ISSN 1606-867X (Print)
ISSN 2687-0711 (Online)
Condensed Matter and Interphases
Kondensirovannye Sredy i Mezhfaznye Granitsy
https://journals.vsu.ru/kcmf/

Original articles

Research article
https://doi.org/10.17308/kcmf.2025.27/12764

On the mechanism of recrystallization of bismuth chalcogenides during photonic treatment with incoherent radiation

E. K. Belonogov[1,2], S. B. Kushev[1]✉, D. V. Serikov[3], S. A. Soldatenko[1], T. L. Turaeva[1]

[1]*Voronezh State Technical University,*
84 20-letiya Oktyabrya st., Voronezh 394006, Russian Federation

[2]*Voronezh State University,*
1 Universitetskaya pl., Voronezh 394018, Russian Federation

[3]*Voronezh Communications Design Bureau,*
16B Krasnodonskaya st., Voronezh 394019, Russian Federation

Abstract

Purpose: The aim of this work is to reveal the nature and systematize the mechanisms of gradient structure formation in the surface layer of bismuth chalcogenide during photon treatment with incoherent radiation from xenon lamps.

Experimental: Semiconductor thermoelectric branches based on Bi_2Te_3–Bi_2Se_3 solid solutions have been investigated by transmission electron microscopy, X-ray diffractometry, and photometry methods. The nature of nanostructuring and formation of gradient layer in the surface region of $Bi_2Te_{3-x}Se_x$ thermoelectric at photon treatment by incoherent radiation of xenon lamps is considered.

Conclusions: It is shown that these processes can be caused by a sequence of independent processes: growth of free electron concentration, decrease of defect formation threshold, localization in skin layer of high temperature gradient, generation and propagation of sonic phonons, collecting and secondary recrystallization, formation of nanocrystalline phase in Bi-Te-Se system.

Keywords: Photon treatment, Recrystallization, Electron microscopic micrograph, X-ray diffractometry, Nanostructured layer, Lattice defects, Bismuth chalcogenides

For citation: Belonogov E. K., Kushchev S. B., Serikov D. V., Soldatenko S. A., Turaeva T. L. On the mechanism of recrystallization of bismuth chalcogenides during photonic treatment with incoherent radiation. *Condensed Matter and Interphases*. 2025;27(2): 203–210. https://doi.org/10.17308/kcmf.2025.27/12764

Для цитирования: Белоногов Е. К., Кущев С. Б., Сериков Д. В., Солдатенко С. А., Тураева Т. Л. О механизме рекристаллизации халькогенидов висмута при фотонной обработке некогерентным излучением. *Конденсированные среды и межфазные границы*. 2025;27(2): 203–210. https://doi.org/10.17308/kcmf.2025.27/12764

✉ Sergey B. Kushev, e-mail: kushev_sb@mail.ru

1. Introduction

Increasing the efficiency of thermoelectric devices along with the search for new materials includes the development of new technologies for the realization of metal-semiconductor switching interconnection. Previously, the authors of this article have conducted a series of studies of the effect of pulsed photon treatment (PT) by radiation of powerful xenon lamps on the mechanical properties of semiconductor thermoelectric branches (based on solid solutions Bi_2Te_3–Bi_2Se_3) and adhesion of interconnect layers [1], electrical properties [2], thermal conductivity and Q-factor of thermoelectric branches [3]. These studies have shown the principal possibility and efficiency of using the PT method in the development of thermoelectric devices. It was shown in [4] that the energy effect of PT stimulates local recrystallization of the surface layer, which leads to the formation at a depth of ~ 500 nm of an area characterized by a gradient dispersion of the crystal structure, namely, adjacent large and nanoscale crystallites and, as a consequence, to changes in the electrical properties, thermal conductivity and thermoelectric Q of semiconductor materials.

The authors of papers [5–7] have shown that the effect of PT compared to conventional thermal treatment is manifested in the acceleration of diffusion processes [5], increase in the dispersity of the formed structures [6], and decrease in the temperature thresholds of phase formation [7]. Possible mechanisms of acceleration at photon activation of metal diffusion processes in semiconductors, synthesis of silicides and recrystallization in metal films have been considered in papers [8-10]. However, as shown in the review [11], the current mechanisms of activation of processes due to their complexity and stages in each specific case are not the same and require individual consideration taking into account the athermic and thermal nature. On the examples of synthesis of thin films of metals, silicides, carbides, nitrides and oxides, the authors considered the effect of PT, manifested in the excitation of the electronic subsystem (for the crystallization of amorphous materials), the rupture of interatomic bonds, the formation of vacancies, recrystallization. Such studies of massive multicomponent semiconductor systems have not been carried out, and the mechanism of the influence of PT on the structure of the surface region of the semiconductor material $Bi_2Te_{3-x}Se_x$ still awaits its detailed characterization.

