Two-frequency stimulated emission in Hg(Cd)Te/CdHgTe heterostructure

© *M.A. Fadeev*[1], *A.A. Yantser*[1,2], *A.A. Dubinov*[1,2], *D.V. Kozlov*[1,2], *V.V. Rumyantsev*[1,2], *N.N. Mikhailov*[3], *V.I. Gavrilenko*[1,2], *S.V. Morozov*[1,2]

[1] Institute of Physics of Microstructures, Russian Academy of Sciences,
603950 Nizhny Novgorod, Russia
[2] Lobachevsky State University,
603022 Nizhny Novgorod, Russia
[3] Rzhanov Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences,
630090 Novosibirsk, Russia

E-mail: fadeev@ipmras.ru

Received August 24, 2023
Revised September 1, 2023
Accepted September 1, 2023

In this work, we studied the spectra of stimulated emission of a waveguide heterostructure with quantum wells based on HgCdTe. In the course of the studies, we used optical pumping, at wavelengths of 2 and 2.3 μm, which are mainly absorbed, in the barriers and quantum wells, respectively. It was found that in both cases optical pumping leads to stimulated emission, with a wavelength corresponding to the energy of the fundamental transition in quantum wells, it being 138 meV. With pumping absorbed in barriers, it was found that a short-wavelength emission line with an energy of 248 meV appeared on the spectra, which can be attributed to transitions involving deep donor levels. At liquid nitrogen temperature, increasing the pumping intensity leads to the appearance of a narrow peak in the short-wave line and, by selecting the pumping parameters, two-frequency generation at 5 and 7 μm wavelengths can be achieved.

Keywords: narrow-gap semiconductors, HgCdTe, deep donors, stimulated emission.

DOI: 10.61011/SC.2023.06.57159.31k

1. Introduction

Solid solutions of HgCdTe are traditionally used to create photodetectors of the mid-infrared (IR) range due to the possibility of continuous variation of the band gap width E_g in this material from 1.6 eV to zero when the composition of the solution changes (see, for example, [1]).

Recently, researchers have been very interested in heterostructures with quantum wells (QW) $\mathrm{Cd}_y\mathrm{Hg}_{1-y}\mathrm{Te}$/$\mathrm{Hg}_{1-x}\mathrm{Cd}_x\mathrm{Te}$/$\mathrm{Cd}_y\mathrm{Hg}_{1-y}\mathrm{Te}$, which have a number of unique properties. For example, if the QW width is greater than the critical one ($d_{\text{crit}} \sim 6.3$ nm), then an inverted band structure occurs: the bottom of the conduction band is formed by hole-type states, and the ceiling of the valence band, respectively, is formed by electronic-type states [2]. If we consider narrower pits, then their zone structure will be normal, and a hyperbolic law of dispersion is formed near the zero quasi-pulse, which makes QW $\mathrm{Hg}_{1-x}\mathrm{Cd}_x\mathrm{Te}$/$\mathrm{Cd}_y\mathrm{Hg}_{1-y}\mathrm{Te}$ are attractive for lasers at interband transitions. In this regard, studies of the generation of radiation in heterostructures with HgCdTe QW and CdHgTe barriers (Cd ~ 0.7) were conducted. Stimulated radiation (SR) in the wavelength range from 2.5 μm (at room temperature) to 31 μm was obtained by optical pumping of waveguide structures (see, for example, [3–6]).

To date, the greatest progress has been made as semiconductor sources The radiation of the mid-IR range was achieved by quantum cascade lasers (QCL) and interband cascade lasers (ICL). In the range from 5 to 20 μm QCL demonstrate record performance in terms of output power and efficiency [7–9]. However, due to the technological difficulties of the growth of QCL, their mass use is impossible. If we consider ICL, then they are a hybrid of QCL and classical diode lasers. As the sources closest in their device to QCL, ICL have comparable operating characteristics in the short-wave region of the mid-IR range [10,11] and the same disadvantages as QCL, namely the relative complexity of production, high cost and low possibility of restructuring.

The growth of a large number of QW is not required for laser diodes based on lead chalcogenides–tin (PbSnSe(Te)) unlike QCL. Like in HgCdTe solid solutions, the band gap of this material can be changed by varying the composition of the solid solution, and Auger recombination, which serves as the main channel of non-radiative recombination in interband IR sources, is suppressed by virtue of the quasi-relativistic law of electron and hole dispersion, which made it possible to obtain radiation using lasers of this type in the entire wavelength range from 3 to 46 μm [12,13]. Lasers based on lead chalcogenides have become widespread as a source of radiation for high-resolution spectroscopy, however, due to the high residual concentration of electrically active defects and difficulties in manufacturing heterojunctions, this type of laser is able to work only at cryogenic temperatures.

