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Influence of Laser Radiation on Optical Properties of High Resistivity CdTe Crystals and $Cd_{1-x}Zn_xTe$ Solid Solutions in the Field of the Fundamental Optical Transition E_0

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In this paper, the transmission and reflection spectra of *p*-CdTe (111) single crystals and $Cd_{1-x}Zn_xTe$ ($x = 0.1$) solid solutions in the range $(0.8\text{-}1.7)\cdot10^{-6}$ m before and after laser irradiation at the wavelength $\lambda = 355$ nm in the energy range 5.8-21.0 mJ/cm² are measured. It is shown that at optimal parameters of laser processing we obtain an increase in the reflectivity of the investigated materials, which in turn is explained by the integral effect, i.e. both a thin near-surface layer and the volume of material take part in the process of optical reflection (the complex refractive index of the surface layer $\tilde{n}_s$ is different from the complex refractive index of the volume material $\tilde{n}_v$). The obtained reflection spectra of the samples indicate that during irradiation there is a laser-stimulated interaction of impurities and defects, which leads to the formation of neutral complexes and a decrease in the intensity of impurity scattering processes. Experimental studies on the effect of laser irradiation on the optical properties of these crystals, and the establishment of the main mechanisms of laser treatment (laser-induced modification) of the near-surface layer are conducted. In *p*-CdTe (111) single crystals and $Cd_{1-x}Zn_xTe$ ($x = 0.1$) solid solutions, cadmium, tellurium, zinc and their complexes play the role of the getter.

Keywords: CdTe, CdZnTe, Transmission, Reflection, Absorption, Laser irradiation.

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1. INTRODUCTION

Semiconductor materials $A^{II}B^{VI}$, including CdTe and $Cd_{1-x}Zn_xTe$, are one of the most promising materials that are used for different kinds of detectors of ionizing radiation [1-4]. In laser irradiation of functional materials of electronic engineering two parameters are very important: laser energy E and magnitude of fundamental optical transition of semiconductor E_0.

To optimize the technological processes of manufacturing detector instrument structures, as well as the control of laser-stimulated processing, much attention is paid to the study of mechanisms and processes that occur during the interaction of this radiation with the surface. Today, there are mechanisms of thermal and non-thermal nature, in particular such as thermal, shock, photochemical and plasma. In most cases, the thermal mechanism of laser treatment is the main mechanism of action of laser radiation, leading to structural changes in the surface. Methods of laser-induced processing of semiconductor materials (polishing, gettering, implantation) allow to avoid additional defects of the crystal and to create the necessary configuration of the near-surface region (local areas) of the studied structures [5-8].

2. EXPERIMENTAL RESULTS AND THEIR DISCUSSION

In this paper, to elucidate the mechanisms of the influence of pulsed laser irradiation on thin surface layers of semiconductors we measured the transmission and reflection spectra of *p*-CdTe (111) single crystals with specific resistivity $\rho = (2\div5)\cdot10^{9}\ \Omega\cdot$cm; $Cd_{1-x}Zn_xTe$ ($x = 0.1$) solid solutions with specific resistivity $\rho = (0.5\div3)\cdot10^{10}\ \Omega\cdot$cm in the range $(0.8\text{-}1.7)\cdot10^{-6}$ m before and after laser irradiation at the wavelength of $\lambda = 355$ nm in the energy range 5.8-21.0 mJ/cm².

The quantitative characteristic of the optical phenomenon of reflection of electromagnetic waves is the energy reflection coefficient R. The reflection coefficient R at normal incidence or the reflection R of a semi-infinite isotropic medium (semiconductor, solid) is determined by the following relation:

$$R = \frac{(n - n_0)^2 + \chi^2}{(n + n_0)^2 + \chi^2}, \tag{1.1}$$

where n, n_0 are the refractive indices of the material under study and the environment, respectively; χ is the extinction coefficient of a semiconductor. The optical depth of d_{opt} penetration of an electromagnetic wave into a semiconductor material is $1/\alpha$, where α is the absorption coefficient of the semiconductor. For semiconductors α above the absorption edge is of the order of $10^4\div10^6$ cm^{-1}, so when reflected, the electromagnetic wave will probe only a very thin layer near the sample surface (about 1 μm or less).