The aim of this work is to reveal the nature and systematize the mechanisms of gradient structure formation in the surface layer of bismuth chalcogenide at PT by incoherent radiation of xenon lamps.

2. Experimental part

Initial samples of $Bi_2Te_{3-x}Se_x$ (x ~ 1) for research were obtained by the method of cold and subsequent hot pressing in steel molds from the powder of material of corresponding composition with dispersity of 0.063÷1 mm.

PT of plates was performed alternately from both sides by powerful radiation of xenon lamps (spectral range λ = 0.2÷1.2 μm) in argon atmosphere on the UOLP-1M installation with radiation doses E_I = 125÷175 J/cm^2, which corresponded to the processing time 1÷1.4 s.

To investigate the wavelength dependence of the reflection coefficient for $Bi_2Te_{3-x}Se_x$ samples, rectangular samples of 10×10×0.5 mm^3 with larger faces normal to the briquette pressing axis (z-cut) and parallel to the briquette pressing axis (x-cut) were used. Reflection spectra of unpolarized radiation were recorded on a Lambda 650 spectrophotometer with a URA module in the wavelength range 0.190÷0.9 μm with a resolution of ± 0.15 nm at a temperature of 300 K, the angle of incidence of radiation on the sample did not exceed 8°.

3. Results and their discussion

Previously, we found [4] that the energy effect of PT at E_I~175 J/cm^2 stimulates local recrystallization of the surface layer with the formation in the surface region of the solid solution $Bi_2Te_{3-x}Se_x$ (n-type) gradient region at a depth of ~ 500 nm and more (Fig.1).), in which large crystallites of 0.5÷3 microns in size border the surface nanostructured layer with a high density of defects (nanopores, nanocracks, inclusions) and crystallite size ~ 15÷30 nm.

The modified layer contains a large number of pores and inclusions (Fig. 1a), the average density of which is ~ 2·10^{10} cm^{-2}. Crystallites are morphologically isotropic (average size

~ 40÷60 nm) and practically do not contain linear defects (dislocations).

The material in the sample volume (starting from a depth of 1 μm) has a large-block structure (Fig. 1b), the crystallite size is 0.5÷3 μm. This grain structure is characterized by the presence of large lamellar inclusions and cracks ranging in size from 50 nm to 1 μm, as well as small globular defects up to 50 nm. Some large crystallites contain a network of dislocations with a linear density of ~ $1–10^6$ cm^{-2}.

No change in the phase composition of the samples after PT was detected, as evidenced by X-ray diffractometry studies (Fig. 2). Thus, when the surface of bismuth telluride is irradiated with high-energy radiation from xenon lamps for a very short period of time (t = 1.4 s), accelerated recrystallization occurs in the surface layer of the material with the formation of a gradient nanocrystalline structure without changing the phase composition.

According to [12] the emission spectrum of xenon lamps INP-16/250 is incoherent, covers the wavelength range of 0.2–1.2 μm and has two maxima near 0.4 and 0.9 μm (Fig. 3). This spectrum was obtained at minimum values of radiation power. With increasing power of xenon lamps, the plasma temperature increases with increasing fraction of ultraviolet radiation and decreasing fraction of infrared radiation [13].

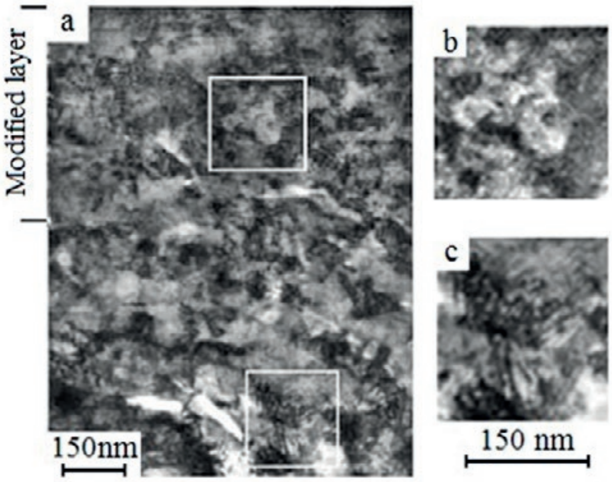

Fig. 1. TEM micrograph of a cross section of a $Bi_2Te_{3-x}Se_x$ sample after PT in argon at E_I ~ 175 J/cm^2 [4]

