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Effect of Cd content in barriers on the threshold energy of Auger recombination in waveguide structures with HgTe/Cd$_x$Hg$_{1-x}$Te quantum wells, emitting at a wavelength of 18 μm

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Abstract. **The threshold energy of Auger recombination in HgTe/Cd$_x$Hg$_{1-x}$Te heterostructures with quantum wells (QWs) is analysed numerically for different compositions of the solid solution in barriers. It is demonstrated that the threshold energy depends nonmonotonically on the cadmium content in barriers and reaches a maximum at x ~0.6–0.7. A comparison of the results of numerical calculations with experimental data on the temperature quenching of stimulated emission in a Cd$_{0.1}$Hg$_{0.9}$Te/Cd$_{0.65}$Hg$_{0.35}$Te structure gives grounds to expect a more than twofold increase in the quenching temperature of stimulated emission in structures with pure HgTe QWs and barriers with a high (~0.6) cadmium content.**

Keywords: *threshold energy, Auger recombination, HgCdTe.*

The development of compact semiconductor far-IR sources is an important problem of modern physics of semiconductors. Promising candidates are lasers based on HgCdTe heterostructures with quantum wells (QWs).

Mercury–cadmium–telluride (HgCdTe or MCT) solid solutions have been investigated for more than four decades. A great amount of data on the technology and properties of these compounds, whose band gap can be varied in wide limits (from zero to 1.5 eV) by changing their composition, have been accumulated during these years. MCT is widely used to produce mid-IR detectors and detector arrays (see, e.g., [1] and references therein). HgCdTe-based lasers have also been known for a fairly long time [2]. Until recently, they could generate at wavelengths up to 5.4 μm at a cryogenic temperature [3] and to 2.2 μm at room temperature [4].

In recent years, the progress in the growth technology of these structures [specifically, molecular-beam epitaxy (MBE)] stimulated the problem of designing MCT-based far-IR sources, as was demonstrated by the latest experimental results. In particular, stimulated emission under optical pumping up to a wavelength of 20 μm (but only at a cryogenic temperature) was observed for the first time in HgCdTe-based waveguide structures with narrow-gap HgTe/HgCdTe QWs [5, 6].

The main factor leading to temperature quenching of stimulated emission in narrow-gap semiconductor structures is Auger recombination: a three-body process, at which the energy released during recombination of an electron–hole pair is transferred to another carrier [7, 8]. However, to onset Auger recombination, the total kinetic energy of the electrons and holes involved in the recombination should exceed some threshold value [9]. Obviously, Auger recombination becomes inefficient at temperatures much below the point corresponding to this threshold. The threshold energy can be determined if the dispersion relation for the carriers involved in the Auger process is known.

Previously it was theoretically predicted [10] and experimentally confirmed [11] that the Auger recombination rate in narrow binary HgTe QWs is lower than in wide Hg$_{1-x}$Cd$_x$Te QWs. Thus, it was found that, using structures with narrow pure HgTe QWs, one can significantly increase the critical quenching temperature of stimulated emission. At the same time, the influence of another important parameter – composition of barrier layers – on the critical temperature has not been analysed yet.

In this work, we investigated the dependence of the threshold energy of Auger recombination on the Cd content in Hg$_{1-x}$Cd$_x$Te barriers with simultaneous variation in the HgTe QW thickness in order to preserve the optical transition energy between the main subbands of electrons and holes in the vicinity of 70 meV (wavelength ~18 μm).

The dispersion relations for electrons and holes were calculated using the four-band Kane model, which provides an excellent agreement with experiment when determining the radiative recombination time in HgTe QWs [12]. We considered QWs grown on the (013) substrate to ensure correspondence with experimental samples. The Kane Hamiltonian for these QWs was reported in [13]. The calculation was performed taking into account the symmetry lowering at the interface using the Ivchenko term [14]. An explicit form of this term for the case under consideration was reported in [15].