It is known from classical physics that the transmittance of the functional materials of electronic engineering for the light wavelength λ is expressed by the reflection coefficient R, the absorption index α, and the thickness of the sample d by means of a relation

$$T = \frac{(1 - R)^2 e^{-\alpha d}}{1 - R^2 e^{-\alpha d}}. \tag{1.2}$$

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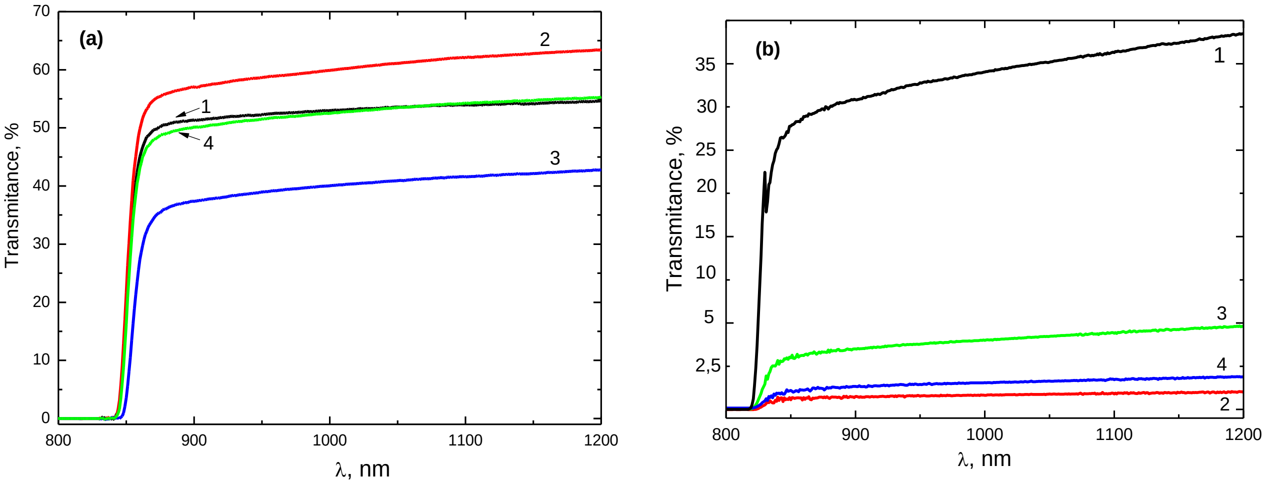

Fig. 1 – Transmission spectra of p-CdTe (111) single crystals (a) and $Cd_{1-x}Zn_xTe$ ($x = 0.1$) solid solutions (b): original sample is curve 1 and the samples are irradiated with energy of 5.8 mJ/cm²; 10.4 mJ/cm², 21.0 mJ/cm² – curves 2-4, respectively. The wavelength of the laser radiation is 355 nm

Fig. 1a shows the optical transmission spectra $T = f(\lambda)$ of p-CdTe (111) single crystals with a specific resistance of $(2\div5)\cdot10^9\ \Omega\cdot$cm (original sample is curve 1 and the samples are irradiated with energy of 5.8 mJ/cm², 10.4 mJ/cm², 21.0 mJ/cm² – curves 2-4 respectively). As seen from the figure, the transmittance of p-CdTe (111) single crystals increases with irradiation energy density of 5.8 mJ/cm² and at an energy of 10.4 mJ/cm² – it decreases. At the same time laser processing of these samples energy densities of 21.0 mJ/cm² transmittance is almost identical to that of the original samples. Such a course of the transmission curves is related to changes that occur in the thin surface layers of the semiconductor material upon laser irradiation.

