# Infrared photoreflectance of $Cd_{0.3}Hg_{0.7}Te$ epitaxial films

© M.S. Ruzhevich[1], K.D. Mynbaev[1,2], D.D. Firsov[3], I.V. Chumanov[3], O.S. Komkov[3], V.S. Varavin[4], M.V. Yakushev[4]

[1] ITMO University,
197101 St. Petersburg, Russia
[2] Ioffe Institute,
194021 St. Petersburg, Russia
[3] St. Petersburg State Electrotechnical University „LETI",
197376 St. Petersburg, Russia
[4] Rzhanov Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences,
630090 Novosibirsk, Russia

E-mail: max.ruzhevich@niuitmo.ru

*Received May 2, 2024*
*Revised September 5, 2024*
*Accepted October 30, 2024*

The results of a study of photoreflectance of $Cd_{0.3}Hg_{0.7}Te$ films grown by molecular beam epitaxy are presented. The results of photoreflectance measurements were compared with data from studies of photoluminescence and optical transmittance of films after growth and after various types of annealing. For films after annealing, an improvement in quality was found, expressed in a decrease in the half-width of the photoreflectance peak.

**Keywords:** solid solutions, CdHgTe, photoreflectance.

DOI: 10.61011/SC.2024.10.59941.6488A

## 1. Introduction

Solid solutions of mercury cadmium telluride ($Cd_xHg_{1-x}Te$, MCT) with composition $x \approx 0.3$ are used for fabrication of infrared (IR) photodetectors, operating in medium-wave IR band (wavelength $\lambda = 3-5\,\mu$m) [1]. These photodetectors are widely used in industry, ecological monitoring systems and medicine. For the growth of MCT epitaxial films, currently molecular-beam epitaxy (MBE) is mainly used.

The prevailing method for studying the electronic structure and structural perfection of the MCT epitaxial films is the photoluminescence (PL). Besides PL, where optical signal is gathered from large volume of sample, as the method which is more sensitive to the surface state, IR photoreflectance (PR) can be used. This method determines the energy of the direct interband transition, and Fabry-Perot oscillation can be analyzed, as it was shown, for example for arsenic-doped MCT with composition $x \approx 0.22$ [2], and for undoped MCT with $x \approx 0.23$ and $x \approx 0.26$ [3]. Based on the analysis of Franz-Keldysh oscillations in IR PR spectra, the values of built-in electric fields were evaluated in graded-gap structures with $x \approx 0.2$ [4]. In the present paper, using IR PR we studied the effect of annealing on structural perfection of the epitaxial films $Cd_xHg_{1-x}Te$ with $x \approx 0.3$, both undoped, and arsenic-doped.

## 2. Structures and experimental procedure

Structures were grown by MBE method on (013)Si substrate with ZnTe and CdTe buffer layers at Rzhanov Institute of Semiconductor Physics of the Siberian Branch of Russian Academy of Sciences. Thickness $d$ and composition $x$ of MCT were monitored during the growth by the method of optical ellipsometry *in situ* [5]. Growth of structures was finalized with fabrication of protective graded-gap layer $\sim 0.4\,\mu$m thick with $x \approx 0.5$ on the surface; to exclude the effect of this layer, it was chemically etched off, so films with $d \approx 6\,\mu$m and permanent composition $x = 0.29$ were studied.

To study the effect of annealing, the annealing aimed at minimization of concentration of mercury vacancies $V_{Hg}$ („filling") was used; it was performed at $T_{ann} = 220\,^\circ$C for 24 h in Hg vapors. Also two-stage („activation" in case of arsenic-doped samples) annealing was used, where the first stage was a high-temperature annealing in Hg vapors at $T_{ann} = 350\,^\circ$C for 2 h, while the second stage was represented by low-temperature annealing at $T_{ann} = 220\,^\circ$C for 22 h.

PR, PL and optical transmittance (OT) were studied using a set-up based on Fourier-transform spectrometer Vertex 80 with step-scan, as described in [4]. The laser diode with $\lambda = 809$ nm was used as a source of modulation emission when studying PR. To exclude the impact of the background thermal emission, PR spectra were recorded with lock-in signal amplification with mechanical modulation of laser emission. The measurements were performed in the temperature range $T = 11-294$ K in a closed-cycle helium cryostat Janis CCS-150. The signal was recorded by a cooled photoresistive detector based on MCT.