HgCdTe heterostructures can serve as the basis for a new type of mid-IR semiconductor lasers due to the suppression of auger recombination similar to PbSnSe(Te) lasers, the high optical quality of heterostructures and the relative ease of production compared to cascade lasers due to the smaller number of QW in the active region.

In this paper, radiation from the heterostructure $Hg_{1-x}Cd_xTe/Cd_yHg_{1-y}Te$ with waveguide layers of variable composition („varizonal“ layers) in the region $7-10\,\mu$m. The use of such layers reduces the heating of the electronic subsystem that occurs during the capture of carriers in QW, i. e. there is a decrease in the energy that must be expended to the electron for thermalization in QW. This is important both for injection lasers and when using optical pumping, which is absorbed in barrier layers.

2. Experiment procedure

A Bruker Vertex 80v IR spectrometer was used to study the photoluminescence and stimulated radiation spectra. The test sample was fixed on the cold finger of a closed-loop helium cryostat and placed in one of the foci of an elliptical mirror. The second focus was coupled with the optical scheme of the spectrometer. For optical excitation of the structure, a pulsed parametric light generator (PLG) „Solar“ with pulse length ~ 10 ns was used. Its feature is the simultaneous generation of radiation at two wavelengths: 2 and $2.3\,\mu$m. One of the beams can be blocked or both wavelengths can be transmitted using the PLG output flap. Attenuation of radiation was performed using a set of optical filters. At the entrance to the spectrometer there was an InAs filter with a transmission range of $400-2700\,\mathrm{cm}^{-1}$, which absorbed the pump radiation.

The studied structure was grown using molecular beam epitaxy method on GaAs(013) substrates at the Institute of Semiconductor Physics of SB RAS (Novosibirsk) [14]. The growth diagram of the test sample is shown in Figure 1. It is a heterostructure with five 4 nm QW $Cd_{0.5}Hg_{0.5}Te$/%break $Hg_{0.05}Cd_{0.95}Te/Cd_{0.5}Hg_{0.5}Te$ surrounded by wider-band HgCdTe layers necessary for waveguide implementation. Radiation localization occurs due to a jump in the refractive index between the waveguide layers and the CdTe buffer on the one hand and air — on the other. The structure implements a dielectric waveguide for radiation at a wavelength of $\sim 9\,\mu$m, however, the localization of the TE mode also occurs at smaller wavelengths. Figure 1 shows the calculation of the distribution of the electric field in the structure at wavelengths 5 and $7.5\,\mu$m.

The differences between the studied structure and typical waveguide heterostructures based on HgCdTe [3] are the higher temperature of the substrate during growth (7100 c.u. compared to the typical temperature of 6500 c.u.) and the variable composition of cadmium in the waveguide layers. In addition, in this structure, barriers separating QW contain only 50% Cd. On the one hand, a decrease in the cadmium content in the barriers leads to a decrease in the threshold energy of auger recombination [15] — according to calculations it is only 35 MeV in the studied structure. At the same time, the use of narrow-band barriers is preferable when using current pumping, since it reduces the energy of carriers captured in QW. The width of the band gap in the studied structure in the barriers $Cd_{0.5}Hg_{0.5}Te$ corresponds to the energy of pumping quanta with a wavelength of $2\,\mu$m, therefore, both the experimental scheme when nonequilibrium carriers are excited directly in the QW, and the case when nonequilibrium carriers are created in barriers and only then captured in QW are possible due to the possibility of changing the wavelength of the radiation of the PLG.

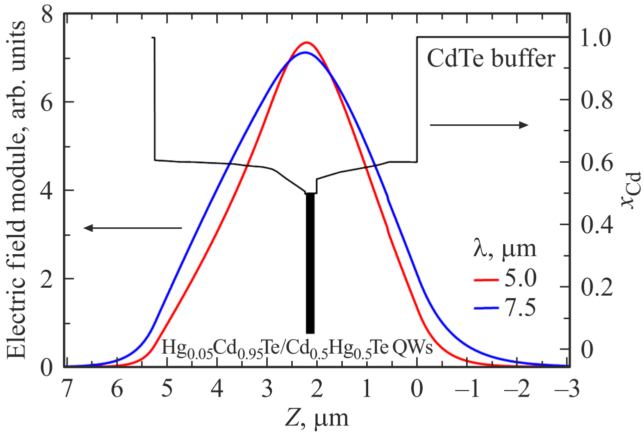

Figure 1. Distribution of cadmium content and electric field TE_0 modes in the structure. The boundary of the CdTe buffer and the main part of the structure is taken as the origin point.

