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Light emission from single thick CdTe under high optical excitation

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The luminescence spectra of a series of CdTe|$Cd_{0.7}Mg_{0.3}Te$ heterostructures with a single quantum well are studied in wide ranges of the optical excitation level and temperature. The change in the luminescence spectra corresponding to the transformation of an exciton gas into an electron-hole plasma is traced. When luminescence was excited by a light strip on the sample surface, stimulated electron-hole plasma emission is polarized perpendicular to the strip.

Keywords: II−VI quantum well structures, luminescence, high excitation, exciton, electron-hole plasma.

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1. Introduction

The transformation of luminescence spectra of bulk semiconductor crystals and semiconductor nanostructures with increasing level of optical excitation has been studied for many years. Depending on properties of the object and experimental conditions, screening of the Coulomb interaction in excitons with increase in excitation results in the formation of either electron−hole plasma (EHP) [1–4], or electron−hole liquid (EHL). The EHL is formed at low temperatures, its properties have been studied mainly in indirect gap systems [5–7]. In [8], a transition has been demonstrated from EHL to EHP with increasing temperature in a system of coupled GaAs|GaAlAs nanowires. The purpose of this study is to investigate the dependence of the emission spectra of CdTe|CdMgTe heterostructures with a thick (QW) on temperature and level of optical excitation, as well as on the method and level of doping of the heterostructure.

2. Samples and experiment technique

The studied CdTe|$Cd_{1-x}Mg_xTe$ heterostructures contain a single CdTe QW with a thickness of 100 nm. The exciton energy of the barrier layer in $Cd_{1-x}Mg_xTe$ is equal to 2.1 eV, which corresponds to $x = 0.3$. The structure was doped with donors using a ZnI_2 source. In two samples, tellurium was replaced with iodine in layers with a thickness of 1 monolayer (ML) and 5 ML, respectively. These layers were formed in the barrier at a distance of 15 nm from the QW interface. In two other samples, the CdTe QW was uniformly doped at ZnI_2 source temperatures of 130 and 140°C; for bulk CdTe samples this corresponds to donor concentrations of $4 \cdot 10^{15}$ and $1 \cdot 10^{16}\,cm^{-3}$. Also, an undoped sample was grown. To excite the luminescence, a Millet Griot 85-DSL-301 CW-laser with a radiation wavelength of 532 nm and a LCS-DTL-374QT laser with a pulse duration of 10 ns, a frequency of 2 kHz and a radiation wavelength of 532 nm were used. The laser radiation was focused onto the surface of the sample in the form of a $0.04 \times 0.40\,cm^2$ strip, the power density during pulsed excitation ranged from 0.2 to 20 kW/cm^2. The luminescence was recorded in a direction perpendicular to the sample surface; the central region of the excitation band was projected onto the spectrometer slit.

3. Results and discussion

The experiment showed that in our case, doping of heterostructures does not qualitatively affect the transformation of the emission spectrum of the thick CdTe QW with changes in the level of optical excitation and temperature. This study presents the data obtained for a sample where one ML of tellurium in the barrier is replaced with iodine. In this sample, the threshold for appearance of stimulated emission turned out to be the lowest; this may be due to the donor compensation for uncontrolled acceptor states in the QW.

The reflectance and luminescence spectra are shown in Figure 1. For an exciton in the CdTe QW with a thickness of 100 nm, a weak size quantization regime is implemented; in this case, the limitation in the direction of growth of the heterostructure affects the movement of the exciton as a whole. This is manifested as a structure on the high energy side from the exciton resonance.

As the excitation level increases, band I of spontaneous emission broadens, and band II of stimulated emission

