

## EFFECT OF ULTRASOUND IRRADIATION ON AN $n$ -CdS/ $p$ -CdTe HETEROSTRUCTURE

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The results of photoelectric researches of an intermediate CdTe<sub>1-x</sub>S<sub>x</sub> layer at the interface of the  $n$ -CdS/ $p$ -CdTe heterostructure, fabricated by depositing CdS in vacuum onto the CdTe surface, are reported. It has been shown that if the substrate temperature falls within the interval  $T_s = 220 \div 240$  °C, besides the stable CdTe<sub>1-x</sub>S<sub>x</sub> compounds, the metastable ones are also formed. The latter disappear after the specimens are subjected to the ultrasound treatment with an irradiation power of 1 W/cm<sup>2</sup> for 10 min. For the CdTe<sub>1-x</sub>S<sub>x</sub> interlayer, the content  $x$  and the crystal lattice constant  $a_0(x)$  of the compounds included are calculated on the basis of the photoconductivity spectra for the  $n$ -CdS/ $p$ -CdTe heterointerface.

Last years, a lot of researches dealing with the designing of solar cells on the basis of polycrystalline  $p$ -CdTe films, which involve a  $n$ -CdS/ $p$ -CdTe heterostructure, were performed [1, 2]. It was demonstrated that the application of such solar cells is very promising for the solar energy usage. Therefore, a large attention has been attracted to the technological methods of fabricating  $n$ -CdS/ $p$ -CdTe heterostructures and the study of electronic processes in them. It has been found that, in the course of growing an  $n$ -CdS/ $p$ -CdTe structure, a thin interlayer is formed at the heterointerface between the CdS and CdTe films. Special experimental researches of the  $n$ -CdS/ $p$ -CdTe heterostructure by the near-field scanning optical microscopy revealed that the intermediate transition layer is formed, under specific technological conditions, owing to the diffusion of sulfur from CdS into CdTe, which gives rise to the emergence of a solid solution CdS <sub>$x$</sub> Te<sub>1- $x$</sub>  [3–5].

The authors of works [6, 7] showed that the semiconductor binary compounds CdS and CdTe, while interacting with each other, can form a solid solution CdS <sub>$x$</sub> Te<sub>1- $x$</sub>  with an arbitrary content  $0 < x < 1$ . The efficiency of solar cells based on the  $n$ -CdS/ $p$ -CdTe heterostructure is determined, in many respects, by the perfection of the solid solution structure, as well as by its geometrical dimensions and phase composition [7]. The continuity of the CdS <sub>$x$</sub> Te<sub>1- $x$</sub>  solid solution content on the heterointerface provides a favorable effect to the solar cell efficiency [6]. The energy gap

width  $E_g$  in the heterostructure increases towards the irradiated surface; the internal electric field, which appears owing to the  $E_g$ -gradient, pulls the minority charge carriers into the bulk of films to the depths that considerably exceed the diffusion length. As a result, the surface recombination becomes reduced, and the collection coefficient for minority charge carriers becomes rather high and close to unity in a wide spectral range of photosensitivity. The decay of photosensitivity in the short-wave range of the spectrum is governed by the thickness of the solid solution layer and the threshold energy of photons, above which the absorption in the wide-band-gap  $n$ -layer at the structure's surface becomes substantial.

So, a layer of the CdS <sub>$x$</sub> Te<sub>1- $x$</sub>  solid solution about 1  $\mu$ m in thickness and with a continuous variation of the content  $x$  across the layer thickness from the cadmium sulfide to the cadmium telluride one is to be created. The use of a high-temperature technology for fabricating the  $n$ -CdS/ $p$ -CdTe heterostructures brings about an increase of the uncontrollable impurity content over the whole structure, including the CdTe film. Therefore, it is of great interest to study the process of formation of the  $n$ -CdS/ $p$ -CdTe heterostructures at just those temperatures, at which the properties of thin CdTe films do not almost change.

In this work, we study the process of formation of a solid solution at the  $n$ -CdS/ $p$ -CdTe heterointerface of solar cells and its dependence on the technological regime and the subsequent stimulating factor, namely, ultrasound irradiation. The 1-cm<sup>2</sup>  $n$ -CdS/ $p$ -CdTe solar cells were fabricated on molybdenum substrates following the technology described in work [8]. The cells were illuminated from the front contact side. The front contact was fabricated of pure indium and deposited, under a pressure of  $10^{-5}$  Torr, onto the substrate in the form of a comb, with the width of the contact strips being 0.8 and the interstrip distance 2 mm. The molybdenum foil served as a back contact.