3. Results and discussion

An increase in the pumping power above the threshold value leads to the generation of a SR with a wavelength of $\sim 9\,\mu$m at a temperature of 20 K, regardless of the used wavelength of the PLG, which is characterized by a superlinear signal growth and narrowing of the spectrum. When radiation with a wavelength of $2\,\mu$m is completely cut off, the quantum energy of which is greater than the width of the band gap in the barriers, an increase in pumping power above the threshold is accompanied by a monotonous signal growth, and the spectra are single lines. The radiation spectra become more complex if the pump with a wavelength of $2\,\mu$m is not cut off (Figure 2). We observe only SR at a wavelength of $\sim 9\,\mu$m (line A) with a slight excess of the threshold power, however, a wide band of radiation occurs (band B) with an increase of pumping in the short-wavelength region of the spectrum ($1300-2000\,\mathrm{cm}^{-1}$). The band B cannot be explained by radiative transitions involving excited states in QW, since an increase in the intensity of the band with an increase in pumping power is accompanied by a „quenching of the“ line of stimulated radiation of the interband transition of the ground state in QW. A further increase in pumping leads to the destruction of SR and only PL is observed on the spectrum.

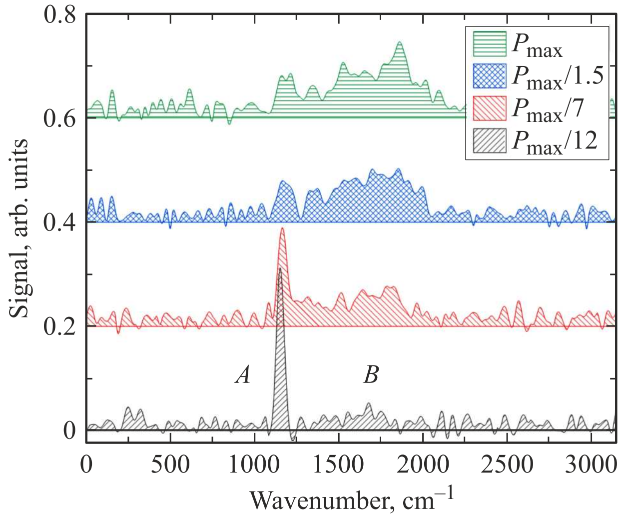

Figure 2. Radiation spectra of the studied structure under pulsed optical pumping with a wavelength of $2\,\mu$m at a temperature of 20 K at different power. $P_{\max}$ corresponds to a power density of 60 kW/cm^2. The letters A and B denote, respectively, the SR line at the interband junctions and a wide band of PL lying higher in energy.

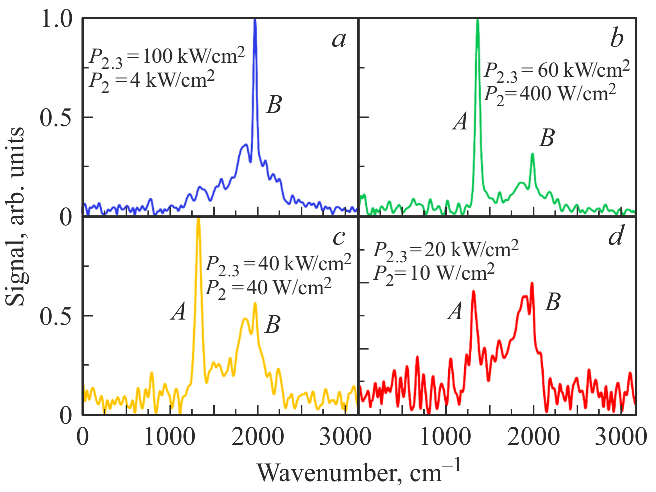

Figure 3. Radiation spectra of the studied structure at a temperature of 80 K. The panels $a-d$ correspond to different pump power ratios at wavelengths 2 and 2.3 μm, which are designated as P_2 and $P_{2.3}$, respectively. The Latin letters A and B denote the position of the lines PL/SR.