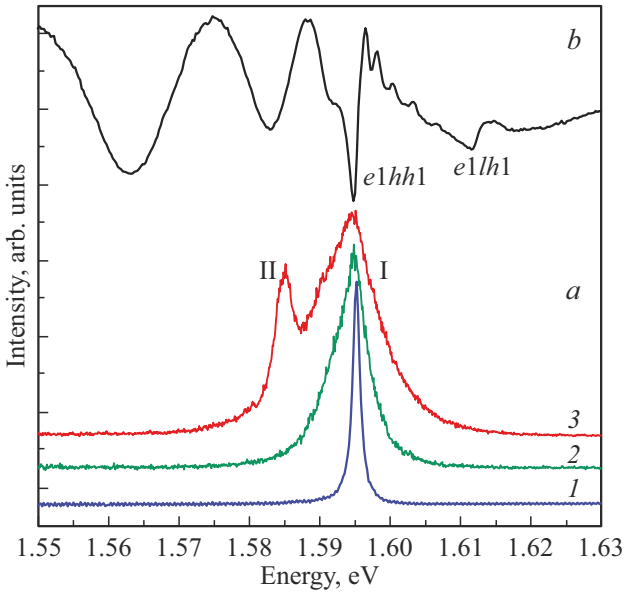

Figure 1. *a* — bands of spontaneous (I) and stimulated (II) emission in the luminescence spectrum of CdTe QW at excitation power densities of 10^{-5} (curve *1*), 0.5 (curve *2*) and 1.5 (curve *3*) kW/cm^2; *b* — reflection spectrum with resonances of heavy and light excitons, $e1hh1$ and $e1lh1$, the structure on the high-energy side from the $e1hh1$ resonance corresponds to the size quantization of the exciton wave vector. $T = 5$ K.

appears on its long-wavelength side (Figure 1). It is known that stimulated emission propagates along the excitation band. The manifestation of stimulated emission in the experimental geometry we used is indicative of the fact that a certain fraction of this emission is scattered and reflected from the boundary with the GaAs substrate. In this case, it is natural to expect that the radiation will be partially polarized perpendicular to the excitation band. The spectra presented in Figure 2 show that band II is completely polarized perpendicular to the exciting light band on the surface of the sample, that is, no depolarization of the stimulated emission takes place upon reflection from the substrate. The experimental geometry used does not allow measuring the intensity of stimulated emission but makes it possible to establish the threshold for its appearance and the dynamics of its development.

Figure 3–5 show the emission spectra of CdTe QW at different excitation power densities P, as well as the dependences of the integral intensity J and full width at half maximum (FWHM) of bands I and II on P at $T = 5$ K. It can be seen that in the interval of P from 10^{-5} to 1 kW/cm^2 band I is intensified sharply and broadened; this spectrum transformation corresponds to the transition from exciton emission to EHP emission. With further growth of P the increase in intensity and the broadening of band I become slower. The dependence of J of band II on P from the moment of its occurrence is close to linear, the FWHM of band II increases sharply up to $P = 1$ kW/cm^2, with further intensification of excitation, the broadening band II slows down. An increase in P from 0 to 20 kW/cm^2 has little effect on the energy position of the maximum of band I, which indicates the absence of a noticeable renormalization of the band gap. With increasing P band II shifts toward low energies along the contour of band I.

The region of the spectrum where stimulated emission occurs depends on the properties of the object. It was observed in the region of localized excitons in the solid solution of $CdS_{1-x}Se_x$ [9], in the region of small bound excitons in the bulk crystal of CdS [10], in the region of impurity–band transitions and donor-acceptor transitions

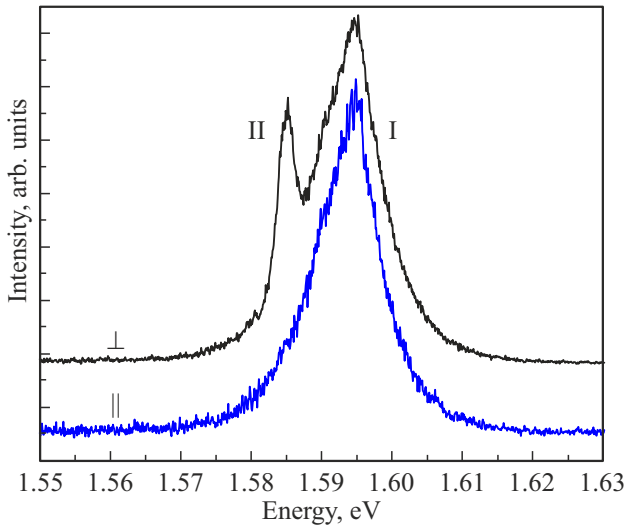

Figure 2. Spontaneous (band I) and stimulated (band II) luminescence of CdTe QW in polarizations parallel to the band of luminescence-exciting light (||) and perpendicular (⊥) to it. Excitation power density $P = 1.5$ kW/cm^2, $T = 5$ K.