## 3. Results and discussion

Figure 1 presents OT spectra of films recorded at $T = 294$ K. The spectra were similar; films composition

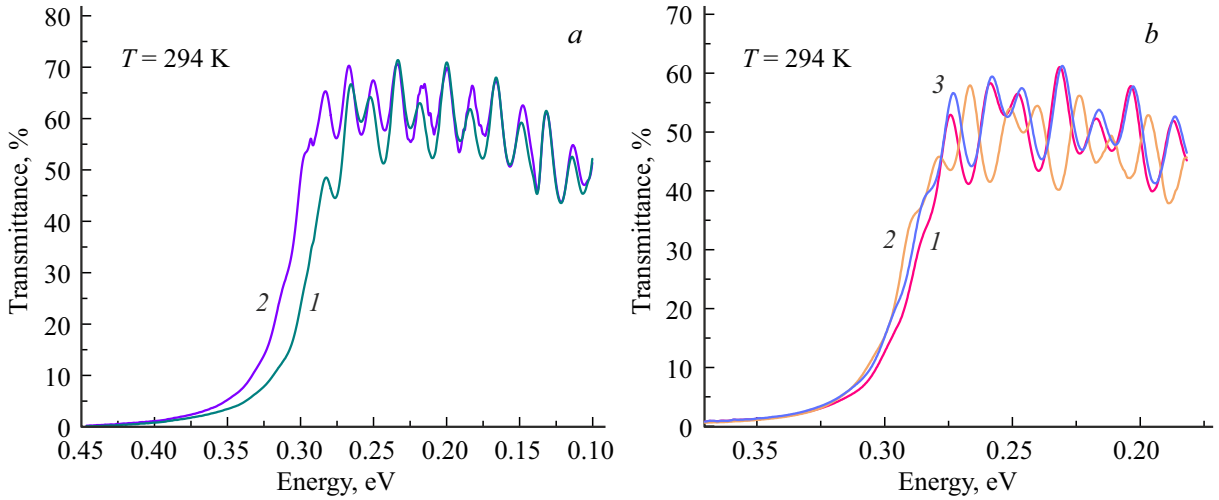


**Figure 1.** *a* — optical transmittance (OT) spectra of doped sample A after growth (*1*) and after activation annealing (*2*) and *b* — undoped sample C after growth (*1*), after vacancy filling annealing (*2*), and after activation annealing (*3*). (A color version of the figure is provided in the online version of the paper).

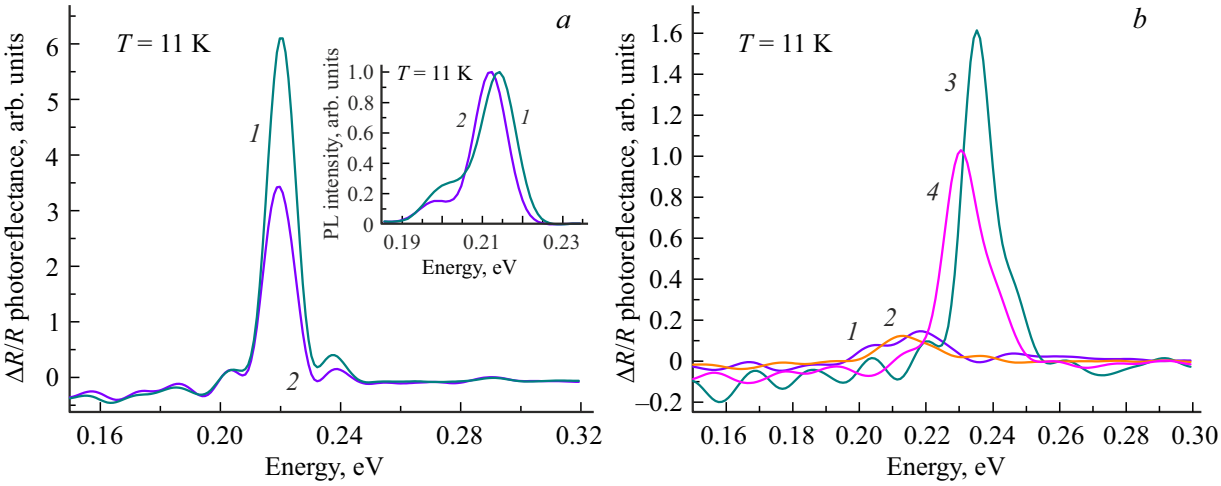


**Figure 2.** *a* — PR and PL spectra (in insert) of sample C after vacancy filling annealing (*1*) and after activation annealing (*2*) and *b* — PR spectra of doped samples after growth (A — (*1*), B — (*2*)) and after activation annealing (A — (*3*), B — (*4*)).

