Optical properties of CdTe/ZnTe structures with thin CdTe layers

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Abstract. The optical properties of series of CdTe/ZnTe heterostructures with two built-in planar CdTe inclusions of thickness 4.0 and 1.5 monolayers are investigated. The temperature behavior of the exciton luminescence intensity at above-barrier and under-barrier excitation depends on the ZnTe barrier thickness which varies from 15 to 55 monolayers. It occurs that the shape of exciton luminescence bands changes strongly under the increasing optical excitation. The excitation luminescence spectra are studied in the temperature range 5 – 80 K.

1. Introduction

The structures with thin [from sub-monolayer (ML) fractions to several ML] planar narrow-gap inclusions embedded in a semiconductor matrix are the important types of heterostructures for various applications. The real structure of the layer depends on its nominal thickness, the mismatch of the lattice constants of thin layer and matrix, and the details of the technological process. The thin layer can be both homogeneous or island-like.

A direct method for studying the thin layer structure is a transmission electron microscopy. The application of optical methods allows not only obtain the information concerning the real structure of layers, but also to study the energy transfer and the dynamics of photocarriers and excitons.

To date, a numerous researches have been done on the optical properties of this type of heterostructures based on II–VI group semiconductors, including the heterostructures with magnetic components [1–9]. The aim of our work is to study the energy transfer and the radiative properties of excitons in the systems containing two CdTe layers with different amount of deposited CdTe separated by ZnTe barriers of various thicknesses.

2. Experimental details

A series of CdTe/ZnTe heterostructures was studied, each sample contains two CdTe layers with nominal thicknesses of 1.5 (D₁) and 4 (D₂) monolayers separated by ZnTe barrier layers with thicknesses of 15, 25, 35, 45 and 55 MLs (samples ##1–5, respectively). The samples were grown on GaAs <100> substrates, D₁ and D₂ layers were formed at a temperature of 360°C. Were grown consistently: ZnTe layer of thickness about 4 μm; 1.5 ML thick CdTe layer; ZnTe barrier layer; 4 ML thick CdTe layer; 0.05 μm thick ZnTe cap layer. The atomic layer epitaxy was used for the formation of thin CdTe layers, the ZnTe layers were grown by standard molecular beam epitaxy.
3. Results and discussion
In the low-temperature photoluminescence (PL) spectra at above-barrier excitation of samples #2–5 two PL bands are observed, due to the recombination of excitons in layers D1 and D2, while only the emission band from the deep quantum well D2 is detected in the PL spectrum of sample #1.

The emission spectra of samples #3 and #4 under the above-barrier excitation conditions are depicted in figure 1. The full width at half maximum (FWHM) of the D2 exciton emission bands is from 10 to 20 meV. The FWHM values of the D1 exciton emission contours are from 2 to 4 meV, which suggests that the D1 layers are much more uniform. The degree of overlap of D1 and D2 exciton wave functions and the magnitude of the strains at the location of each narrow-gap layer depend on the distance between the layers D1 and D2. These factors determine the real construction of the layers and, in turn, the energies and FWHM of the exciton emission contours. Note, that the study of the effect of the barrier layer thickness on the luminescence of CdTe/ZnTe structure with thick narrow-gap layers was carried out in [9].

The thicknesses of D1 and D2 layers are an order of magnitude smaller as compared with the exciton radius, so that the excitons localized on the CdTe layers belong mainly to ZnTe. The thickness of barrier layers ranges from 1 to 4 exciton radii in ZnTe, so that both narrow-gap layers affect significantly the parameters of the exciton localization.

The temperature dependence of the intensity of D2 exciton luminescence in samples #1 and #5 under the above-barrier excitation is monotone, while in samples #2 and #4 the maximum intensity is reached at the temperatures 40–50 K. In samples #2–4, a heating enhances the excitons and free carriers transfer from D1 layer to D2 layer. As for the sample #1 with the thin barrier layer, this transfer is effective already at low temperatures, as for the sample #5 with the thick barrier layer, the temperature degradation of D2 exciton luminescence is not compensated by the transfer from the D1 layer.

![Figure 1](image1.png)

**Figure 1.** Exciton luminescence spectra of samples #3 and #4 at \( T = 5 \) K. Reflection spectrum of ZnTe matrix is shown by dashed line.

![Figure 2](image2.png)

**Figure 2.** Temperature dependence of D2 exciton luminescence intensity in samples #3 and #4 at the under-barrier excitation (see figure 1).

The temperature degradation of D1 exciton luminescence turned out to be monotone in all our samples. This confirms that the temperature maxima of the luminescence from D2 layers are due to the exciton and photocarrier transfer from the D1 layer, but not from ZnTe matrix.