Fig. 1b shows the optical transmission spectra $T = f(\lambda)$ of $Cd_{1-x}Zn_xTe$ ($x = 0.1$) solid solutions with a specific resistance of $(0.5\div3)\cdot10^{10}\ \Omega\cdot$cm (original sample is curve 1 and the samples are irradiated with energy of 5.8 mJ/cm², 10.4 mJ/cm², 21.0 mJ/cm² – curves 2-4 respectively). As can be seen from the figure, the irradiation of $Cd_{1-x}Zn_xTe$ ($x = 0.1$) solid solutions by these energy densities significantly decreases compared to the original samples. Fig. 2 shows the spectra of optical reflection of p-CdTe (111) single crystals and $Cd_{1-x}Zn_xTe$ ($x = 0.1$) solid solutions in the region of fundamental optical transition E_0 at this laser treatment (original sample is curve 1 and the samples are irradiated with energy of 5.8 mJ/cm²; 10.4 mJ/cm², 21.0 mJ/cm² – curves 2-4 respectively).

As can be seen from Fig. 2, the reflectivity of the studied materials increases with increasing laser energy density. This is due to the integral effect, that is, in the process of optical reflection involves a thin surface layer of semiconductor material and volume of material (the complex refractive index of the surface layer $\tilde{n}_s = n_s + i\chi_s$ is different from the complex refractive index of the volume material $\tilde{n}_v = n_v + i\chi_v$). The obtained reflection spectra of the samples show that irradiation occurs laser-induced interaction of impurities and defects, leading to the formation of neutral complexes and reducing the intensity of impurity scattering.

Since the reflection coefficient $R = f(\lambda)$ is related to the transmittance $T = f(\lambda)$ and the absorption coefficient $D = f(\lambda)$ by the ratio $R + T + D = 1$ (thus the scattering of the light wave in the sample is not taken into account), the absorption spectra $D = 1 - (R + T)$ of the light (electromagnetic) wavelength λ are also constructed in this paper [8].

The constructed optical absorption spectra $D = [1 - (T + R)] = f(\lambda)$ of these materials are completely correlated with the optical transmission spectra $T = f(\lambda)$ and the reflection $R = f(\lambda)$. From the absorption spectra (Fig. 3) of the material it is seen that the lower energies, i.e. at the energies of light (electromagnetic) waves E which is much lower than the fundamental optical transition energy E_0, absorption of p-CdTe (111) single crystals after laser treatment with an energy density of 5.8 mJ/cm² and 21.0 mJ/cm² becomes smaller compared to the original samples (Fig. 3a, curves 1, 2, 4). In laser processing of p-CdTe (111) single crystals with an energy density of 10.4 mJ/cm², the absorption of the samples is significantly increased (Fig. 3a, curve 3). For $Cd_{1-x}Zn_xTe$ ($x = 0.1$) solid solutions, the absorption of the samples is significantly increased after laser treatment compared to the original samples (Fig. 3b, curves 1-4).

From relation (1.2) it is possible to obtain an absorption coefficient α for a given wavelength λ of the material under study

$$\alpha = \frac{1}{d} ln \frac{2RT^2}{-(1-R)^2 + \sqrt{(1-R)^4 + 4T^2R^2}}. \qquad (1.3)$$

Based on the Heisenberg uncertainty principle for energies E and time t ($\Delta E \cdot \Delta t \geq \hbar$), the relaxation effects in light absorption by a crystal are described by the expansion parameter $\Delta E = \hbar/\tau$ (the broadening of the electronic transition E_0 is related to the free charge carrier life due their interaction with lattice vibrations, impurities, defects including surface character), where τ is the time of energy relaxation of the photo-generated charge carriers [8].

