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Photoluminescence and photoreflectance of long-wavelength HgTe/CdHgTe heterostructure

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Abstract. This paper presents the results of optical studies of a long-wavelength HgTe/CdHgTe heterostructure performed using photoluminescence and photoreflectance methods. Optical transitions involving several electron and hole levels were observed, with the dominant levels switching with changes in temperature. Using the photoreflectance method, optical transitions not detectable by the photoluminescence were observed. It is demonstrated that the combination of the methods allows for the most detailed evaluation of optical transitions in the HgTe/CdHgTe quantum wells.

Keywords: CdHgTe, heterostructures, photoluminescence, photoreflectance

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Фотолюминесценция и фотоотражение длинноволновой гетероструктуры HgTe/CdHgTe

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Аннотация. В работе представлены результаты оптических исследований длинноволновой гетероструктуры HgTe/CdHgTe, выполненных методами фотолюминесценции и фотоотражения. Обнаружены оптические переходы с участием нескольких электронных и дырочных уровней, причем доминирующие уровни переключались с изменением температуры. Методом фотоотражения обнаружены переходы, не детектируемые методом фотолюминесценции. Показано, что сочетание использованных методов позволяет наиболее детально оценить оптические переходы в квантовых ямах HgTe/CdHgTe.

Ключевые слова: CdHgTe, гетероструктуры, фотолюминесценция, фотоотражение

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Introduction

Mercury cadmium telluride (HgCdTe, MCT) is a semiconductor solid solution that occupies a dominant position in infrared (IR) optoelectronics due to its small bandgap and high charge carrier mobility. In addition to classical structures based on bulk MCT of various compositions (mole fraction CdTe x), interest is growing in MCT-based heterostructures (HSs) with quantum wells (QWs). These HSs are used in fabrication of lasers for the mid-IR range (wavelengths $\lambda = 3 - 6$ μm) [1] and long-IR range ($\lambda > 10$ μm) [2]. They are also used in the production of photodetectors [3] and structures with topological insulators [4]. The energies of optical transitions in such structures depend on the width of the QW and on x in the wells and barrier layers. Careful selection of these parameters allows one not only to obtain a structure with emission at the desired wavelength, but also to suppress Auger recombination processes [5]. Growth of an ‘ideal’ HS, however, using the widespread method of molecular beam epitaxy (MBE), is limited by the impossibility of an instant transition from growing CdTe to HgTe and back, as well as by the difference in the optimal growth temperatures of HgTe and CdTe by more than 100 °C [6]. Therefore, a complete characterization of ‘real’ structures with HgTe/CdHgTe QWs is a very relevant task. In this paper, we report the results of optical studies of a HS with HgTe/CdHgTe QWs, where in addition to the ‘classical’ photoluminescence (PL) method, the modulation Fourier-transform infrared (FTIR) spectroscopy, photoreflectance (PR), was used. This method has been successfully used in the studies of III–V semiconductors [7], however, its application to MCT has been limited to just a few works performed solely on epitaxial films [8–11].

Materials and Methods

The HS was grown by MBE on a (013)GaAs substrate with ZnTe and CdTe buffer layers [12]. The structure contained 11 QWs with a thickness $w = 7.1$ nm with composition in the wells set during the growth as corresponding to pure HgTe ($x = 0$), and composition in the barriers, $x_b = 0.62$. The waveguide layers (spacers) in the HS with a thickness $d \approx 4–5$ μm had a composition $x_s \approx 0.7$; a layer of pure CdTe with a thickness of 30 nm was grown *in situ* on the HS surface.

The PL and PR studies were carried out using a setup based on a Vertex 80 FTIR spectrometer operating in step scan mode [13]. A diode laser ($\lambda = 809$ nm) was used to excite the PL signal and as a source of modulating radiation when recording the PR spectra. Lock-in signal amplification was used to eliminate the influence of background thermal radiation. The laser emission was mechanically modulated at a frequency $f = 2.5$ kHz. The PL and PR spectra were recorded in the temperature range $T = 12 - 294$ K using a Janis CCS-150 closed-cycle helium cryostat. The signal was recorded with an MCT photoconductive detector.

Results and Discussion

Several peaks were observed in the PL spectra of the HS (Fig. 1); changes in their intensity and energy with temperature are described below. With an increase in temperature to $T \approx 90$ K, a 'blue' shift of line A was observed, and its intensity decreased (Fig. 1, *a*). Along with that, a 'blue' shift of another, low-energy peak (line *B*) was observed, the intensity of which increased due to a gradual transition of the signal into the working range of the photodetector (~ 75 meV and higher). Its energy reached a value of ~ 92 meV at $T \approx 90$ K. Also, at $T \approx 90$ K, this peak exhibited a noticeable high-energy shoulder in the energy range of 115–118 meV (line *C*).