The results of calculating the spectrum of electrons and holes for two cases are shown in Fig. 1. In the first case (Fig. 1a), the calculation was carried out for an experimentally investigated Cd$_{0.1}$Hg$_{0.9}$Te/Cd$_{0.65}$Hg$_{0.35}$Te QW with a thickness of 8.7 nm. In the second case (Fig. 1b), we analysed

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a 4.2-nm-thick HgTe/$Cd_{0.65}Hg_{0.35}Te$ QW. It can be seen in Fig. 1a that in the first case the valence subbands contain additional peaks at 7 meV below the top of the valence band. At the same time, these peaks are practically absent for the HgTe QW located between $Cd_{0.65}Hg_{0.35}Te$ layers (Fig. 1b). As will be shown below, the form of the dispersion relation for holes is important for determining the threshold energy of Auger recombination.

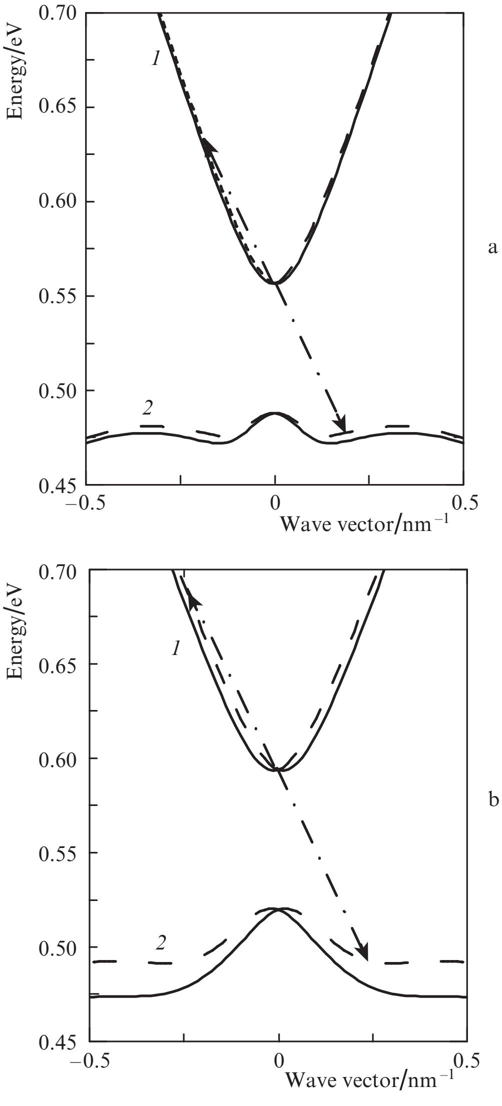

Figure 1. Energy band diagrams at a temperature of $T = 20$ K, calculated for the (a) 8.7-nm-thick $Cd_{0.1}Hg_{0.9}Te/Cd_{0.65}Hg_{0.35}Te$ and (b) 4.2-nm-thick HgTe/$Cd_{0.65}Hg_{0.35}Te$ QWs. The wave vector is directed along the [100] axis. There are two pairs of subbands due to the spin splitting: (*1*) electron and (*2*) hole subbands (solid and dashed lines, respectively). The arrows indicate the electron transitions corresponding to the Auger recombination threshold in the CHCC process.

Optical pumping of the waveguide structure with 8.7-nm-thick $Cd_{0.1}Hg_{0.9}Te$ QWs and $Cd_{0.65}Hg_{0.35}Te$ barriers provided stimulated emission at 18 μm, which was observed in the temperature range from 20 to 40 K. This structure was MBE-grown on a semi-insulating (013) GaAs substrate with ZnTe and CdTe buffers. The heterostructure contains ten $Cd_{0.1}Hg_{0.9}Te/Cd_{0.65}Hg_{0.35}Te$ QWs separated by 30-nm-thick barriers. Stimulated-emission spectra were recorded using a Bruker Vertex 80v Fourier spectrometer in the step-scan mode. The sample was mounted on a cold finger of a closed-cycle helium cryostat with a possibility of controlling temperature in the range from 8 to 300 K. The optical excitation source was a pulsed CO_2 laser with a maximum intensity of 1 MW cm^{-2}. The pump beam was incident normally to the structure surface, and the stimulated emission was collected from the facet of the sample. The threshold energy calculated for the CHCC process (two electrons in the lowest subband of the conduction band and one hole in the highest valence subband in the initial state) was about 10 meV. This energy is approximately three times higher than the thermal energy at which stimulated emission was suppressed. The processes with two holes and one electron in the initial state have threshold energies several times higher than that for CHCC and, therefore, can be disregarded.

