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ELECTRONIC AND OPTICAL PROPERTIES OF SEMICONDUCTORS

Stimulated and Spontaneous Emission of $Cd_xHg_{1-x}Te$ Structures in the Range 3.2–3.7 μm at 77 K

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Abstract—Stimulated emission of radiation from $Cd_xHg_{1-x}Te$ samples pumped by a Nd:YAG laser at temperature $T \approx 77$ K is obtained. Both spontaneous and stimulated emission is observed for the wavelengths λ in the range 3300–3600 nm. Experimental emission spectra are presented. The special features of the spectra and the possible applications of the structures are discussed. © *2004 MAIK "Nauka/Interperiodica".*

1. INTRODUCTION

There is currently great interest worldwide in the fabrication of active emitting devices (lasers) and photodetectors that operate in the middle and far infrared (IR) ranges (λ ≈ 3–20 μm). Mastering this wavelength range is of interest, particularly for

(1) communication purposes, since this range includes the Earth's atmospheric transparency windows (3.5–4 μm, 4.5–5 μm, 8–14 μm, and 16–23 μm);

(2) spectroscopy and environment monitoring, since this range includes the frequencies of vibrational–rotational transitions of many molecules.

Among the few active devices that can really function within this region are semiconductor laser diodes and quantum cascade lasers. Given the principle on which they operate, both devices incorporate highly inhomogeneous structures. These are *p–n* junctions in laser diodes and quantum superlattices with a fairly large number (usually from one to several tens) of quantum-confinement layers in quantum cascade lasers. This circumstance complicates the production of the devices and increases their cost. As is well known, the characteristic frequencies of radiative band-to-band transitions in films of narrow-gap semiconductors, for example, $Cd_xHg_{1-x}Te$, can fall within the operation range of quantum cascade lasers. Moreover, it is now common practice to synthesize CdHgTe samples with a stoichiometry such that the characteristic frequencies of radiative band-to-band transitions (defined by the band gap E_g) come right in the middle IR region. CdHgTe may be considered as a promising material as the source of stimulated radiation since it is a direct-gap semiconductor (direct radiative band-to-band transitions are allowed). The carrier lifetime may be rather long there (if the band gap is quite wide).

From this point of view, if CdHgTe-based lasers were designed for a fairly broad range of stoichiometric compositions, they could compete with cascade lasers. A single CdHgTe film is much easier to handle than the quantum superlattice of a cascade laser. A CdHgTe film itself represents a waveguide in view of the high permittivity of the CdHgTe material (15–20), which can be conducive to the formation of cavity modes due to the total internal reflection from the film boundaries. Furthermore, in contrast to the structures of quantum cascade lasers, there is no need to grow quantum-confinement layers with the use of high-precision technology here, since the typical thickness of CdHgTe films usually ranges from several to several tens of micrometers. The technology of high-quality epitaxial CdHgTe films has now been developed in detail due to the production of IR photodetectors based on them. The main methods currently used for growing CdHgTe films are liquid-phase epitaxy, molecular-beam epitaxy, and metal–organic chemical vapor deposition (MOCVD). As experimental samples, we used structures grown at the Institute of High-Purity Substances, Russian Academy of Sciences, where an MOCVD method for growing epitaxial CdHgTe layers with various stoichiometric compositions is being developed [1, 2].

Until now, there are only a few studies dedicated to CdHgTe-based lasers, and most of the main questions remain to be clarified (for example, how far is it possible to move towards longer wavelengths and higher temperatures). For the first time, the spontaneous and coherent emission of radiation from a $Cd_xHg_{1-x}Te$ crystal optically pumped by a GaAs diode laser was observed in [3] (see also [4, 5]). Stimulated radiation was observed in the range λ = 3.8–4.1 μm at temperature $T \approx 12$ K, and spontaneous radiation was detected up to 15 μm.

Hartman [6] reported on optically pumped lasers operating in the range 1.25–2.97 μm at the liquid-nitrogen temperature. Continuous-wave lasing at 2.79 μm took place at 12 K. Stimulated emission was observed for CdHgTe films with $x = 0.5$ at 2.13 μm [7]. In this case, the lasing threshold was ~10 kW/cm^2 at the liquid-nitrogen temperature.