according to them was confirmed as $x \approx 0.29$. For as-grown samples grown under identical conditions, both doped sample A (to concentration $2 \cdot 10^{16}\,\mathrm{cm}^{-3}$, curve *1* in Figure 1, *a*) and B (to concentration $5 \cdot 10^{16}\,\mathrm{cm}^{-3}$, not shown), and undoped sample C (curve *1* in Figure 1, *b*), the spectra were identical. For annealed doped films, a shift of OT edge towards high energies (HE) by $\sim 12$ meV was observed. For film C, the shift of OT edge after annealing was insignificant, $\sim 3$ meV. In the low-energy (LE) part of OT spectra of all samples, the noticeable interference bands with period $\sim 18$ meV are observed, confirming good planarity of the films.

Figure 2, *a* shows PR spectra at $T = 11$ K for sample C with two types of annealing. Full-widths at half-maximum (FWHMs) of PR peaks were $\sim 11$ meV after both types of annealing, but intensity of PR peak was higher after vacancy filling annealing. Presumably, this low-temperature annealing has favorable effect on the sample quality, while the activation annealing, namely, its high-temperature part, decreases it. Spectra of low-temperature PL, see Figure 2, *a* in insert, contained HE peak of high intensity and low intensive LE shoulder at $\sim 14$ meV below HE peaks. Shift of the HE PL peak for the sample after vacancy filling annealing relative to the HE peak of the as-grown sample (not shown) was practically the same as that for the sample after activation annealing.

Figure 2, *b* shows PR spectra of doped films at $T = 11$ K. Positions of main peak of PR for samples after activation annealing is shifted towards HE relative to those of as-grown samples by $\sim 17$ meV for sample A and by $\sim 18$ meV for sample B. At that, FWHM of the peaks as a result of annealing changes from $\sim 16$ to $\sim 11$ meV for sample A

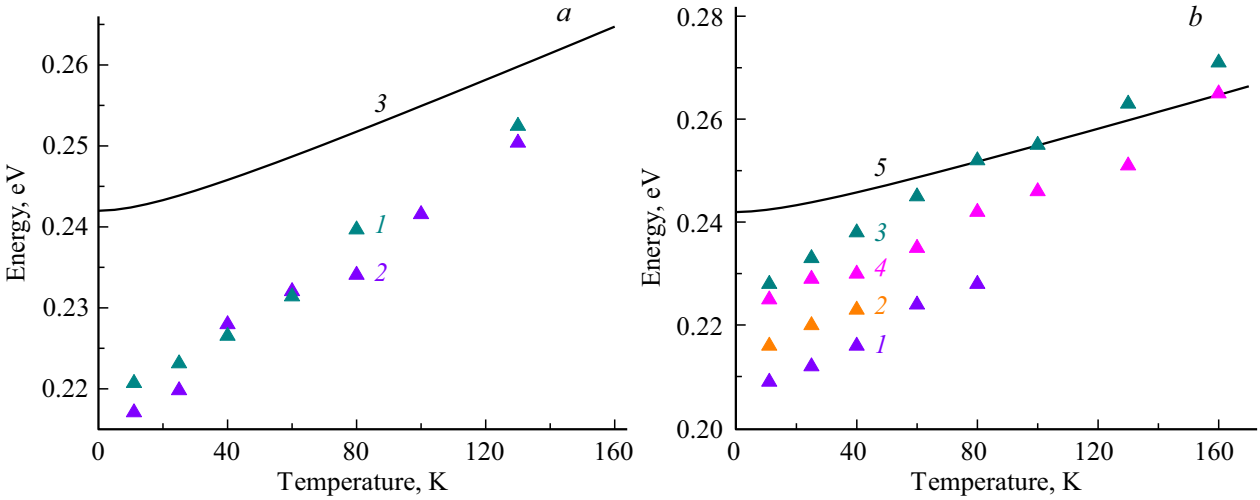


**Figure 3.** *a* — temperature dependences of energies of PR peaks of undoped sample C after vacancy filling annealing (*1*) and after activation annealing (*2*), dependence $E_g(T)$ for $x = 0.30$ (*3*), *b* — same dependences for doped samples after growth (A — (*1*), B — (*2*)) and after activation annealing (A — (*3*), B — (*4*)), dependence $E_g(T)$ for $x = 0.30$ (*5*).