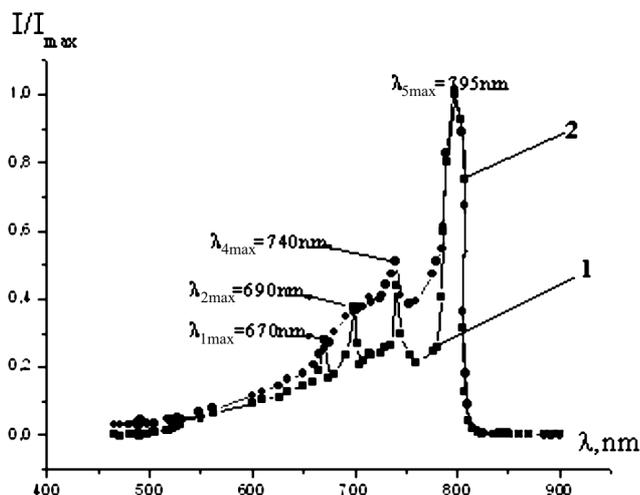


Fig. 1. Spectral distributions of the photosensitivity of an  $n$ -CdS/ $p$ -CdTe heterostructure ( $T_s = 180^\circ\text{C}$ ) before (1) and after (2) ultrasound irradiation

The spectral dependence of the photosensitivity was measured on a ZMR-2 monochromator at room temperature. A xenon lamp of the DKSSh-1000 type, operating in the mode of the minimal allowable power of a light flux of 53000 Lm, with a brightness of up to 120 Mcd/m<sup>2</sup> and the central light spot served as an illuminating source. The light irradiation was calibrated in absolute units with the help of an RTE-9 thermoelement with a quartz window. The specimens under investigation were also subjected to ultrasound irradiation. The ultrasonic treatment was carried on during 10–15 min at the frequency  $\nu = 2.5$  MHz and the irradiation power  $W = 0.5 \div 1$  W/cm<sup>2</sup>.

Our researches showed that the phase composition and the thickness of the intermediate solid solution layer strongly depend on the technological regime of the heterostructure formation, mainly, on the substrate temperature and the growth duration. In the framework of our method, the intermediate CdS<sub>*x*</sub>Te<sub>1-*x*</sub> layer starts its formation at the substrate temperature  $T_s \approx 150^\circ\text{C}$ . It was established experimentally that the growth of the substrate temperature is accompanied by the process of enrichment of the CdS<sub>*x*</sub>Te<sub>1-*x*</sub> solid solution with S atoms, so that the content  $x$  starts to grow [1, 9]. It is known [7, 9, 10] that every value of the content  $x$  of a solid solution is related with the corresponding value of the lattice constant  $a_0$ , which falls between the constants of CdS ( $a_0 = 5.832 \text{ \AA}$ ) and CdTe ( $a_0 = 6.423 \text{ \AA}$ ) lattices.

In Figs. 1 and 2, *a*, curves 1 demonstrate the spectral distributions of the photosensitivity of an  $n$ -CdS/ $p$ -CdTe heterostructure at the substrate temperatures

$T_s = 180$  and  $220^\circ\text{C}$ , respectively. In the former case, the spectral distribution of the heterostructure's photosensitivity revealed well-pronounced peaks at  $\lambda_{\text{max}} = 670, 690, 740,$  and  $795$  nm which are located between the edges of the intrinsic absorption of CdS and CdTe. After the specimens having been subjected to ultrasonic treatment for 10 min, the peaks at  $\lambda_{\text{max}} = 670$  and  $690$  nm disappeared. At the same time, the amplitude of the peak at  $\lambda_{\text{max}} = 670$  nm increased considerably, while that of the main peak at  $\lambda_{\text{max}} = 795 \div 797$  nm remained practically constant (Fig. 1, curve 2). The ultrasonic treatment enhanced the structure photosensitivity within the whole spectral range, especially in the interval  $\lambda = 600 \div 750$  nm.