Mahavadi *et al*. [8] reported stimulated emission from CdHgTe films with $x = 0.46$ grown on a semi-insulating CdTe substrate and subjected to Nd:YAG-laser pumping: generation at 2.42 μm had a power of above 2.8 kW/cm^2 at 10 K.

As can be seen from the data presented above, the longest wavelength of stimulated radiation at the liquid-nitrogen temperature was 2.97 μm. This circumstance is conventionally associated with the fact that, at narrower band gaps (for comparatively small x, $x \approx 0.2$ and smaller), the relative role of nonradiative transitions attributed to Auger recombination increases (see [9]), although apparently the lasing frequency may be limited by nonradiative recombination via impurities. Evidently, with higher-quality and purer samples, one can hope to obtain a lasing effect for longer wavelengths as well. However, an important unsolved problem is the optimization of the thickness of the sample. Our experimental data suggest that, in the CdHgTe films under study, the emission of electromagnetic radiation at lower frequencies can be obtained at considerably higher temperatures than before.

2. RESULTS AND DISCUSSION

In this study, we measured the characteristics of electromagnetic radiation obtained from epitaxial $Cd_xHg_{1-x}Te$ layers pumped by a Nd:YAG laser (λ = 1.064 μm) at the liquid-nitrogen temperature. We used the $Cd_xHg_{1-x}Te$ samples with thicknesses from several micrometers to several tens of micrometers on semi-insulating GaAs substrates with a high-resistivity CdTe buffer layer. The samples placed at a copper heat sink were photoexcited on the side of the epitaxial layer. A metal spherical mirror focused the radiation from the edge of the epitaxial layer onto the entrance slit of a conventional monochromator. The output signal was detected by a photodetector kept at the liquid-nitrogen temperature. As a photodetector, we also used $Cd_xHg_{1-x}Te$ samples with an appropriate stoichiometric composition. When required, the scattered pump radiation was suppressed by Ge filters placed in front of the photodetector. The signal from the photodetector was applied to an oscilloscope synchronized with the Nd:YAG laser pulse.

Figure 1 shows one of the emission spectra (in the form of the photodetector signal versus the wavelength) obtained for the $Cd_xHg_{1-x}Te$ (MST 638/1) sample with $x \approx 0.376$ and thickness $h \approx 8.9$ μm at 77 K; the p-type sample was grown on a (111)-oriented GaAs substrate. The sample was shaped like an equilateral triangle with sides of ~5 mm. For the optical pump intensity $P <$ 4 kW/cm^2, the spectrum is shaped like a wide low pedestal, which is shown by the dashed line in Fig. 1. At $P \gtrsim 4$ kW/cm^2, a narrow line appears against the pedestal background. It is reasonable to associate the pedestal with spontaneous radiation and the narrow line, with stimulated radiation (superluminescence). Thus, we observed that the emission spectrum narrowed when the photoexcitation exceeded a certain threshold, which in our case was $P \approx 4$ kW/cm^2.

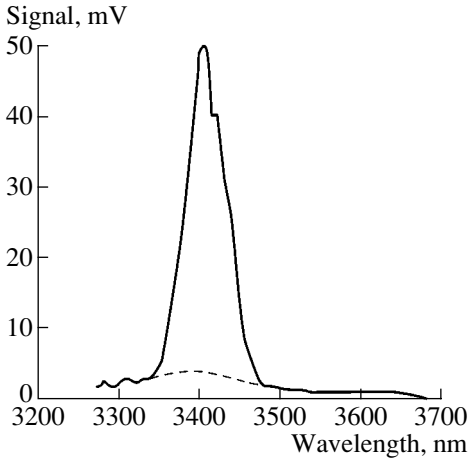

Fig. 1. Emission spectrum for the $Cd_xHg_{1-x}Te$ sample (MST 638/1, $x \approx 0.376$) at $T \approx 77$ K. The photodetector is the MST 641/1 sample, $x \approx 0.272$. Dashed and solid lines show the spectra at the photoexcitation below ($P < 4$ kW/cm^2) and above ($P \geq 4$ kW/cm^2) the threshold, respectively.

This value best agrees with the result reported in [8], where the stimulated radiation line corresponded to $\lambda \approx$ 2420 nm and had a width that nearly coincides with that of the line shown in Fig. 1. It is important to note that the measurements in [8] were carried out at $T = 12$ K, while our experiments were performed at $T \geq 77$ K. The fact that a six- or sevenfold difference in temperature has almost no effect on the line width ($\Delta\lambda \approx$ 50–60 nm) confirms the stimulated nature of this radiation.

