Photoluminescence of CdTe/CdMnTe and CdTe/CdMgTe heterostructures with quantum wells separated by thick barriers

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The low-temperature photoluminescence (PL) and PL excitation (PLE) spectra of two systems of CdTe quantum wells (QWs) separated by CdMnTe and CdMgTe barriers 20 nm thick are studied. The experimental PL spectra are compared with calculations that take into account the exciton effect and the influence of internal strains. The scatter of our data does not exceed that expected for monolayer fluctuations of the QW width. In the PLE spectra of a thick QW, bands were found that correspond to the increase of PL from a thick QW upon excitation of a neighbor narrow QW. The mechanism of energy transfer between QWs separated by thick barriers is discussed.

Keywords: CdTe, quantum wells, photoluminescence, photoluminescence excitation.

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1. Introduction

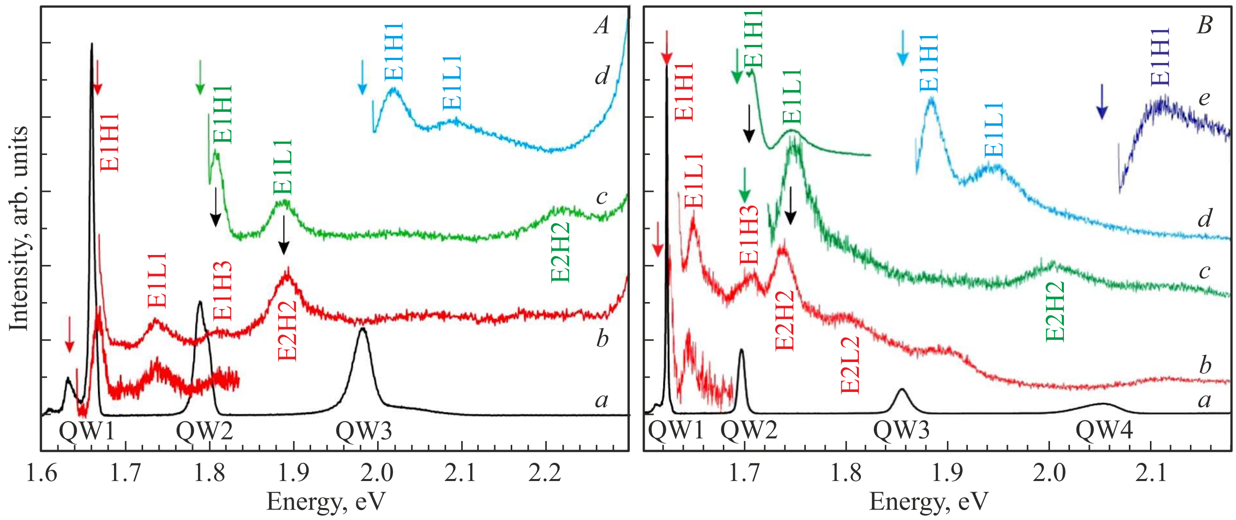
An important characteristic of semiconductor nanostructures is the degree of coupling between their individual elements. Transport properties of nanostructures depend on the electron, hole and exciton transfer, that is a tunneling of particles through potential barriers plays an important role. It has been shown that tunneling is efficient between quantum wells (QWs) separated by a narrow, typically < 10 nm barrier (see, for example, [1,2]). In the structures under consideration, the barrier thickness is 20 nm, which allows to conclude that we are dealing with a different mechanism of energy transfer between QWs. In addition to tunneling, transport can take place via a Förster-type dipole-dipole interaction (DDI) mechanism. The role of DDI in energy transfer in solid-state nanostructures of various types has been actively studied [3–5]. In this respect, it seems relevant to study the mechanism of interaction between QWs separated by thick barriers.

The temperature dependence of the energy transfer probability is determined by the activation energy equal to the barrier height. One can expect that the QWs separated by a thick barrier will be isolated at low temperature, since energy transfer due to thermal excitation is inefficient in this case. However, a number of works have presented results on QW photoluminescence (PL), which manifest efficient energy transfer at low temperature between the wells separated by a thick $(10-30$ nm) barrier. In these works, it is suggested that an important role in energy transfer under such conditions belongs to the dipole-dipole interaction, which does not require the overlap of wave functions or thermal activation of carriers [6–9]. This mechanism was proposed by Förster [10], who showed that the transfer rate between dipoles decreases as R^{-6}, where R — the distance between the dipoles. Generalization of the Förster model to excitation transport in dipole-layer or layer-layer systems in molecular structures and to transport between QW separated by thick barriers in semiconductor structures leads to power law with exponential function from -4 to -2 or even to a weaker logarithmic dependence on the barrier thickness [6–8].

In the present work an energy transfer between QW separated by thick barriers in structures CdTe/$Cd_{1-x}Mn_xTe$ $(x = 0.45)$ and CdTe/$Cd_{1-x}Mg_xTe$ $(x = 0.35)$ is studied and the mechanism of this process is discussed.

2. Samples and experimental details

In our work, the PL and PL excitation spectra of samples A and B fabricated by molecular-beam epitaxy (MBE) on a GaAs $\langle 100 \rangle$ substrate with a CdMgTe buffer layer have been investigated. Sample A consists of three CdTe QW1−QW3 QW of 16, 8, and 4 monolayer (ML) thicknesses (1 ML CdTe = 0.32 nm) separated by $Cd_{0.55}Mn_{0.45}Te$ barriers of 20 nm thick. Sample B consists of four QW CdTe QW1−QW4 of widths 32, 16, 8, and 4 ML separated by $Cd_{0.65}Mg_{0.35}$ Te barriers of the same thickness. The samples were placed in an optical cryostat, and the PL was excited by the 456 nm line of a solid-state laser. The halogen lamp radiation passed through



a — PL spectra of samples A and B at the above-barrier excitation 2.805 eV; *b* — QW1 PL excitation spectra, samples A and B; *c* — QW2 PL excitation spectra, samples A and B; *d* — QW3 PL excitation spectra, samples A and B; *e* — QW 4PL excitation spectrum, sample B. The vertical black arrows indicate the resonance bands in the PL excitation spectra of QW1 and QW2. The recording energies of the PL excitation spectra are shown with colored arrows. $T = 5$ K. (The colored version of the figure is available on-line).

a monochromator was used to obtain the PL excitation spectra.

