Spectroscopic evidence of tunnel coupling between CdTe quantum wells in the CdTe/ZnTe heterostructures

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Abstract The photoluminescence (PL) spectra of CdTe/ZnTe double quantum wells (QWs) are studied on a series of samples containing two CdTe layers with nominal thicknesses of 2 and 4 monolayers (ML) in the ZnTe matrix. The QWs were grown in atomic-layer epitaxy and separated by ZnTe spacers with the thicknesses \(d_{sp}=40–160\) ML. The dependences of the relative intensity of shallow QW\textsubscript{1} and deep QW\textsubscript{2} PL bands (\(I_1\) and \(I_2\), respectively) on the pump intensity (\(J\)) when excited by the lasers with different radiation wavelengths are investigated. It is found that in the sample with \(d_{sp}=40\) ML, the ratio \(Y(J)=I_1/I_2\) depends on \(J\) and the shape of the \(Y(J)\) dependency changes with the excitation wavelength. In the samples with \(d_{sp}>70\) ML \(Y(J)\) also changes with the excitation intensity \(J\), but the shape of this dependence is the same for various excitation wavelengths. It is concluded that the energy relaxation in these samples is influenced not only by the tunneling of charge carriers from QW\textsubscript{1} to QW\textsubscript{2}, but also by carrier relaxation at the nonradiative centers, for which the recombination rate is different for shallow and deep QWs.

1. Introduction
Investigation of the tunneling of charge carriers in semiconductor heterostructures is of great importance for a detailed study of quantum mechanical processes and for applications in devices using the tunnel effect. Of particular interest are the structures based on wide-gap II-VI compounds, especially Zn and Cd tellurides. A characteristic feature of heterostructures which contain several layers of narrow gap compound (CdTe) embedded into a wide gap matrix (ZnTe) is the formation of a quantum well (QW) from a spatially inhomogeneous solid solution of ZnCdTe. The nanoscale regions with a high CdTe content in comparison with the average occurs in these QWs, which in many respects have the properties of quantum dots. The properties of such objects depend at large extent on growth technologies.

This work is dedicated to the study of charge and energy transfer processes in a system of double QWs formed by the atomic layer deposition of two and four CdTe monolayers in ZnTe matrix.

2. Samples and experimental details
CdTe/ZnTe heterostructures consisting of two CdTe QWs (DQW) separated by ZnTe barriers of different thicknesses were grown on semi-isolated GaAs (001) substrates by molecular beam epitaxy.
(MBE). ZnTe buffer layer of these structures with a thickness of about 2.5 micrometers was deposited in the standard mode of MBE. The consistent growth of two CdTe wells with nominal thicknesses of 2 and 4 monolayers was performed by the atomic-layer epitaxy mode. The structures were covered with a cap layer consisting of 100 nm ZnTe and 50 nm ZnMgTe grown by the standard MBE mode. In total, five samples of DQW structures with ZnTe barrier thicknesses of 40, 70, 100, 130, and 160 monolayers (ML) were grown and studied. In addition to the DQW structures two reference samples with single CdTe QW of nominal thickness of 2 and 4 ML were grown under the same conditions.

The He-Cd laser with 442 nm wavelength and the semiconductor lasers with wavelengths in the range of 507–405 nm were used for photoluminescence (PL) excitation. The samples were placed in a closed-cycle He cryostat, and low-temperature PL spectra were recorded using a double monochromator and Hamamatsu R928 photoelectron multiplier.

The excitation power density in our experiments did not exceed 10 W/cm², which corresponds to the creation of less than one e-h pair per one CdTe quantum dot [1, 2].

3. Results and discussion

Figure 1 shows the low-temperature \((T = 5 \text{ K})\) PL spectra of samples with different barrier thicknesses \(d_{\text{sp}}\) obtained at maximum pump level \(J_{\text{exc}} = 10 \text{ W/cm}^2\). The PL spectra which include two bands are normalized to the intensity of the low energy PL band. Emission band in the range \((2.30 \pm 0.01) \text{ eV}\) with full width at half maximum (FWHM) about 10–12 meV appears due to the exciton recombination in the shallow (narrow) QW1, while the emission band in the range \((2.17 \pm 0.02) \text{ eV}\) with FWHM 23–25 meV corresponds to exciton recombination in the deep (wide) QW2. As can be seen in Figure 1, PL bands from QW1 and QW2 in samples with the barrier thicknesses \(d_{\text{sp}} > 70\) ML have comparable intensities \(I_1\) and \(I_2\), which may indicate that these QWs are isolated from each other. In the sample with a thinner barrier \((d_{\text{sp}} = 40\) ML\) the intensity \(I_1\) of QW1 band (thick solid line in Figure 1) is noticeably weaker as compared with the intensity \(I_2\) of QW2 band which apparently points to a tunnel-coupling between QW1 and QW2. As shown in [3] and [4], the tunneling between QW1 and QW2

![Figure 1](image-url)

Figure 1. Low-temperature \((T = 5 \text{ K})\) PL spectra of CdTe/ZnTe double QW structures with different ZnTe barrier thicknesses \(d_{\text{sp}}\) at above-barrier excitation in the region of 2.807 eV. Symbols 1–5 correspond to the samples with \(d_{\text{sp}} = 40\) (thick solid line), 70, 100, 130 and 160 ML, respectively.