and from $\sim 15$ to $\sim 13$ meV for sample B. For all studied samples, in the PR spectra, similar to the OT spectra, the Fabry-Perot interference bands are observed at low energies, with a period $\sim 18$ meV.

Figure 3 shows the temperature dependences of the energy of PR peaks of the samples. Solid line shows the calculated dependence of band gap $E_g(T)$ for MCT with composition $x = 0.30$, plotted according to [6]. In the temperature range shown, the positions of PR maxima are below the calculated value $E_g(T)$, both for undoped epitaxial films (Figure 3, *a*), and for doped ones (Figure 3, *b*). Such result was multiple times observed for PL of MCT [7], and is indicative of the disorder of solid solution. Perhaps, such temperature dependence in case of PR can be interpreted similarly. Then, at low temperatures the position of the main PR peak can be associated with excitons localized on composition fluctuations. At $T = 11$ K peak energy of PR is below $E_g$ by $\sim 24$ meV. Improvement in structural perfection of the films after the annealing is confirmed by the fact that PR signal was registered up to the room temperature, unlike to films after the growth, where no signal was detected even after $\sim 80$ K.

## 4. Conclusion

Thus, in this paper we studied epitaxial films $Cd_{0.3}Hg_{0.7}Te$ by PR method. This method allowed for evaluating the quality of the epitaxial films after the growth and after annealing. For the doped samples, PR data correlate well with the results of previous optical studies [7], namely, they confirm the improvement in structural perfection after annealing. For undoped films, we identified that high-temperature annealing slightly worsens the sample quality, while low-temperature annealing has a positive effect. The signal position in the spectrum of low-temperature PR, as in the case of PL, can correspond in energy to transitions involving excitons localized on composition fluctuations in MCT. The paper results can be used during further studies of the electronic structure of MCT solid solutions, and for the development of optoelectronic devices based on them.

### Conflict of interest

The authors declare that they have no conflict of interest.

## References

[1] M. Kopytko, A. Rogalski. Sensors Actuators: A-Phys., **339**, 113511 (2022). DOI: https://doi.org/10.1016/j.sna.2022.113511
[2] J. Shao, L. Chen, W. Lu, X. Lü, L. Zhu, S. Guo, L. He, J. Chu. Appl. Phys. Lett., **96** (12), 121915 (2010). DOI: https://doi.org/10.1063/1.3373595
[3] M. Motyka, G. Sęk, F. Janiak, J. Misiewicz, K. Kłos, J. Piotrowsk. Meas. Sci. Technol., **22** (12), 125601 (2011). DOI: 10.1088/0957-0233/22/12/125601
[4] O.S. Komkov, M.V. Yakushev. Semiconductors, **57** (6), 425 (2023). DOI: 10.61011/FTP.2023.06.56469.33k
[5] V.A. Shvets, D.V. Marin, V.G. Remesnik, I.A. Azarov, M.V. Yakushev, S.V. Rykhlitskii. Opt. Spectrosc., **128** (12), 1815 (2020). DOI: 10.21883/OS.2020.12.50315.349-20
[6] C.R. Becker, V. Latussek, A. Pfeuffer-Jeschke, G. Landwehr, L.W. Molenkamp. Phys. Rev. B, **62** (15), 10353 (2000). DOI: https://doi.org/10.1103/PhysRevB.62.10353
[7] M.S. Ruzhevich, D.D. Firsov, O.S. Komkov, K.D. Mynbaev, V.S. Varavin, M.V. Yakushev. Semiconductors, **57** (6), 484 (2023). DOI: 10.61011/FTP.2023.06.56479.5375

*Translated by I.Mazurov*