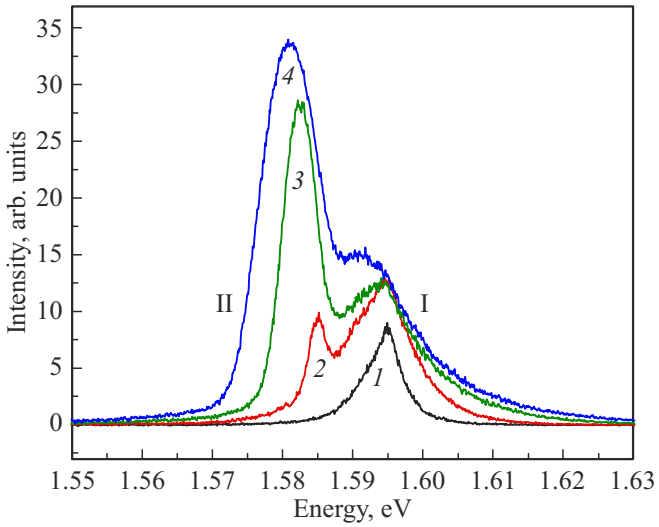

Figure 3. Spontaneous (band I) and stimulated (band II) luminescence of CdTe QW at excitation power densities of 0.2 (curve *1*), 1.5 (curve *2*), 10 (curve *3*), and 15 (curve *4*) kW/cm^2. $T = 5$ K.

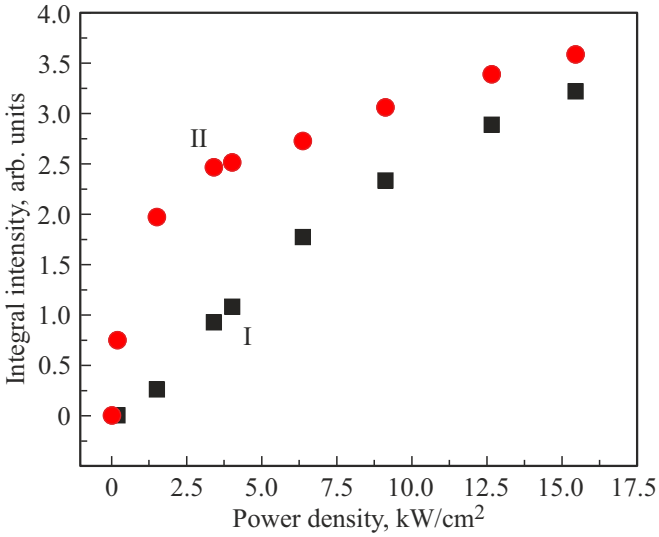

Figure 4. Dependence of integral intensities of bands I and II in the luminescence spectrum of CdTe QW on the excitation power density, $T = 5$ K.

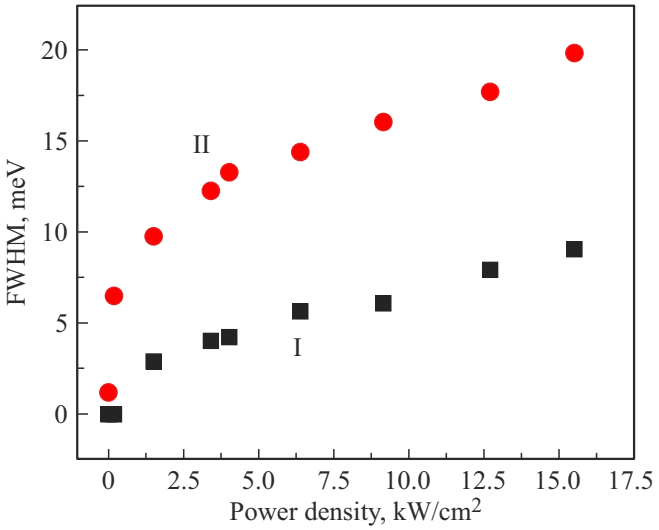

Figure 5. Dependence of FWHM of bands I and II in the luminescence spectrum of CdTe QW on the excitation power density, $T = 5$ K.

in the GaAs film of *p*-type [11]. The results obtained for our series of samples show that in a thick CdTe QW, processes associated with impurities are insignificant. The region of the greatest enhancement is the low-energy side of the electron-hole plasma emission band, into which the luminescence of free excitons is transformed as the level of optical excitation increases.