According to paper [14], the concentration of free electrons in bismuth telluride is $n = (2.0÷2.25)·10^{20}$ cm^{-3}. The concentration of free electrons increases at the PT surface of Bi_2Te_3 due to the internal photoeffect. The maximum intensity of electromagnetic radiation from xenon lamps in the infrared range of 0.8÷1.0 μm corresponds to the energy interval of photons $(2.0÷2.5)·10^{-19}$J (1.4÷1.6 eV). At the irradiation dose with E_I = 125 J/cm^2 delivered to the sample in 1.4 s, the photon flux is more than $3·10^{20}$ cm^{-2}·s^{-1}.

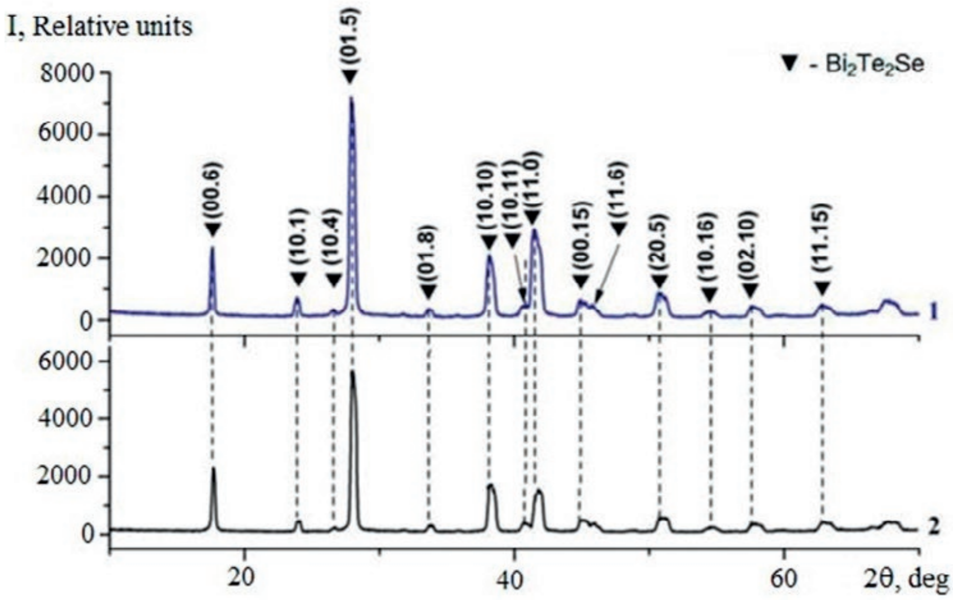

Fig. 2. X-ray diffractograms from the surface of the studied samples before (*1*) and after PT in Ar with E_I ~ 125 J/cm^2 (2) [4]

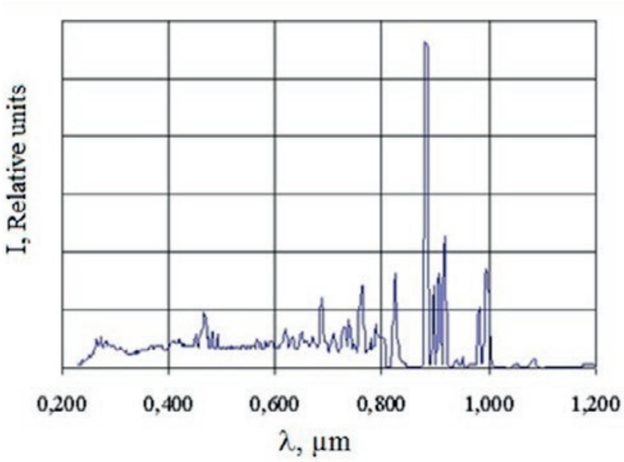

Fig. 3. Spectral distribution of the emission intensity of xenon lamps INP 16/250 [12]

The band gap of bismuth telluride is 0.15÷0.17 eV [15], so the photon energy of xenon lamps is sufficient to activate electronic conduction in the surface layer of the material, the thickness of which is equal to the thickness of the skin layer for the infrared range in Bi_2Te_3. Thus, the concentration of electrons in the surface layer of bismuth telluride at the moment of PT is comparable to the concentration of free electrons in the metal. The free electrons in the metal in the process of scattering electromagnetic waves form a reflected wave of high intensity, allowing a small fraction of the radiation in. As a rule, in the infrared and visible parts of the spectrum the reflection coefficient is larger than in the ultraviolet range [16].