With increasing temperature, the radiation spectrum shifts to the short-wave region, and the pumping power at which the band B is observed decreases. At a temperature of 80 the K band B is present on all spectra. As the pumping intensity increases at a wavelength of $2\,\mu$m, the amplitude of the band B increases, and a narrow line of SR is observed against the background of a wide spectrum of photoluminescence. At high pumping levels, the radiation in the long-wavelength region of the spectrum completely disappears, and we observe only SR in the vicinity of the band B. The radiation spectra of the structure under various conditions are shown in Figure3.

It is interesting that by exciting the structure simultaneously at the wavelengths of 2.3 and $2\,\mu$m and selecting the ratio between their amplitudes, it is possible to control the ratio of the intensities of the bands A and B. This makes it possible to ensure that stimulated radiation occurs at the wavelength ~ 5, $\sim 7.5\,\mu$m or at both wavelengths simultaneously. At temperatures > 80 K, only a wide line PL is observed, the position of which corresponds to the band B.

The attenuation of SR with an increase in the intensity of optical pumping was observed earlier in heterostructures based on HgCdTe and was associated with the heating of the electron gas [16], however, a narrow line lying above the energy of the main transitions is observed in such experiments for the first time. Since the high-frequency band appears only when using short-wave pumping, which is more efficiently absorbed in barriers, it is natural to associate it with transitions in barrier layers. The energy of the observed transitions at $T = 20$ K is in the range $0.29E_g < \hbar\omega < 0.45E_g$, where E_g — the width of the band gap of barriers $Hg_{0.5}Cd_{0.5}Te$ ($E_g = 564.5$ MeV) and can be explained by the participation of deep impurity centers in recombination. Deep centers with energies $E_v + 0.4E_g$, $E_v + 0.75E_g$, where E_v is the energy of the ceiling of the valence zones were found practically in all studies of CMT [17–20] in addition to mercury vacancies which are small acceptors. The nature of these centers, which are called, respectively, D_1 and D_2, is not clearly established, however, the paper [19] showed that the concentration of centers D_1 is proportional to the concentration of holes, which it made it possible to link this center with vacancies of cations. Thus, it can be assumed that the observed PL band occurs as a result of electron capture at deep centers D_1 and subsequent radiative recombination with holes from shallow acceptor levels. In this case, the attenuation of the line A with an increase in pumping is due to the fact that a large proportion of electron-hole pairs excited in the barriers recombine through impurity centers and do not contribute to radiation from QW.

Earlier it was reported about the observation of similar transitions during optical measurements [20,21]. PL lines associated with spontaneous transitions between the deep donor level lying almost in the center of the band gap and the valence band were recorded at 94 K in [20]. However, none of the papers reported an observation SR caused by transitions involving deep impurities.

4. Conclusion

The radiation spectra of a waveguide heterostructure with QW based on CdHgTe with a variable composition of solid solution in waveguide layers are studied in this paper. It is shown that SR occurs in the structure both when using a pump absorbed in QW, and in the case when the pump is absorbed in barriers. This result can be useful when creating current-pumped sources and for improving the characteristics of SR with optical pumping.

In the course of the study, in addition to stimulated radiation associated with interband radiative transitions from the ground state to QW, radiation in the short-wavelength region of the spectrum was detected. By selecting the parameters of the experiment, we were able „to switch“ the wavelength of SR from 5 to 7.5 μm and simultaneously observe two lines. This effect can be useful for changing the wavelength of HgCdTe-based lasers faster than using temperature.