Note that the threshold energy in CHCC is mainly determined by the hole kinetic energy. With allowance for the fact that the kinetic energy of holes under population inversion conditions is determined by not only the temperature but also the position of the quasi-level Fermi in the valence band, the agreement between the theory and experiment can be considered as satisfactory.

It is of interest to compare the threshold energies of the above-described structure and the structures based on HgTe QWs. Figure 2 shows the dependences of the threshold energy of Auger recombination (calculated within the model proposed in [9]) and the HgTe QW thickness on the Cd content in barriers for $T = 20$ and 77 K, at a fixed optical transition energy of 70 meV. It can be seen that the maximum threshold energy (which is optimal from the point of view of the maximum temperature of stimulated emission) reaches 30 meV at a Cd content of 0.67 for $T = 20$ K and 27 meV at a Cd content of 0.62 for $T = 77$ K.

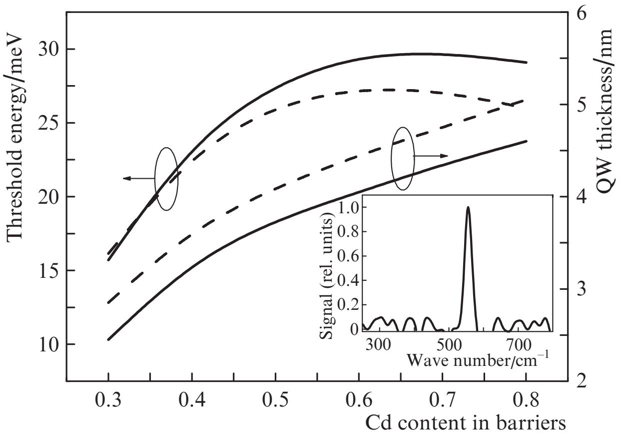

Figure 2. Dependences of the Auger recombination threshold energy and the HgTe QW thickness on the Cd content in barriers for temperatures T = (solid line) 20 and (dashed line) 77 K at a fixed optical transition energy: 70 meV. The inset shows the stimulated emission spectrum for the structure with 8.7-nm-thick $Cd_{0.1}Hg_{0.9}Te/Cd_{0.65}Hg_{0.35}Te$ QW at $T = 20$ K (the Auger threshold energy for this structure is 10 meV).

To explain the difference in the threshold energies for the HgTe and $Cd_{0.1}Hg_{0.9}Te$ QWs, we demonstrate in Fig. 1 the initial and final states of electrons and holes corresponding to the Auger recombination threshold. A comparison shows that the 'effective mass' of holes for the Auger process in HgTe QWs is much smaller than for the $Cd_{0.1}Hg_{0.9}Te$ QW.

This is related to the presence of a pronounced lateral extremum in the upper valence subband in the $Cd_{0.1}Hg_{0.9}Te$ QW. It is well known that an increase in the hole effective mass leads to a decrease in the Auger threshold energy [9]. The presence of a maximum in the dependence of the threshold energy on the cadmium content in the $HgTe/Cd_xHg_{1-x}Te$ QW is due to the minimum of the hole effective mass at a certain cadmium content. Note, that the term ‘effective mass’ for the valence subbands is conventional, because the dispersion relation for it is nonquadratic and, generally speaking, nonmonotonic. We consider this term as a value providing a relationship between the kinetic energy and wave vector of a hole. The larger the wave vector at a fixed kinetic energy, the larger the ‘effective mass’.

Thus, it was demonstrated that, at a specified energy of interband transition, the threshold energy of Auger recombination in structures with $HgTe/Cd_xHg_{1-x}Te$ QWs is a nonmonotonic function on the cadmium content in barriers. In the case of optimal cadmium content in barriers and an HgTe QW, one would expect an almost threefold increase in the critical temperature of stimulated emission as compared to the prototype structure with $Cd_{0.1}Hg_{0.9}Te/Cd_{0.65}Hg_{0.35}Te$ QWs.

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