A further increase in temperature (Fig. 1, *b*) led to a shift of *B* and *C* lines into the high-energy region; a simultaneous decrease in the intensity of line *B* and an increase in the intensity of line *C* were observed. At $T \approx 150$ K, line *D* appeared, representing a shoulder with a higher energy of 133 − 135 meV. At $T \approx 180$ K, a signal with an energy of ~160 meV (line *E*) appeared. Heating the structure to $T \approx 210$ K made it possible to obtain the most intense PL signal, where the largest contribution came from lines *C* and *D*, which represented a peak with a shoulder in the high-energy region. A further increase in the temperature up to room temperature led to a decrease in the intensity of lines *C* and *D*, as well as an increase in the intensity of line *E*. At room temperature, the spectrum represented a broad band with several energy lines, among which the most intense lines *C* and *E* could clearly be distinguished. According to the energy range of these peaks, they obviously corresponded to the long-wavelength (up to 15 μm) IR emission from the QWs. In the case of PL, most likely, we observed optical transitions involving levels closest to the ground states in the QWs.

a) *b*)

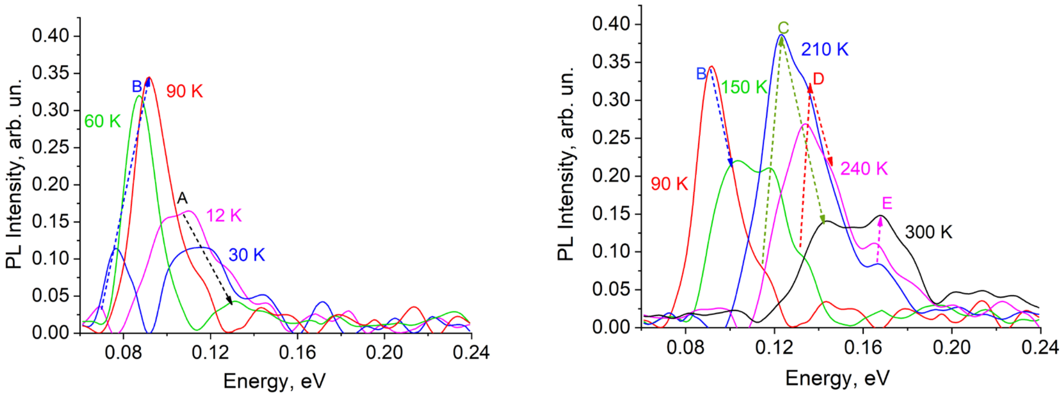

Fig. 1. PL spectra of the HS at different temperatures

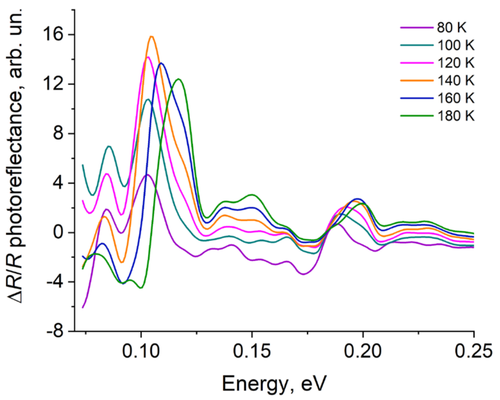

Fig. 2. PR spectra of the HS at different temperatures

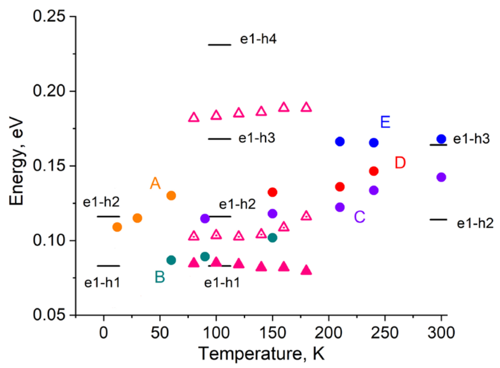

Fig. 3. Temperature dependence of the energies of optical transitions detected with PL (circles) and PR (triangles), and the calculated values of possible transitions in the QWs (dashes)

The optical signal from the QWs was also obtained with the PR method (Fig. 2). Using the technique described in [14], the energies of three PR peaks were obtained at $T = 80$ K: ~84 meV, ~102 meV, and ~180 meV. The first two peaks were likely associated with the *e*1-*h*1 (representing the first levels of quantization for electrons and holes), and *e*1-*h*2 transitions, respectively. The positions of the peaks remained virtually unchanged with varying temperature. The peak with the energy ~180 meV (at $T = 80$ K) in the PR spectra was not previously observed in the PL spectra. Thus, it can be concluded that PR allows one to detect transitions involving deeper levels in MCT-based HSs, which is promising for the comprehensive characterization of such structures.

Fig. 3 presents the summary data on the PL and PR energies for the HS with temperature variation. Also, the transition energies in the QWs estimated using [15] are presented. It should be noted that the estimates at this stage were very rough, in particular, due to the non-obvious choice of calculation parameters, such as the exact value of the bandgap in the wells as well as the electron effective mass. However, it can still be concluded that the PL and PR methods detected transitions between the states closest to the ground ones. The energy of all PL peaks also increased with increasing temperature.

Conclusion

A long-wavelength HgTe/CdHgTe-based QW heterostructure was studied using PL and PR methods. It is demonstrated that these methods can be used to determine the energy of optical transitions in the QWs. PL detected transitions involving levels closest to the ground states, and with increasing temperature, the dominance of various transitions was observed. Using the PR method, transitions with energies of ~180 meV were additionally detected. Thus, a comprehensive study of the optical properties of MCT-based heterostructures using PL and PR methods enabled the most accurate determination of the energies of optical transitions in the QWs.

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