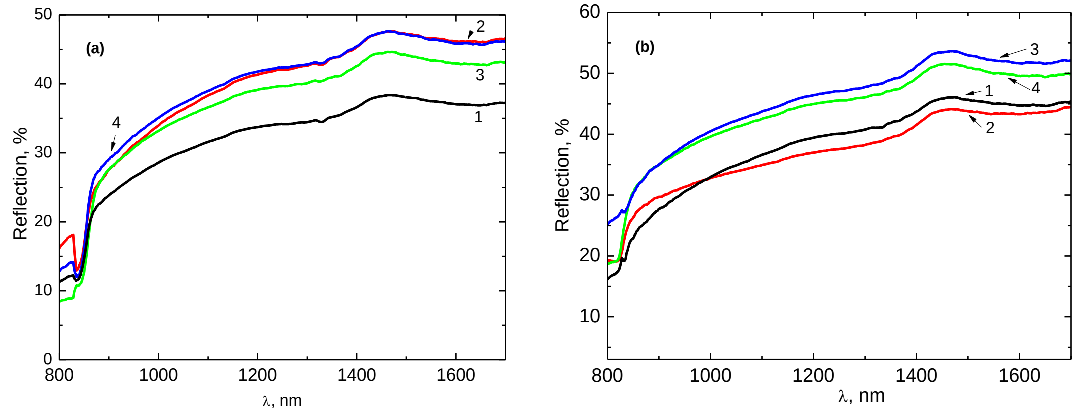

Fig. 2 – Reflection spectra of *p*-CdTe (111) single crystals (a) and $Cd_{1-x}Zn_xTe$ ($x = 0.1$) solid solutions (b): original sample is curve 1 and the samples are irradiated with energy of 5.8 mJ/cm², 10.4 mJ/cm², 21.0 mJ/cm² – curves 2-4, respectively. The wavelength of the laser radiation is 355 nm

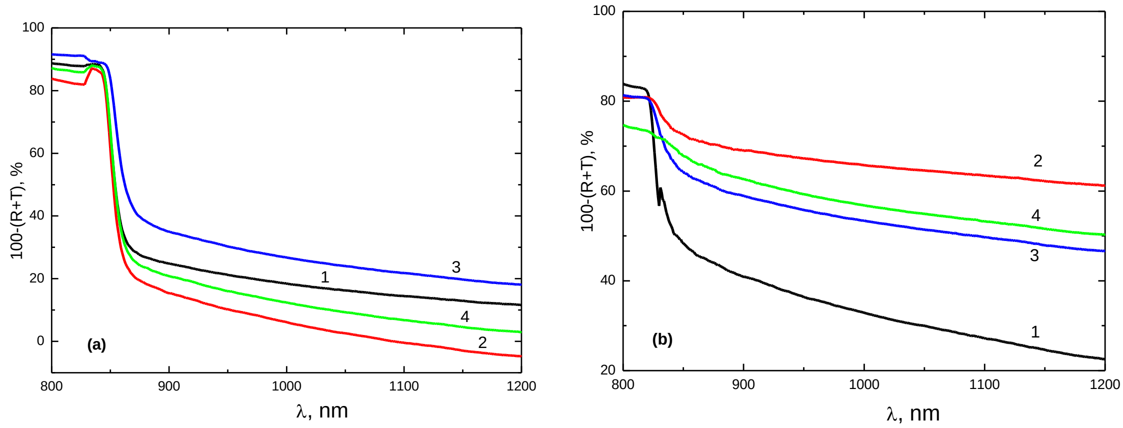

Fig. 3 – Absorption spectra of *p*-CdTe (111) single crystals (a) and $Cd_{1-x}Zn_xTe$ ($x = 0.1$) solid solutions (b): original sample is curve 1 and the samples are irradiated with energy of 5.8 mJ/cm², 10.4 mJ/cm², 21.0 mJ/cm² – curves 2-4 respectively. The wavelength of the laser radiation is 355 nm

According to the experimental data on the optical transmission and reflection spectra (Fig. 1, Fig. 2) for *p*-CdTe (111) single crystals with specific resistance of $(2\div5)\cdot10^9$ Ω·cm and solid solutions $Cd_{1-x}Zn_xTe$ ($x = 0.1$) with a specific resistance of $(0.5\div3)\cdot10^{10}$ Ω·cm the energy expansion of the optical spectra of these materials is 0.05 eV; 0.078 eV, respectively.