In our experiments, various surface regions were illuminated, rather than the entire surface of the sample at once. Therefore, we actually measured the superluminescence spectra from different illuminated areas of the surface. The reliable observation of simulated radiation (even in the absence of a cavity) is an indication of the high gain in the system. This fact is consistent with the theoretical estimate [10] that indicates that the gain α can be as high as ~10^3 cm^{-1}.

Figure 2 shows the emission spectra of various samples each fabricated from a $Cd_xHg_{1-x}Te$ film with $x \approx$ 0.376, as well as the spectral lines obtained upon the illumination of different parts of the same sample. These spectral lines are seen to differ in their peak position λ_{max}, as well as in their width and shape. The values of λ_{max} related to different areas differ by ~3.6%, which suggests that the $Cd_xHg_{1-x}Te$ film under study is inhomogeneous: the corresponding fluctuations of its composition (nonstoichiometry) should vary from 3 to 4%.

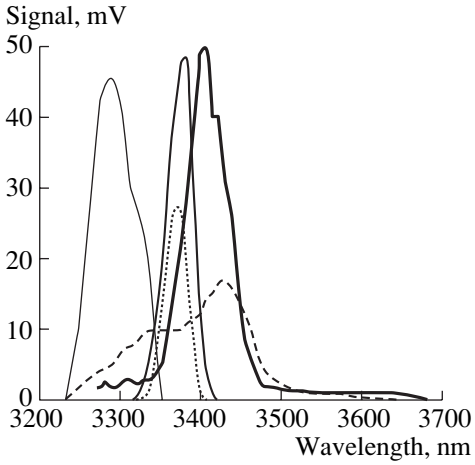

Fig. 2. Emission spectra of different samples (MST 638/1, $x \approx 0.376$) fabricated from the same $Cd_xHg_{1-x}Te$ film.

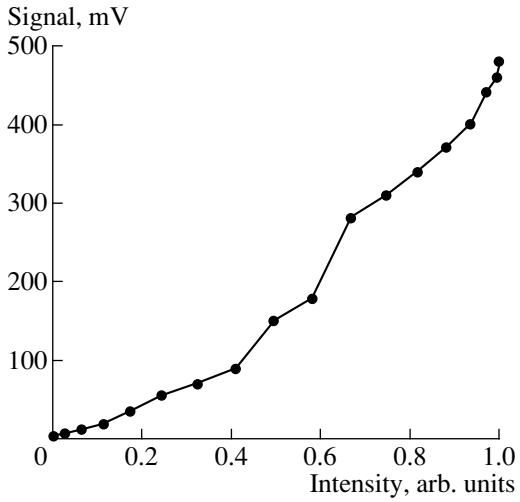

Fig. 3. Intensity of radiation at $T = 77$ K vs. the pump intensity for the $Cd_xHg_{1-x}Te$ sample (MST 638/1, $x \approx 0.376$).

Another indication of the spatial inhomogeneity of the film is the observed "improper" shape of the line (see, e.g., the dashed spectrum in Fig. 2). The spread in the conditions of photoexcitation (illumination of neighboring dissimilar areas) results in the inhomogeneous broadening of the superluminescence line.

Let us consider a simple estimation of the temperature dependence of the spontaneous spectrum line width for a spatially homogeneous sample in the case of an abrupt absorption edge. It is known (see, e.g., [11]), that the photoluminescence (spontaneous radiation) intensity can be expressed as

$$I_{\mathrm{PL}}(\hbar\omega) \propto \begin{cases} (\hbar\omega - E_g)^{1/2} \exp\left(-\dfrac{\hbar\omega - E_g}{k_B}\right) \\ \text{at } \hbar\omega > E_g, \\ 0 \text{ at } \hbar\omega < E_g. \end{cases}$$

We can use this expression to estimate the width of the spontaneous-emission line width as

$$\Delta(\hbar\omega) \approx (2\text{–}3)k_BT. \quad (1)$$

At the liquid-nitrogen temperature of our experiment, this formula yields a line width (in temperature terms) approximately equal to 160–240 K.