The insert shows a diagram of the studied heterostructures.
layers should manifest itself in the dependence of relative intensities \( I_1 \) and \( I_2 \) on the excitation level, as well as in the change in this dependence upon excitation with different wavelengths.

Figure 2 shows the dependences of the ratio \( Y = I_1/I_2 \) of the integral intensities of \( I_1 \) and \( I_2 \) emission bands on the pump intensity \( J \) in PL spectrum of the sample with barrier thickness of \( d_{sp} = 40 \) ML under above barrier excitation with 442, 480 and 507 nm wavelengths. Such a change of the \( Y(J) \) dependence with a change in the excitation wavelength is expected in the case when the barrier is tunnel-transparent for the single carriers, but the probability of exciton tunneling between QW1 and QW2 layers is lower than the probability of exciton radiative recombination [3, 4]. Indeed, in the limit of strong excitation, when the concentration of photo-excited free electrons and holes is high enough, exciton state in the quantum dot is formed mainly as a result of the independent capture of electrons and holes. Under these conditions, the intensities of the \( I_1 \) and \( I_2 \) bands are governed only by the pump intensity, that is, the \( I_1/I_2 \) ratio does not depend on the excitation wavelength. At low excitation level the tunneling of a single carrier (electron) from the shallow QW1 to the deep QW2 exceeds the probability of exciton formation in QW1. In this case the PL intensity from QW1 is determined by the recombination of hot excitons that has successfully completed the energy relaxation as a whole. In this way, the value of \( Y = I_1/I_2 \) depends on the initial kinetic energy of hot excitons, i.e. on the excitation wavelength [4].

![Figure 2](image_url)

**Figure 2.** Dependence of the relative PL intensities from the shallow QW1 and deep QW2 on the excitation intensity for the sample with a barrier thickness of \( d_{sp} = 40 \) ML when excited with wavelengths 442, 480 and 507 nm (crossed, full and open circles, respectively). Solid lines are guides to the eye, only.

We have found that, in contrast to the behavior of \( Y(J) \) in the sample with 40 ML barrier, in the samples with a barrier thickness of 70 ML or more, the \( Y(J) \) ratio does not depend on the excitation wavelength (Figure 3). At first glance, this result can be seen as a direct evidence of the tunneling independence of the QW1 and QW2 layers. Indeed, in the ideal case of a 100% quantum yield, the ratio \( I_1/I_2 \) should depend neither on the intensity nor on the excitation wavelength. However, as can be seen from Figure 3, the value of \( Y \) also increases in the PL spectra of samples with thick barriers with increasing pump level. One can suppose that the process of energy relaxation in the DQW systems under consideration is determined not only by the tunneling of charge carriers from shallow QW to a deep QW, but also by the relaxation on the centers of non-radiative recombination. It can be assumed
[5] that the process of self-organization leads to the quantum dot formation in the QW plane. At the boundaries which separate the QW and quantum dots and/or quantum dots and the barrier, a wide spectrum of states appear, which act as the centers of non-radiative recombination. In this case, the experimentally observed dependence of \( Y \) on the pump intensity \( J \) corresponds to gradual saturation of these centers, their saturation rate being different for shallow and deep QWs. It seems natural that the saturation effect is most pronounced for a shallow QW, since it has fewer centers of both radiative and non-radiative types than a deep QW.

One more factor that determines the difference in the saturation rates of the centers of non-radiative recombination in the vicinity of shallow and deep QWs is the different degree of localization of their electron wave functions of these QWs.

![Graph](image.png)

**Figure 3.** Dependence of the relative PL intensity from the shallow and deep QWs on the intensity of excitation of the sample with barrier thickness of \( d_{sp} = 70 \) ML by lasers with the indicated wavelengths. The inset shows the dependence \( I_{2ML}/I_{4ML} \) for the PL band intensities on the excitation level in reference CdTe/ZnTe samples with the single QWs with nominal thicknesses of 2 and 4 ML.

The influence of non-radiative recombination centers should also be manifested in the dependences of the PL band intensities on the excitation level in the samples containing single QW. We have studied these dependences in the reference samples with single CdTe QWs 2 ML and 4 ML grown in the same conditions as the DQW samples. The dependence of the ratio of PL bands integral intensities in these samples on the excitation levels is shown in the inset to Figure 3. As can be seen in Figure 3, the dependences \( Y(J) \) in the PL spectra of DQW separated by thick barriers, and the dependences of the ratio \( I_{2ML}/I_{4ML}(J) \) in the PL spectra of reference samples are qualitatively the same.

Thus, we have shown that a comprehensive study of the dependence of the intensity of the PL bands on the pump intensity under the above-barrier excitation with different wavelengths make it possible to establish the presence or absence of tunnel coupling in an asymmetric DQW system, as well as to elucidate the effect of the centers of non-radiative recombination on this dependence.

**Acknowledgements**
Authors thank G.V.Budkin for useful discussions. This research was supported within the State Assignments from the Ministry of Science and Higher Education of the Russian Federation to the Ioffe
Institute (0040-2019-0006), the St. Petersburg State University project INI 2019 id 36463378, and National Science Center (Poland) (project no. 2018/30/M/ST3/00276).

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