It should be noted that the threshold power density P for the excitation of stimulated luminescence in a thick CdTe QW turned out to be lower by an order of magnitude or more compared to the bulk semiconductors considered in the above-mentioned studies. A high excitation threshold for stimulated emission was also observed in *n*As|InAsSb|InAsSbP [12] and InGaAs|GaAs|AlGaAs [13] heterostructures, as well as in GaN|AlN heterostructures with ultrathin QWs [14], where fluctuations in the QW thickness appear to be an important factor. Numerical calculations of the threshold power density for bulk crystals also yield high threshold powers [15]. A low excitation threshold for stimulated emission was observed in the narrow-gap HgTe|CdHgTe heterostructure [16].

With $P = 3$ kW/cm^2, the stimulated emission in a thick CdTe QW is observed at temperatures of up to $T = 200$ K, the intensity of band II changes non-monotonically with increasing temperature reaching its maximum at $T = 40$ K

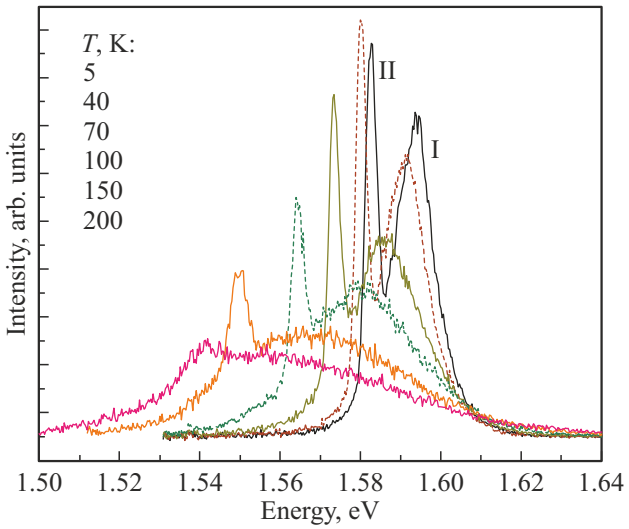

Figure 6. Spectra of spontaneous (band I) and stimulated (band II) luminescence of CdTe QW in a temperature range of 5–200 K at an excitation power density of $P = 3$ kW/cm^2.

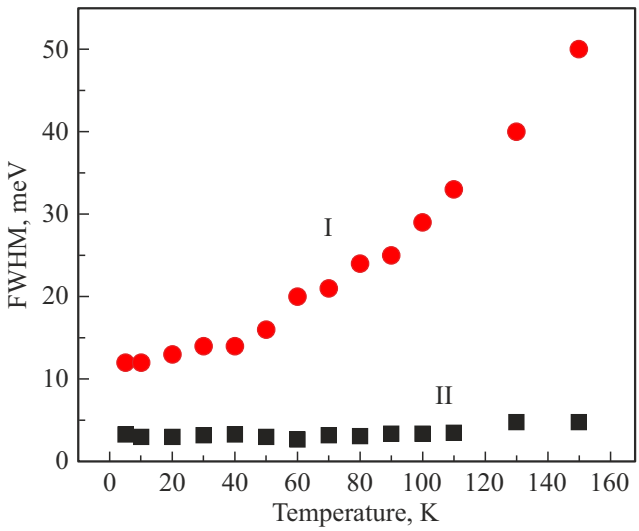

Figure 7. Temperature dependence of FWHM of bands I and II in the luminescence spectrum of CdTe QW at an excitation power density of $P = 3$ kW/cm^2.

(Figure 6). An increase in temperature from 5 to 150 K does not significantly affect the FWHM value of the stimulated emission band, and the FWHM of the spontaneous emission band in the same temperature range increases by 5 times (Figure 7).