Fig.4 shows the reflection spectra of the surfaces of *z*- and *x*-sections of the original $Bi_2Te_{3-x}Se_x$ samples. As can be seen from the figure, for both samples in the spectrum there are no maxima or minima, indicating polarization or absorption of radiation by the crystal in this region of the spectrum. The curves are monotonic and similar to the dependences observed for metals in the corresponding wavelength range [16]. The reflection coefficient is 20÷28 and 42÷48 % in the ultraviolet and infrared ranges, respectively. A slight difference in the reflectivity of *z*- and *x*-cut samples indicates the lowest roughness of the briquette faces, which are cut perpendicular to the pressing axis. The obtained results are in agreement with the data of [17, 18], in which the lumen studies of thin films of Bi_2Te_3 and $Bi_2Te_{2.7}Se_{0.3}$ with a thickness of ~ 100 nm in the wavelength range of 0.2÷1.1 μm showed low transmittance. Thus, the transmittance ratio for Bi_2Te_3 was not more than 15% and for $Bi_2Te_{2.7}Se_{0.3}$ not more than 3 %.

It can be assumed that for the investigated $Bi_2Te_{3-x}Se_x$ samples the skin effect, i.e. exponential decrease of the absorbed energy at removal from the surface, will be manifested in the process of PT. The skin-layer thickness in bismuth telluride for a given emission spectrum can be estimated by the known approximation $\delta = \frac{1}{\sqrt{\pi \nu \mu \mu_0 \sigma}}$, where ν – emission frequency, μ_0 – magnetic constant;

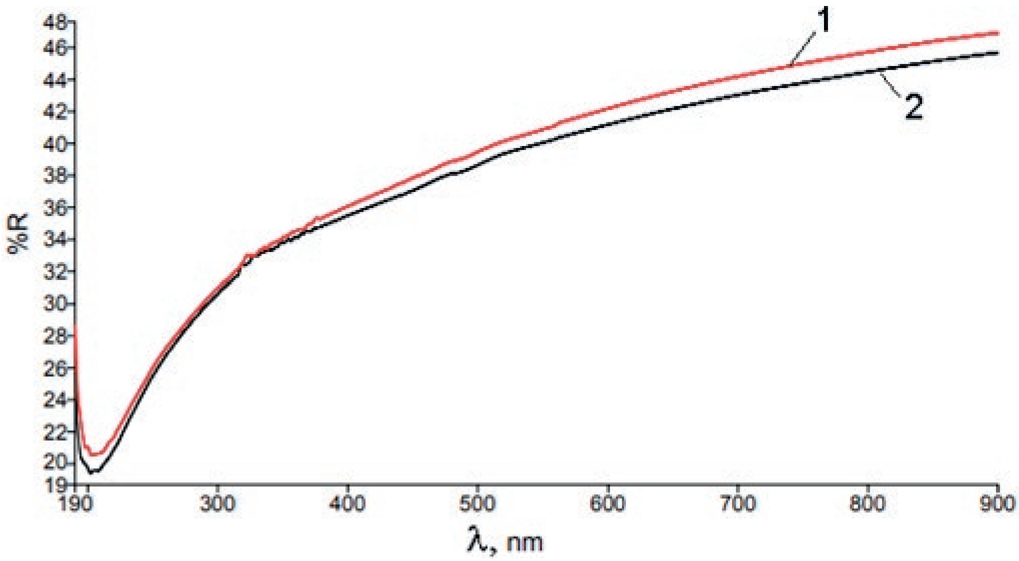

Fig. 4. Reflection coefficient spectra of $Bi_2Te_{3-x}Se_x$ crystals: curve *1* - *z*-cut, curve 2 - *x*-cut

μ – relative magnetic permeability; σ – specific electrical conductivity [19, 20].