Energy relaxation time of photogenerated pairs τ for *p*-CdTe (111) single crystals and $Cd_{1-x}Zn_xTe$ ($x = 0.1$) solid solutions is respectively equal to $1.316\cdot10^{-14}$ s and $0.844\cdot10^{-14}$ s.

The authors of [8, 9] showed that oxide coatings that are formed on the surface of the studied materials are amorphous films with an approximate thickness of 0.5-7 nm. It should also be borne in mind that there is a transition layer of oxide on the oxide-semiconductor interface.

3. CONCLUSIONS

Optical studies of the transmission and reflection spectra of single crystals *p*-CdTe (111), solid solutions $Cd_{1-x}Zn_xTe$ ($x = 0.1$) in the range $(0.8\text{-}1.7)\cdot10^{-6}$ m before and after laser irradiation at the wavelength of the light wave $\lambda = 355$ nm in the energy range of 5.8-21.0 mJ/cm² showed:

a) an increase in the reflectivity of the investigated materials in this laser treatment, which is explained by the integral effect, that is, in the process of optical reflection a thin surface layer of the semiconductor material and a material volume are involved (the complex refractive index of the surface layer $\tilde{n}_s = n_s + i\chi_s$ is different from the complex refractive index of the volume material $\tilde{n}_v = n_v + i\chi_v$). On the basis of the obtained reflection spectra, the studied samples, as well as taking into account the parameters of laser-induced surface treatment is laser-stimulated interaction of impurities and defects, which in turn leads to the formation of neutral complexes and reduce the intensity of impurity scattering.

b) experimental studies have shown that the main mechanism of influence of pulsed laser irradiation on the optical properties of thin surface layers of the investigated crystals is structural gettering, that is, the absorption due to the presence of sections of semiconductors that have a defective structure and have the ability to actively absorb defects. In *p*-CdTe (111) single crystals and $Cd_{1-x}Zn_xTe$ ($x = 0.1$) solid solutions, the role of getters play cadmium, tellurium, zinc and their complexes.

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Вплив лазерного опромінення на оптичні властивості високоомних кристалів CdTe та твердих розчинів $Cd_{1-x}Zn_xTe$ в області фундаментального оптичного переходу E_0

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У даній роботі проведено оптичні дослідження спектрів пропускання та відбивання монокристалів *p*-CdTe (111) та твердих розчинів $Cd_{1-x}Zn_xTe$ ($x = 0,1$) в діапазоні $(0,8\text{-}1,7)\cdot10^{-6}$ м до та після лазерного опромінення на довжині електромагнітної хвилі $\lambda = 355$ нм в інтервалі енергій 5,8-21,0 мДж/см^2. Показано збільшення відбиваючої здатності досліджуваних матеріалів при даній лазерній обробці, що пояснюється інтегральним ефектом, тобто в процесі оптичного відбивання приймає участь тонкий приповерхневий шар напівпровідникового матеріалу та об'єм матеріалу (комплексний показник заломлення приповерхневого шару $\tilde{n}_s$ відрізняється від комплексного показника заломлення об'ємного матеріалу $\tilde{n}_v$). Отримані спектри відбивання зразків свідчать, що при опроміненні відбувається лазерно-стимульована взаємодія домішок і дефектів, що приводить до утворення нейтральних комплексів та зменшення інтенсивності процесів домішкового розсіювання. Встановлено, що основним механізмом впливу імпульсного лазерного опромінення на оптичні властивості тонких приповерхневих шарів досліджених кристалів є структурне гетерування, тобто поглинання, обумовлене наявністю ділянок напівпровідників що мають дефектну структуру і володіють здатністю активно поглинати точкові дефекти і зв'язувати домішки. В монокристалах *p*-CdTe (111) та твердих розчинах $Cd_{1-x}Zn_xTe$ ($x = 0,1$) роль гетера виконують окисли кадмію, телуру, цинку та їх комплекси.

Ключові слова: CdTe, CdZnTe, Пропускання, Відбивання, Поглинання, Лазерне опромінення.