Funding

This study was supported by the Russian Science Foundation (grant No. 22-12-00298).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] A. Rogalski. Rep. Progr. Phys., **68** (10), 2267 (2005).
[2] B.A. Bernevig, T.L. Hughes, S.C. Zhang. Science, **314** (5806), 1757 (2006).
[3] S.V. Morozov, V.V. Rumyantsev, M.S. Zholudev, A.A. Dubinov, V.Y. Aleshkin, V.V. Utochkin, M.A. Fadeev, K.E. Kudryavtsev, N.N. Mikhailov, S.A. Dvoretskii, V.I. Gavrilenko, F. Teppe. ACS Photonics, **8** (12), 3526 (2021).
[4] S.V. Morozov, V.V. Rumyantsev, M.A. Fadeev, M.S. Zholudev, K.E. Kudryavtsev, A.V. Antonov, A.M. Kadykov, A.A. Dubinov, N.N. Mikhailov, S.A. Dvoretsky, V.I. Gavrilenko. Appl. Phys. Lett., **111** (19), 192101 (2017).
[5] K.E. Kudryavtsev, V.V. Rumyantsev, V.Y. Aleshkin, A.A. Dubinov, V.V. Utochkin, M.A. Fadeev, N.N. Mikhailov, G. Alymov, D. Svintsov, V.I. Gavrilenko, S.V. Morozov. Appl. Phys. Lett., **117** (8), 083103 (2020).
[6] M.A. Fadeev, A.O. Troshkin, A.A. Dubinov, V.V. Utochkin, A.A. Razova, V.V. Rumyantsev, V.Y. Aleshkin, V.I. Gavrilenko, N.N. Mikhailov, S.A. Dvoretsky, S.V. Morozov. Opt. Eng., **60** (08), 1 (2020).
[7] A.M. Kadykov, F. Teppe, C. Consejo, L. Viti, M.S. Vitiello, S.S. Krishtopenko, S. Ruffenach, S.V. Morozov, M. Marcinkiewicz, W. Desrat, N. Dyakonova, W. Knap, V.I. Gavrilenko, N.N. Mikhailov, S.A. Dvoretsky. Appl. Phys. Lett., **107** (15), 152101 (2015).
[8] Y. Yao, A.J. Hoffman, C.F. Gmachl. Nat. Photonics, **6** (7), 432 (2012).
[9] Y. Bai, N. Bandyopadhyay, S. Tsao, S. Slivken, M. Razeghi. Appl. Phys. Lett., **98** (18), 181102 (2011).
[10] I. Vurgaftman, W.W. Bewley, C.L. Canedy, C.S. Kim, M. Kim, C.D. Merritt, J. Abell, J.R. Lindle, J.R. Meyer. Nat. Commun., **2** (1), 585 (2011).
[11] R.Q. Yang, J.L. Bradshaw, J.D. Bruno, J.T. Pham, D.E. Wortman. IEEE J. Quant. Electron., **37** (2), 282 (2001).
[12] J.O. Dimmock, I. Melngailis, A.J. Strauss. Phys. Rev. Lett., **16** (26), 1193 (1966).
[13] L. Kurbatov, A. Britov, S. Karavaev, S. Sivachenko, S. Maksimovskii, I. Ovchinnikov, M. Rzaev, P. Starik. Sov. J. Exp. Theor. Phys. Lett., **37**, 422 (1983).
[14] N.N. Mikhailov, R.N. Smirnov, S.A. Dvoretsky, Y.G. Sidorov, V.A. Shvets, E.V. Spesivtsev, S.V. Rykhlitski. Int. J. Nanotechnol., **3** (1), 120 (2006).
[15] M.A. Fadeev, A.A. Dubinov, V.Ya. Aleshkin, V.V. Rumyantsev, V.V. Utochkin, V.I. Gavrilenko, F. Teppe, H.-V.H.-V. Hubers, N.N. Mikhailov, S.A. Dvoretsky, F. Tepe, H.-V.H.-V. Hubers, N.N. Mikhailov, S.A. Dvoretsky, F. Teppe, H.-V.H.-V. Hubers, N.N. Mikhailov, S.A. Dvoretsky, S.V. Morozov. Kvant. elektron., **49** (6), 556 (2019). (in Russian).
[16] K.E. Kudryavtsev, V.V. Rumyantsev, V.V. Utochkin, M.A. Fadeev, V.Y. Aleshkin, A.A. Dubinov, M.S. Zholudev, N.N. Mikhailov, S.A. Dvoretskii, V.G. Remesnik, F. Teppe, V.I. Gavrilenko, S.V. Morozov. J. Appl. Phys., **130** (21), (2021).
[17] C.W. Myles, P.F. Williams, R.A. Chapman, E.G. Bylander. J. Appl. Phys., **57** (12), 5279 (1985).
[18] J. Shao, L. Chen, W. Lu, X. Lü, L. Zhu, S. Guo, L. He, J. Chu. Appl. Phys. Lett., **96** (12), 1 (2010).
[19] K. Lischka. Phys. Status Solidi, **133** (1), 17 (1986).
[20] D.L. Polla, R.L. Aggarwal. Appl. Phys. Lett., **44** (8), 775 (1984).
[21] S.V. Morozov, V.V. Rumyantsev, A.V. Antonov, A.M. Kadykov, K.V. Maremyanin, K.E. Kudryavtsev, N.N. Mikhailov, S.A. Dvoretskii, V.I. Gavrilenko. Appl. Phys. Lett., **105** (2), 22102 (2014).

Translated by A.Akhtyamov