Based on the obtained data, Fig. 5 shows the dependence of the skin layer thickness for Bi_2Te_3 on the wavelength and photon energy of PT. The skin layer thickness does not exceed 90 nm for the whole radiation spectrum.

Also, for comparison, we evaluated the radiation absorption depth δ in polycrystalline bismuth telluride films for the wavelength range 0.2÷1.4 μm using in calculations the optical parameters of the material [21, 22]: $\delta = 2/\alpha$, where $\alpha = 4\pi k/\lambda_0$ is the attenuation coefficient, k is the extinction coefficient [22], λ_0 is the wavelength of the incident radiation. The results are presented in Fig. 6.

Comparison of the skin-layer thickness determined from the electrical and optical characteristics in the wavelength range 0.4÷1.2 μm with the results described above allows us to conclude that the entire radiation energy is absorbed in the $Bi_2Te_{3-x}Se_x$ surface layer with a thickness not exceeding 60 nm. Electron-photon interaction takes place in the whole range of xenon lamps, so several mechanisms of acceleration of the recrystallization process of the surface layer are possible. First, energy absorption in a small surface layer leads to surface heating, which initiates active propagation of acoustic phonons in the surface region. Second, a pulsed multiple increase in the number of charge carriers (exclusively in the surface region of the material) will lead to a concentration gradient and diffusion of charge carriers from the surface region into the material volume. These factors will lead to an intense interaction between electrons and acoustic phonons in a skin layer no thicker than 60 nm. As a result of electron-phonon interaction, the concentration of defects, primarily vacancies, increases sharply in the surface region of the material, which accelerates the recrystallization process.

Due to the gradient nature of the energy impact at PT, the collecting recrystallization within the skin layer is very difficult, and secondary recrystallization is possible both within the skin layer and in the volume of the material, which leads to the formation of a gradient grain structure at the surface of the material. Activation of secondary recrystallization in the surface layer of bismuth telluride is due to the nonequilibrium concentration of vacancies that actively diffuse from the skin layer.

The photon energies of xenon lamps are sufficient for the formation and migration of tellurium vacancies (1.41÷1.18 and 0.94÷1.17 eV, respectively [15]). Consequently, for an absorption coefficient $\mu = 2.1–10^7$ m^{-1} (λ ≈ 0.55 μm) [23] at a skin-layer depth of 50 nm, the intensity of absorbed light energy ($I = 0.62 - I_0\exp(-\mu h) \approx 0.2I_0$) is up to 20% of the incident at PT, which corresponds to the number of absorbed quanta of light ≈ $6\cdot10^{19}$. The same layer of irradiated material contains about $3.3\cdot10^{16}$ atoms, so the fraction of atoms in the excited state can be extremely large. It was shown in papers [24–25] that laser irradiation

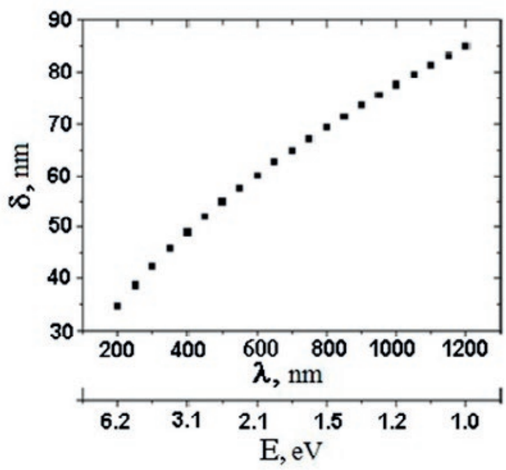

Fig. 5. Graph of dependence of skin layer thickness on the wavelength / photon energy of incident radiation

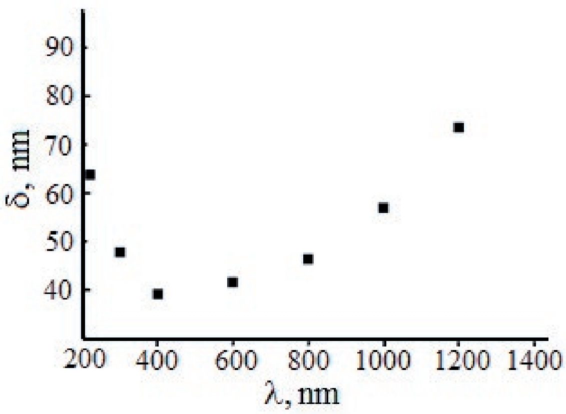

Fig. 6. Dependence of absorption depth for polycrystalline films of bismuth telluride on the wavelength of incident radiation

of metal films initiates a high concentration of nonequilibrium vacancies (up to 10^{-4}). Taking into account practically equal values of vacancy formation energies in metals and bismuth telluride 1.2÷1.4 eV [26] and 1.18÷1.41 eV [15], respectively, we can assume for bismuth telluride the vacancy concentration of ~10^{-4}.