The spectral distribution of the heterostructure's photosensitivity measured at  $T_s = 220^\circ\text{C}$  also demonstrated several peaks at  $\lambda_{\text{max}} = 670, 710, 740,$  and  $795$  nm (Fig. 2, *a*; curve 1), as well as a weak peak at  $\lambda_{\text{max}} = 850$  nm, whose amplitude was about two orders of magnitude smaller than the amplitudes of the peaks discovered in the visible spectral range (Fig. 2, *b*). The latter peak was found in the photosensitivity spectra of practically all investigated structures, provided the substrate temperature  $T_s = 180^\circ\text{C}$ . It should be also noted that the peak amplitudes varied from specimen to specimen, but the amplitude of the peak at  $\lambda_{\text{max}} = 740$  nm remained comparatively constant.

The ultrasound irradiation of the  $n$ -CdS/ $p$ -CdTe structure fabricated at  $T_s = 220^\circ\text{C}$  resulted in the disappearance of the peak at  $\lambda_{\text{max}} = 710$  nm and the emergence of a new, amplified peak at  $\lambda_{\text{max}} = 700$  nm, the amplitude of which reached about 90% of the amplitude of the main peak at  $\lambda_{\text{max}} = 795$  nm. After the ultrasonic treatment, some specimens demonstrated a new peak at  $\lambda_{\text{max}} = 640$  nm (Fig. 2, *a*; curve 2). The ultrasound irradiation stimulated the photosensitivity enhancement, which was practically the same in the whole spectral range (see Fig. 2, *a*; curve 1).

For every peak, which was found in the spectral distribution of photosensitivity, we determined the corresponding fundamental absorption edge  $\lambda_{\text{fae}}$  by extrapolating the long-wave side of the photosensitivity peak to the  $\lambda$ -axis. Afterwards, these values were used to calculate the energy gap widths of solid solutions formed at the  $n$ -CdS/ $p$ -CdTe heterointerface.

Making use of the dependence  $E_g(x)$  between the solid solution content and the energy gap width [11], we found the content of the CdS<sub>*x*</sub>Te<sub>1-*x*</sub> solid solution. The values of the fundamental absorption edge  $\lambda_{\text{fae}}$ , the energy gap width  $E_g$ , and the content  $x$  of the solid

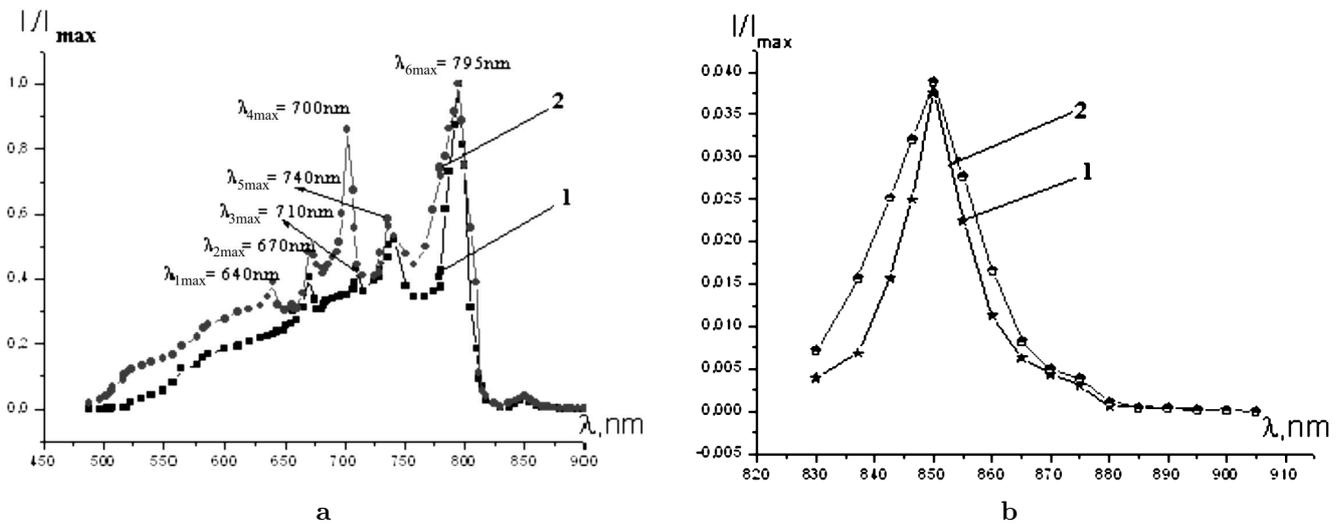


Fig. 2. (a) The same as in Fig. 1, but for  $T_s = 220$  °C. (b) The long-wave sections of the distributions shown in panel a

solution, which were determined for all peaks revealed in the photosensitivity spectra at the substrate temperatures  $T_s = 180$  and  $220$  °C, are quoted in the Table. The values of the crystal lattice constant  $a_0(x)$ , which were calculated for  $\text{CdS}_x\text{Te}_{1-x}$  solid solutions at the  $n\text{-CdS}/p\text{-CdTe}$  heterostructure interface by the empirical formula  $a_0(x) = 0.6477 - 0.057x$  [10], are also given there.