3. Experimental results

Figure, *a* shows the low-temperature PL spectrum of sample A obtained under excitation to the barrier energy region. At temperature 5 K, the spectrum consists of three bands with half-widths (FWHM) of 6, 20, and 33 meV. These bands correspond to exciton recombination in QW QW1–QW3. The fine structure of the PL bands, clearly manifested in the emission spectra QW1 and QW2, is due to the contribution of free excitons and excitons localized on the QW broadening. In the figure, *a* the spectra of PL excitation obtained by registration at the points indicated by the arrows are also shown, and the interpretation of the spectra features on the basis of the model described below is given. It can be seen that in PL excitation spectra of thick QW1 in addition to the peaks corresponding to the excitation of heavy and light exciton (E1H1 and E1L1, respectively), there is a strong band with energy 1.89 eV coinciding with the E1L1 band in the QW2 PL excitation spectrum. This result indicates an energy transfer between QW2 and QW1. Similar evidence of energy transfer is also observed in the PL excitation spectra of QW2 and QW1 in sample B (see Figure, *b*).

To estimate the efficiency of energy transfer between narrow and thick QWs, we can use the ratio of the PL intensity of the thick QW under excitation to the energy band shown by the vertical arrows in panels A and B (see Figure) to the PL intensity under direct excitation in the E1H1 transition. As can be seen from the figure, the efficiencies of this transfer in samples A and B are comparable.

4. Discussion

As follows from the figure, the QW1 PL excitation spectra for of both samples show at least 4 peaks. The first two peaks can be identified with exciton transitions E1L1 and E1H1, the origin of the other two peaks is not so unambiguous. In order to verify the resonance between the QW1 and QW2 energy levels, numerical calculations by the variations method within the framework of the self-consistent field approximation [11] were carried out. When calculating exciton energies, it is necessary to use a number of parameters of heterostructures, the values of which, according to literature data, have a significant variation. Our calculation was aimed to show that the energies of certain peaks in the PL excitation spectra of thick QWs correspond to the exciton energies of narrower QWs. The QW potential was assumed to be rectangular, the effective mass of particles was assumed to be constant in the direction of the structure growth and independent of the QW thickness. In result, a set of parameters (see table) was found that allows identification of all observed peaks in the PL excitation spectra (see figure) by varying only the thickness of the QW.

The energy gap width of E_g was determined from the exciton energy of the barrier: Q — the ratio of barrier height for electron and hole, dQ (meV) — the strain caused by the lattice constant mismatch of the barrier material and the QW (see table).

$$U_b = E_g - E_{g\mathrm{CdTe}}, \quad U_\mathrm{E} = Q \cdot U_b + dQ_\mathrm{E},$$

$$U_\mathrm{H} = (1 - Q) \cdot U_b - dQ_\mathrm{H}, \quad U_\mathrm{L} = (1 - Q) \cdot U_b + dQ_\mathrm{L},$$

U_b — total barrier height for electron and holes, indices E, H and L correspond to electron, heavy and light holes, $\gamma_{1,2}$ — Luttinger constants, $m_{\mathrm{H}\perp} = 1/(\gamma_1 + \gamma_2)$, Parameters used in the calculation

E_g, meV	Q	dQ_E	dQ_H	dQ_L	m_E	m_H	m_L	γ_1	γ_2	ε	ML, nm
Sample A											
2.348	0.7	0.005	0.005	0.012	0.12	0.8	0.12	5.35	1.73	10	0.32
Sample B											
2.372	0.8	0	0	0.005	0.09	0.8	0.12	5.35	1.73	10	0.32

$m_{L\perp} = 1/(\gamma_1 - \gamma_2)$, ε — dielectric permittivity, ML — monolayer thickness. For each of the QWs, a series of calculations were performed for the nominal QW thickness and its one monolayer fluctuations.

Evidence of efficient exciton effect in thick QWs while exciton generation in narrow QWs was also observed in [12] for the CdTe/$Cd_{1-x}Mn_x$Te structure with CdTe QWs with thicknesses of 4, 6, and 10 nm separated by 50 nm barriers. The authors proposed the hypothesis of long-range magnetic interaction along the chains of spin-polarized manganese ions connecting QWs. Our results show that efficient excitation transfer between QWs is also observed in sample B, where magnetic manganese atoms are replaced by nonmagnetic magnesium atoms in the barriers. This is in favor of the Förster mechanism of energy transfer in the samples investigated in our work, as well as in the sample investigated in [12].

5. Conclusion

In work, efficient energy transfer at low temperature was observed between the exciton states in two sets differing in QW width CdTe/$Cd_{1-x}Mn_x$Te and CdTe/$Cd_{1-x}Mg_x$Te. In both sets, the thickness of the barriers separating the QWs CdTe is 20 nm, which excludes the possibility of carrier and exciton tunneling. The analysis of the obtained data indicates in favor of the energy transfer via the resonant dipole-dipole interaction.

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Conflict of interest

The authors declare that they have no conflict of interest.

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