heterostructure GaAs/$Al_{0.4}Ga_{0.6}As$ was investigated to study energy transfer between the quantum wells (QWs). The sample contains three 9.6, 4.8 and 2.4 nm thick QWs separated by 14 nm thick barriers. The experimental data was analyzed based on the model that has been previously used to II−VI heterostructures.

Keywords: quantum wells III = V, luminescence, energy transfer.

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1. Introduction

Many properties of multilayer heterostructures are governed by the degree of coupling of their elements. Excitation transfer is studied in structures containing quantum wells (QWs), quantum dots, as well as in the hybrid type structures [1–7]. The tunneling of charge carriers and excitons as well as the Foerster dipole-dipole interaction are the main transport mechanisms. The probability of transfer increases when the energy levels of individual elements of the heterostructure coincide, which is facilitated by the inhomogeneous broadening of the energy spectrum, which is relevant for arrays of quantum dots, as well as the temperature increase of the energy interval populated by carriers and excitons. The possibilities of optical spectroscopy are used in this study to characterize the coupling of QWs separated by a thick barrier.

2. Results and their discussion

The studied structure was grown by molecular beam epitaxy on a substrate of undoped semi-insulating (100) GaAs. A 600 nm thick GaAs buffer layer and a multilayer heterostructure containing three quantum wells QW32, QW16, and QW8 with thickness of 32, 16, and 8 monolayers (ML = 0.28 nm) of GaAs were grown on the substrate. They are separated from each other and from the buffer layer by $Ga_{0.6}Al_{0.4}As$ barriers with a thickness of 14 nm (Figure 1), the heterostructure is covered by an AlGaAs layer with a thickness of 50 nm and a thin passivating GaAs layer.

Photoluminescence (PL) of the heterostructure was excited using a set of semiconductor lasers with 405, 455, and 532 nm wavelengths. The data obtained using different lasers turned out to be identical, as a result, the authors presented the results obtained using a laser with a of 532 nm wavelength.

Photoluminescence with an abovebarrier excitation has been studied in the temperature range of 5−300 K. Three bands corresponding to exciton recombination in QWs with a comparable intensities are observed in the spectrum at T = 5 K (Figure 2). It should be noted that GaAs substrate emission dominates in case of an belowbarrier excitation. It has been found that the integral PL intensity of the

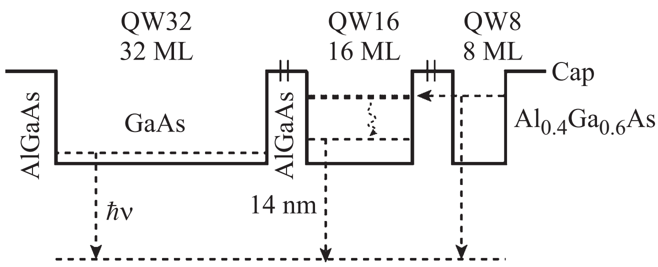

Figure 1. The energy profile of the sample in the exciton representation.

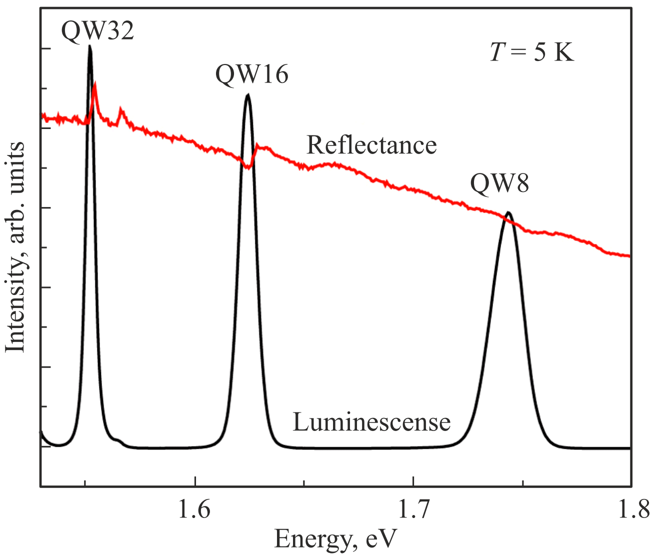

Figure 2. Photoluminescence and reflection spectra of the $GaAs/Al_{0.4}Ga_{0.6}As$ structure.

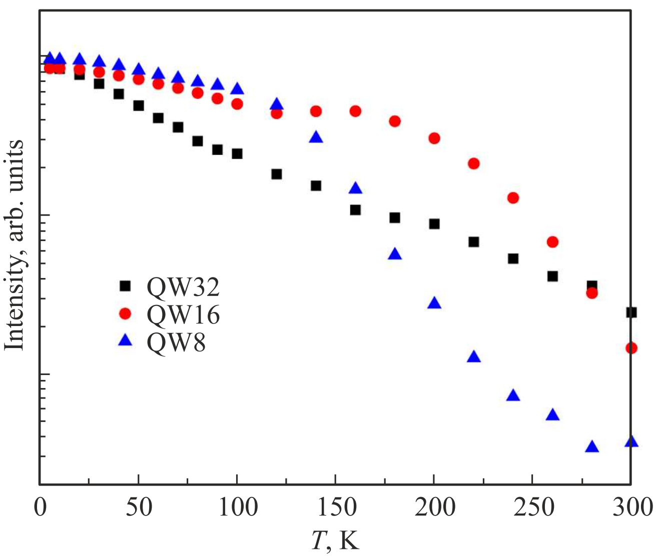

Figure 3. Temperature dependence of the PL integral intensities of QW32, QW16, and QW8.