The following circumstance should be noted. While determining the solid solution content by the empirical formula  $E_g(x) = 1.74x^2 - 1.01x + 1.51$  [10], two positive solutions for  $x$  were obtained in the case of  $\text{CdS}_x\text{Te}_{1-x}$  with  $E_g = 1.4$  eV. Every other experimental value of  $E_g$  is linked with only one positive  $x$  root. Therefore, two values of the solution content are given in the Table for  $E_g = 1.4$  eV and only one for other energy gap values.

**Dependences of the crystal lattice constant  $a_0$ , the energy gap width  $E_g$ , and the content  $x$  of the  $\text{CdTe}_{1-x}\text{S}_x$  solid solution on the substrate temperature  $T_s$  and ultrasonic treatment**

Substrate temperature $T_s$ , °C	Ultrasonic treatment	$\lambda_{\text{max}}$ , nm	$\lambda_{\text{fae}}$ , nm	$E_g$ , eV	$x$	$a_0(x)$ Å
180	before	670	674	1.84	0.81	0.5942
180	before	690	704	1.76	0.77	0.5972
180	before	740	760	1.63	0.68	0.6030
180	before	795	810	1.53	0	0.6477
180	before	850	880	1.4	0.38	0.6181
					0.21	0.6346
180	after	740	760	1.63	0.68	0.6030
180	after	795	810	1.53	0	0.6477
180	after	850	880	1.4	0.38	0.6181
					0.21	0.6346
220	before	670	673	1.84	0.81	0.5942
220	before	710	630	1.7	0.73	0.5997
220	before	740	760	1.63	0.59	0.6030
220	before	795	810	1.53	0	0.6477
220	before	850	880	1.4	0.38	0.6181
					0.21	0.6346
220	after	640	650	1.9	0.84	0.5929
220	after	670	673	1.84	0.81	0.5942
220	after	700	710	1.74	0.75	0.5984
220	after	740	760	1.63	0.68	0.6030
220	after	795	810	1.53	0	0.6477
220	after	850	880	1.4	0.38	0.6181
					0.21	0.6346

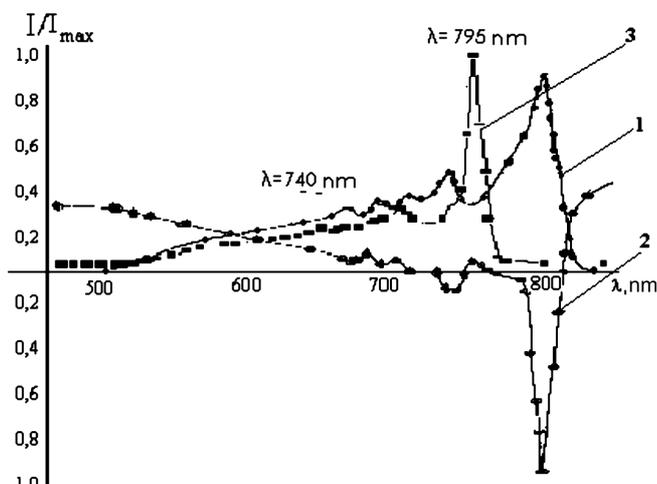


Fig. 3. Spectral distributions of the photosensitivity of an  $n$ -CdS/ $p$ -CdTe heterostructure ( $T_s = 220$  °C) in the gate (1) and photodiode (2) modes, and (3) in the gate mode after ultrasonic treatment