QWs under conditions of strong excitation are characterized by the appearance of new luminescence bands corresponding to high excited states (see, in particular, [4]). In our case, such bands were not observed; apparently, in a thick CdTe QW, the transition from excitons to EHP takes place earlier than levels $e1$ and $hh1$ become saturated.

Thus, the transformation of the exciton gas into EHP in a thick CdTe QW at $T = 5$ K occurs at $P > 1\,\mathrm{kW/cm^2}$. When the luminescence is excited by a $0.04 \times 0.40\,\mathrm{cm^2}$ light strip at a power density P of about $1.5\,\mathrm{kW/cm^2}$ a narrow band of stimulated emission appears at the low energy side of the EHP band. In the experimental geometry we used, this band is observed due to scattering and reflection of the emission from the substrate. The polarization of the stimulated emission band is close to 100% and is oriented perpendicular to the excitation band. The methods and levels of doping applied to the studied samples do not qualitatively affect the luminescence characteristics of CdTe QWs.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] J. Rubio, L. Pfeiffer, M.H. Szymanska, A. Pinczuk, S. He, H.U. Baranger, P.B. Littlewood, R.W. West, B.S. Dennis. Solid State Commun. **120**, *11*, 423 (2001).
[2] F.B. Sousa, R. Perea-Causin, S. Hartmann, L. Lafetá, B. Rosa, S. Brem, C. Palekar, S. Reitzenstein, A. Hartschuh, E. Malic, L.M. Malard. Nanoscale **15**, *15*, 7154 (2023).
[3] K. Henneberger, T. Schmielau. Progress in Nonequilibrium Green's Function II (2003). P. 248.
[4] V.D. Kulakovskii, E. Lach, A. Forchel, D. Grützmacher. Phys. Rev. B **40**, *11*, 8087(R) (1989).
[5] S.G. Tikhodeev. Sov. Phys. Usp. **28**, *1*, 1 (1985).
[6] N.N. Sibeldin. Phys. Usp. **60**, *11*, 1147 (2017).
[7] S. Nihonyanagi, Y. Kanemitsu. Appl. Phys. Lett. **85**, *23*, 5721 (2004).
[8] H. Kalt, R. Nötzel, K. Ploog, H. Gießen. Solid State Commun. **83**, *4*, 285 (1992).
[9] F.A. Majumder, S. Shevel, V.G. Lyssenko, H.E. Swoboda, C. Klingshirn. Z. Phys. B Condens. Matter **66**, *4*, 409 (1987).
[10] V.G. Lysenko, V.I. Revenko, T.G. Tratas, V.B. Timofeev. JETP **31**, *1*, 163 (1975).
[11] R.I. Dzhioev, K.V. Kavokin, Yu.G. Kusraev, I.A. Merkulov. FTP **23**, *1*, 104 (1989). (in Russian).
[12] A.A. Semakova, M.S. Ruzhevich, V.V. Romanov, N.L. Bazhenov, K.D. Mynbaev, K.D. Moiseev. Semiconductors **56**, *9*, 659 (2022).
[13] V.Ya. Aleshkin, N.V. Dikareva, A.A. Dubinov, S.A. Denisov, Z.F. Krasil'nik, K.E. Kudryavtsev, S.A. Matveev, S.M. Nekorkin, V.G. Shengurov. JETP Lett. **100**, *12*, 795 (2014).
[14] E.V. Lutsenko, A.V. Nagorny, N.V. Rzheutsky, D.V. Nechaev, V.N. Zhmerik. V sb.: Kvantovaya elektronika, Materialy XIII Mezhdunar. nauch.-tekh. konf. Minsk (2021). S. 245–248. (in Russian).
[15] C. Klingshirn, H. Haug. Phys. Rep. **70**, 315 (1981).
[16] L.A. Kushkov, V.V. Utochkin, V.Ya. Aleshkin, A.A. Dubinov, K.E. Kudryavtsev, V.I. Gavrilenko, N.S. Kulikov, M.A. Fadeev, V.V. Rumyantsev, N.N. Mikhailov, S.A. Dvoretskii, A.A. Razova, S.V. Morozov. Semiconductors **54**, *10*, 1365 (2020).

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