QWs changes in a nontrivial way with the increase of the temperature (Figure 3).

The experimental data are analyzed based on the model developed in Ref. [8] and used earlier in the study of energy transfer between CdTe QWs [9]. This model describes the temperature dependence of the efficiency of energy transfer between neighboring QWs, which affects the redistribution of PL intensity. This is most clearly observed for the QW8–QW16 pair in our case as a rapid decrease of the integral PL intensity $I_{QW8}(T)$ and a slowdown of the temperature quenching of integral PL intensity $I_{QW16}(T)$ (Figure 4). As shown in Ref. [8], the

Calculation results

	QW8 + QW16	QW8
I_0	1	0.55
a	2.15	2.15
b	905	905
c	–	$1.8 \cdot 10^5$
E_1, meV	130	130
E_2, meV	905	905
E_t, meV	–	1730

temperature dependence of the integral PL intensity $I(T)$ of isolated QWs is described by the function

$$I(T) = I_0/\{1 + a\exp(-E_1/k_BT) + b\exp(-E_2/k_BT)\}. \quad (1)$$

Here, the parameters a, b, E_1 and E_2 describe the transfer of excitation to two types of nonradiative recombination centers. In the case of the coupling of two QWs of different thicknesses, the PL intensities between these QWs are redistributed in a certain temperature interval. It was shown in Ref. [9] that the total PL intensity of two neighboring QWs is described by the formula (1). The equation (1) is supplemented by the term with $\exp(-E_t/kT)$ to account the transfer of excitation from a thin QW to a thick QW:

$$I(T) = I_0/\{1 + a\exp(-E_1/k_BT) + b\exp(-E_2/k_BT) + c\exp(-Et/k_BT)\}, \quad (2)$$

The parameters c and E_t are free here.

It should be taken into account that the exciton binding energy in GaAs QW does not exceed 9 meV, so that the exciton ionization becomes significant at $T > 80$ K. It was shown in Ref. [10] that the transition from shallow exciton states to band states has insignificant effect on the process of excitation transfer between QWs.

The integral PL intensity $I_{QW8}(T)$ rapidly decreases at $T > 140$ K with a simultaneous slowdown of the temperature quenching of $I_{QW16}(T)$ (Figure 4). The total PL intensity of QW8 and QW16 can be described by equation (1) as can be seen from the figure, while the partial temperature dependence $I_{QW8}(T)$ requires the inclusion of an additional term with an activation energy of E_t [equation (2)]. We have considered the balance equations for two pairs of neighboring QW8–QW16 and QW16–QW32. It turned out that the model proposed in Ref. [8] and used earlier in Ref. [9] allows to select parameters that satisfactory describe the energy transfer from QW8 to QW16, for this pair E_t is 1.7 eV (Table).

The evaluation of the wave function overlaping QW8–QW16 states shows that tunneling for a barrier

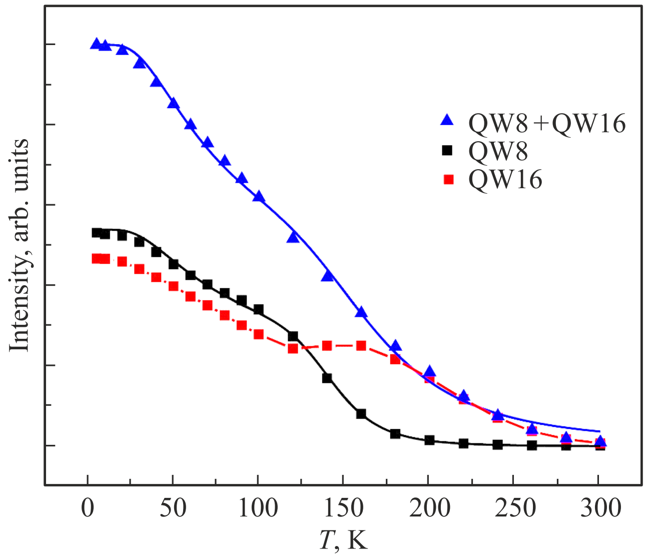

Figure 4. Temperature dependence of the integral PL intensities of QW8, QW16 and PL total intensity. Solid lines correspond to calculations based on the equations (1) and (2).

thickness of 14 nm cannot provide a significant contribution to energy transfer even if the energies of the excited states of the thick QW and the ground state of the thin QW coincide. Foerster type transfer (dipole-dipole interaction) may be the mechanisms responsible for the experimentally observed coupling between QWs [1] or transfer through the states of real or virtual photons [5]. It is shown in these studies that the choice of the mechanism of excitation transfer between QWs separated by thick barriers requires studying the dependence of the rate of this transfer on the thickness of the barrier. The dipole-dipole interaction mechanism of QWs does not have an obvious temperature dependence, but the temperature population of their energy levels can impart it a resonant character.

The temperature dependences of the transfer rate due to dipole-dipole interaction or through the of real or virtual photons [1,5] based on the model of simple parabolic electron and hole bands. It is concluded that even in such a simple model, these dependences have a complex non-monotonic character due to the temperature influence on the energy distributions of carriers and excitons in thin QW. Calculations of the transfer rate in a wide range of energies are required for a detailed description of the energy transfer in the $GaAs/Al_{0.4}Ga_{0.6}As$ heterostructure under consideration. For this, in turn, it is necessary to take into account the complex structure of the valence band and valence band and band nonparabolicity as well as to calculate the QW wave functions.

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Conflict of interest

The authors declare that they have no conflict of interest.

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