The growth of the substrate temperature  $T_s$  enhances the process of penetration of S atoms into CdTe and the formation of a stable solid solution with phases  $\alpha_1$  and  $\alpha_2$  [7], the contents of which correspond to the ranges of mutual solubility of the components on the diagram of equilibrium states of the system. At a relatively low temperature of the substrate  $T_s \approx 180$  °C, a solid solution CdTe<sub>0.32</sub>S<sub>0.68</sub>, which is associated with the peak at  $\lambda_{\max} = 740$  nm and the fundamental absorption edge  $\lambda_{\text{fae}} = 755 \div 770$  nm, and a solid solution with the content  $x = 0.21$  were synthesized. The latter is characterized by the peak at  $\lambda_{\max} = 850$  nm and the fundamental absorption edge  $\lambda_{\text{fae}} = 890$  nm (see Fig. 2, *b* and the Table) in the photosensitivity spectrum. According to the results of work [12], the solid solution CdTe<sub>1-x</sub>S<sub>x</sub> with the content  $x = 0.2 \div 0.22$  has the energy gap width  $E_g = 1.39$  eV; hence, its absorption manifests itself in the interval  $\lambda = 845 \div 850$  nm of the photosensitivity spectrum. This solid solution seems to have a stable content, so that its peak in the photosensitivity spectrum practically did not change after the ultrasound irradiation. As was indicated above, the small amplitude of this peak might be probably caused by a small thickness of the solid solution layer. Metastable solid solutions with characteristic peaks at  $\lambda_{\max} = 670$  and  $690$  nm were also formed at the heterointerface, but they disappeared during the ultrasound irradiation.

From the Table, one can see that the crystal lattice constant of the CdTe<sub>1-x</sub>S<sub>x</sub> solid solution with the

content  $x = 0.68$  is equal to 0.6030, i.e. differs by only 3.4% from the parameter  $a_0$  of CdS. At the same time,  $a_0(x) = 0.6346$  Å for CdTe<sub>1-x</sub>S<sub>x</sub> with  $x = 0.21$ , which comprises a mismatch of only 0.5% with  $a_0$  of CdTe. Therefore, the intermediate layer of the CdTe<sub>1-x</sub>S<sub>x</sub> solid solution with the varying content from  $x = 0.68$  (near the CdS phase) to  $x = 0.21$  (near the CdTe phase) strongly smoothed the discrepancy between the values of the parameter  $a_0$  for cadmium sulfide and telluride.

According to the results of work [13], if the relative difference between the crystal lattice constants of semiconducting materials is less than 4%, a heterojunction without surface states can be formed between them. The estimation made above satisfies that requirement. It is confirmed by the high values of the rectification factor for the dark current ( $K = I_{\text{fwd}}/I_{\text{back}} = 10^4 \div 10^5$ ), the short-circuit current ( $I_{\text{sc}}$ ), and the fill factor of the light current-voltage characteristic ( $Q \approx 0.5$ ).

As the temperature of the substrate grows, the probability of the formation of a CdTe<sub>1-x</sub>S<sub>x</sub> solid solution with varying content also increases, which is evidenced for by the number of peaks in the spectrum of the heterostructure's photosensitivity (Fig. 2, curves 1 and 2). If the substrate temperature  $T_s \geq 240$  °C, a rather thick intermediate layer, about 3 μm in thickness, appeared at the  $n$ -CdS/ $p$ -CdTe heterointerface, which is confirmed by an image of the heterostructure's transverse cross-section obtained on an M8 electron microscope (Fig. 3). This layer consisted of domains with various geometrical dimensions, which were composed of solid solutions with different specific resistances. The spectral distributions of the photosensitivity in the gate and photodiode modes (Fig. 3; curves 1 and 2, respectively) clearly illustrate this statement. The zero value of the photocurrent at four wavelengths of the incident radiation (Fig. 3, curve 2) testifies that the intermediate layer did consist of solid solution phases, which differed from one another by their content, electrophysical properties, and geometrical dimensions.

The potential barriers, formed between the solid solution layers, became apparently amplified in the photodiode mode; this is confirmed by the difference between the spectral distributions of the photosensitivity measured in the gate and photodiode modes (Fig. 3, curves 1 and 2, respectively).

After the ultrasound irradiation, the spectral distribution of the photosensitivity strongly changed, namely, the extreme points disappeared, and the well-pronounced peaks at  $\lambda_{\max} = 737 \div 740$  and 795 nm appeared (Fig. 3, curve 3). In this case, the peak at

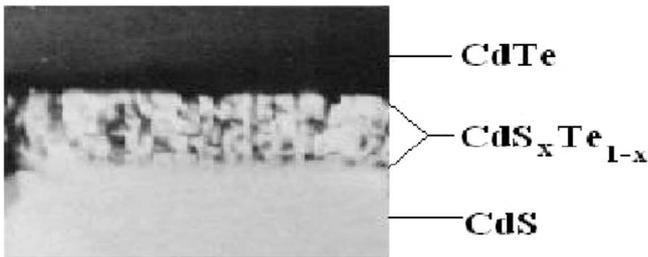


Fig. 4. Electron microscopy image of the transverse cross-section of a  $n$ -CdS/ $p$ -CdTe heterojunction ( $T_s = 240$  °C). Magnification of 3500

$\lambda_{\max} = 850$  nm in the long-wave range of the photosensitivity spectrum remained practically unchanged.