At the under-barrier excitation with a photon energy \( h\nu_{\text{exc}} = 2.330 \) eV (see figure 1), the temperature dependence of D2 exciton emission is much more complex (figure 2). Its behavior is determined by the temperature shift of the energy levels of D1 layer and ZnTe matrix with respect to \( h\nu_{\text{exc}} \). The efficiency
of the optical excitation of D$_2$ layer increases, when $h\nu_{\text{exc}}$ matches with the energy of the exciton resonance or differs from it by the energy of one or two LO phonons of ZnTe lattice.

Let us consider as an example the temperature dependence of the peak luminescence intensity of D$_2$ exciton in sample #3. Several characteristic intervals can be distinguished: 1) maximum I at 50 K; 2) plateau about 90 K; and 3) plateau at 130 K; 4) maximum II at 160 K. Under high excitation conditions we are able to observe the luminescence of excitons from D$_1$ and D$_2$ and ZnTe layers up to high temperatures. It turned out that maximum II corresponds to the temperature at which the energy of the ZnTe barrier exciton matches with the laser energy $h\nu_{\text{exc}}$. Maximum 1 occurs when the exciton energy D$_1$ becomes less than $h\nu_{\text{exc}}$ by the LO phonon energy of ZnTe equal to 26 meV. The plateau at 90 K corresponds to the difference between ZnTe exciton energy and $h\nu_{\text{exc}}$ equal to the energy of 2LO phonons. Similar features which correspond to the resonance excitation conditions are observed in the temperature dependence of D$_2$ exciton luminescence for all samples under our study.

**Figure 3.** Luminescence spectra of sample #3 at excitation levels 1 (1), 10 (2) and 100 (3) W/cm$^2$. Spectra are distorted by interference fringes.

**Figure 4.** Excitation luminescence spectra of D$_2$ exciton in sample #3.

The dependence of the exciton band shape on the intensity of optical excitation demonstrates the differences in the real structure of D$_1$ and D$_2$ layers. With an increase in the excitation power density of sample #3 from 1 up to 100 W/cm$^2$, D$_1$ band broadens slightly, while the D$_2$ band becomes strongly asymmetric and its tail extends to the high-energy side up to the D$_1$ exciton energy (figure 3). Thus, it can be concluded that the D$_2$ layer contains the nanoislands (quantum dots – QDs) with significant lateral size dispersion, while the thinner D$_1$ layer is a more homogeneous.

Flat QDs of D$_2$ layer can be coupled, so that under a weak optical excitation, photocarriers and excitons could relax to the large QDs. Under a strong optical excitation, large QDs can be saturated, and smaller-sized QDs become optically active, what explained a formation of high-energy tail of the D$_2$ exciton band. The enhancement of ZnTe exciton luminescence confirms a saturation of D$_1$ and D$_2$ layers. Another reason for the appearance of a high-energy tail of the D$_2$ exciton band may be the luminescence from the excited states of large quantum dots. We believe that further investigations of the pumping dependence of the PL spectra will help to choose between these two models.

Due to the small thickness and homogeneity of D$_1$ layer, its exciton resonance is well detected in the reflection spectrum (see figure 1), unlike the exciton of D$_2$ layer.

The PL excitation (PLE) spectra of the D$_2$ exciton in the sample #3 are shown in figure 4. In the region below ZnTe exciton energy $E_{\text{ZnTe}}$ several maxima are observed, which correspond either to the D$_1$ exciton ground and excited states, or to the energies which differ from the exciton resonances by the
LO phonon. It was found that the PLE spectrum in the region above $E_{\text{ZnTe}}$ shows the strong temperature dependence. At low temperatures, the efficiency of D$_1$ exciton luminescence excitation much higher than $E_{\text{ZnTe}}$ exceeds significantly its efficiency near $E_{\text{ZnTe}}$. Contrary, above $40$ K, the excitation becomes the most effective in the $E_{\text{ZnTe}}$ region. This can be explained by a fast energy relaxation of hot excitons and photocarriers with the emission of LO phonons at high temperatures.

4. Conclusions
The exciton luminescence of CdTe/ZnTe heterostructures containing two CdTe layers with a nominal thickness of 1.5 and 4 ML, which are separated by ZnTe barrier layers of different thickness, has been studied at various temperatures and excitation levels. The results testify that the thicker CdTe layer consists of flat nanoislands with significant lateral size dispersion, while the thinner CdTe layer appears be more homogeneous. Under the conditions of under-barrier excitation at $2.33\, eV$, the resonant excitation of CdTe layer exciton occurs at certain temperatures that results in the increase of luminescence quantum yield. The CdTe exciton luminescence excitation spectrum strongly depends on the temperature.

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