Evidently, formula (1) gives the minimal value of the spontaneous line width, since the possible heating of the sample is disregarded. In our experiment (and in [8]), the typical intensities were fairly high. Recall that the lasing threshold was observed at the pumping intensity $P \approx 4$ kW/cm^2. Another possible cause of the spontaneous line broadening is the spatial inhomogeneity of the $Cd_xHg_{1-x}Te$ solid solution (and, hence, the spatial inhomogeneity of the band gap).

In terms of temperature, the half-width (the width at the peak's half-height, $0.5I_{\max}$) of the spectral line and the pedestal in Fig. 1 is ~86 and ~400 K, respectively. These estimates indicate that the line is two to three times narrower than the value predicted for an "ideal" photoluminescence line and, therefore, cannot represent spontaneous radiation. Furthermore, the spectral width of the pedestal is larger than the "ideal" estimation, so that the pedestal can be attributed to spontaneous radiation. Note once again that, in all the studies available (see, e.g., [3, 6–8]), the spectrum appears just like a narrow line of stimulated radiation against the background of a broad pedestal governed by spontaneous radiation.

Figure 3 shows the emission intensity for the $Cd_xHg_{1-x}Te$ sample (MST 638/1, $x \approx 0.376$) as measured at $T = 77$ K by the detector with the band gap corresponding to the wavelength ~6 μm versus the optical pump intensity. It can be seen that the dependence is nonlinear but has a fairly smooth appearance. Thus, in order to find a clear manifestation of the lasing threshold, one should analyze the corresponding spectral dependences.

3. CONCLUSIONS

The width of the superluminescence spectrum shown in Fig. 1 almost coincides with the value reported in study [8]. However, in contrast to our results, the emission in [8] was obtained at a lower temperature ($T = 12$ K) and corresponded to a shorter wavelength ($\lambda_{\max} \approx 2420$ nm). Melngailis and Strauss [3] observed lines of stimulated emission in the region of $\lambda \approx 4100$ nm but also at $T = 12$ K. Thus, in this paper, we apparently report for the first time the observation of stimulated emission from the $Cd_xHg_{1-x}Te$ structures at 77 K in the wavelength range $\lambda \approx 3250$–3450 nm. The observation of stimulated emission at 77 K makes it possible to state that these structures are promising in the context of various applications. Note especially that the observed variations of the superluminescence frequency for different regions of the same sample can be

used to detect stoichiometric nonuniformities. This possibility is important for improving the technology of $Cd_xHg_{1-x}Te$ structures. In turn, the better quality of these structures will lead to a narrower spectrum of stimulated radiation.

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REFERENCES

1. A. N. Moiseev, A. P. Kotkov, V. V. Dorofeev, and N. D. Grishnova, Neorg. Mater. **40** (1), 1 (2004).
2. K. O. Boltar', N. I. Yakovleva, V. P. Golovin, *et al.*, Prikl. Fiz., No. 5, 95 (2003).
3. I. Melngailis and A. J. Strauss, Appl. Phys. Lett. **8** (7), 179 (1966).
4. R. Dornhaus and G. Nimtz, Springer Tracts Mod. Phys. **78**, 1 (1978).
5. N. S. Baryshev, *Properties and Applications of Narrow-Gap Semiconductors* (UNIPRESS, Kazan, 2000) [in Russian].
6. T. C. Hartman, J. Electron. Mater. **8** (2), 191 (1979).
7. V. I. Ivanov-Omskiĭ, K. E. Mironov, R. B. Rustamov, and V. A. Smirnov, Pis'ma Zh. Tekh. Fiz. **10**, 1021 (1984) [Sov. Tech. Phys. Lett. **10**, 428 (1984)].
8. K. K. Mahavadi, J. Bleuse, X. Chu, and J. P. Faurie, Appl. Phys. Lett. **55**, 1285 (1989).
9. G. Nimtz, Phys. Rep. **63**, 265 (1980).
10. G. M. Genkin, A. V. Okomel'kov, and I. D. Tokman, Fiz. Tekh. Poluprovodn. (Leningrad) **22**, 2151 (1988) [Sov. Phys. Semicond. **22**, 1358 (1988)].
11. P. Yu and M. Cardona, *Fundamentals of Semiconductors* (Springer, Berlin, 1996; Fizmatlit, Moscow, 2002), p. 312.

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