To summarize, a conclusion can be drawn that a layer of the solid solution  $\text{CdTe}_{1-x}\text{S}_x$  with the varying content  $x$  is formed at the  $n$ -CdS/ $p$ -CdTe heterointerface, when depositing CdS by the thermal evaporation in vacuum onto the  $p$ -CdTe substrate; the distribution of the content  $x$  across the layer thickness depends on the substrate temperature. In the course of this process, metastable solid solutions  $\text{CdTe}_{1-x}\text{S}_x$  are also formed. The latter decay under the ultrasonic treatment for  $10 \div 15$  min with the frequency  $\nu = 2.5$  MHz and the irradiation power  $W = 0.5 \div 1$  W/cm<sup>2</sup>. The ultrasound irradiation enhances the photosensitivity of the  $n$ -CdS/ $p$ -CdTe heterostructures fabricated at  $T_s \geq 220$  °C in the whole spectral range, while the specimens fabricated at  $T_s \leq 180$  °C demonstrate such an enhancement mainly in the spectral range  $\lambda = 610 \div 750$  nm.

1. Xuanzhi Wu, *Solar Energy* **77**, 803 (2004).
2. N. Romeo, A. Bosio, V. Canevari, and A. Podestà, *Solar Energy* **77**, 795 (2004).
3. M.K. Herndon, A. Gupta, V.I. Kaydanov, and R.T. Collins, *Appl. Phys. Lett.* **75**, 3503 (1999).

4. A.S. Gilmore, V.I. Kaydanov, T.R. Ohno et al., *IEEE Photovoltaic Specialists Conference* (2002), p. 604.
5. A.S. Gilmore, Ph. D. thesis, 2002.
6. R.A. Reynolds, M.J. Brau, H. Kraus, et al., *J. Phys. Chem. Sol., Suppl.* **42**, 511 (1971).
7. A.P. Belyaev, V.P. Rubets, and I.P. Kalinkin, *Fiz. Tekhn. Polupr.* **31**, 635 (1997).
8. Sh.A. Mirsagatov, A.I. Sultanov, and S.A. Muzafarova, *Geliotekhnika* N 2, 5 (1986).
9. X. Wu, J.C. Keane, R.G. Dhere et al., in *Proceedings of the 17-th European Photovoltaic Solar Energy Conference, Munich, Germany, 22-26 October, 2001* (Munich, 2001), p.995.
10. D. Bonnet and H. Rabenhorst, in *Proceedings of the International Conference on Physics and Chemistry of Semiconductor Heterojunction and Layer Structure* (Akad. Kiado, Budapest, 1971), Vol. 1, p. 119.
11. A. Ambrozyak, *Construction and Fabrication Technology of Semiconductor Photoelectric Devices* (Sovetskoe Radio, Moscow, 1970) [in Russian].
12. K. Ohata, J. Saraie, and T. Tanaka, *Jap. J. Appl. Phys.* **12**, 1641 (1973).
13. A.G. Milns and J.J. Feucht, *Heterojunctions and Metal-Semiconductor Junctions* (Academic Press, New York, 1972).

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#### ДОСЛІДЖЕННЯ УЛЬТРАЗВУКОВОЇ ДІЇ НА ГЕТЕРОСТРУКТУРУ $n$ -CdS/ $p$ -CdTe

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#### Резюме

Наведено результати дослідження фотоелектричним методом проміжного шару  $\text{CdTe}_{1-x}\text{S}_x$  на гетеромежі структур  $n$ -CdS/ $p$ -CdTe, одержаних осадженням CdS у вакуумі на поверхню CdTe. Показано, що при температурах підкладки  $T_{\text{п}} = 220 \div 240$  °C разом зі стабільними утворюються метастабільні сполуки  $\text{CdTe}_{1-x}\text{S}_x$ , які зникають після обробки зразків ультразвуком потужністю 1 Вт/см<sup>2</sup> протягом 10 хв. Для шару  $\text{CdTe}_{1-x}\text{S}_x$  зі спектрів фотопровідності  $n$ -CdS/ $p$ -CdTe розраховано його склад  $x$  та сталі кристалічної ґратки  $a_0(x)$ .