The nature of the PT effect can be analyzed in the framework of the theory of excitation of the electronic subsystem of the crystal by high-energy quanta of light [27]. The skin effect limits light penetration to depths on the order of wavelength. The absorbed energy excites surface electronic states relaxing as a result of electron-phonon interaction mainly by the radiationless mechanism. The probability of such a transition in the Bickson–Jortner model [28] is $P = e^{-\frac{2\pi}{h}\nu_{\text{eff}}^2\rho_{\text{eff}}}$, where ν_{eff}^2 – some effective matrix element of the electron-phonon interaction, and ρ_{eff} – the effective density of electronic states. Excited surface centers propagate hypersonic waves into the sample volume. Emerging phonons of resonance frequencies, determined by elastic parameters and crystal symmetry, have amplitude of oscillations significantly higher than thermal ones. The high energy of vibrating atoms allows them to initiate phase transformations and leads to structural rearrangements. Since the hypersonic velocity is three orders of magnitude greater than the thermal field propagation velocity, powerful hypersonic waves lead to the formation of point crystal defects, which do not occur during heat treatment, or occur at higher temperatures. This photon activation mechanism explains the acceleration of the recrystallization process in metal thin films at PT [11].

It can be seen that the formation of the gradient structure in the surface layer (~500 nm) during the PT of $Bi_2Te_{3-x}Se_x$ plates can be caused by the complex interaction of the processes simultaneously occurring during PT: amorphization, formation of nanocrystalline phase, growth of free electron concentration, generation of nonequilibrium vacancies under the action of hypersonic phonons, flux from the skin layer of point defects, growth of material plasticity, secondary recrystallization initiated by sonic phonons and temperature gradient [29].

A significant increase in the sample surface temperature to 0.4÷1.0 T_{PL} at PT [29] precludes amorphization of the surface region of $Bi_2Te_{3-x}Se_x$ plates. The diffractograms from Bi_2Te_3-Bi_2Se_3 plates after PT show no peaks (Fig. 2), indicating the formation of new phases. Consequently, the processes of phase transformations, formation of superstructures, and spinoidal decomposition can be considered unlikely in the PT process.

Fig. 7 schematically presents an illustration of the processes assisting phase and structural transformations in the PT process.

A conventional division into structural zones near the surface of $Bi_2Te_{3-x}Se_x$ plates can be proposed: 1) the most defective region preserving nanocrystalline phases after PT; 2) the region of structural rearrangement of the material by hypersonic phonons; 3) the region of secondary recrystallization initiated by sonic phonons, a high concentration of mobile point defects

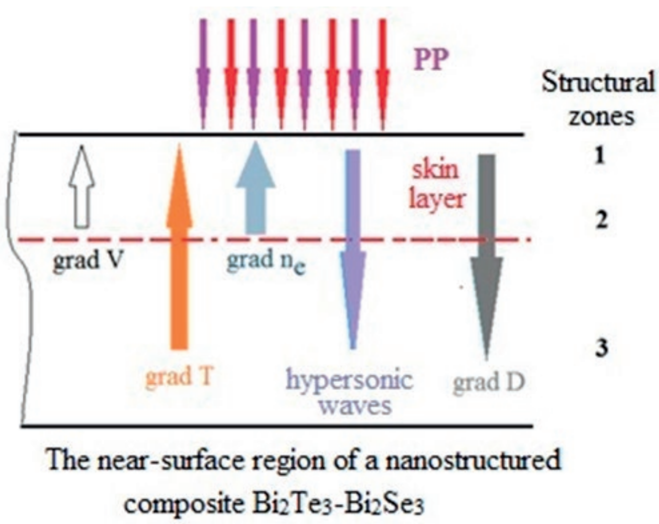

Fig. 7. Schematic illustration of the processes assisting structural transformations at the surface of $Bi_2Te_{3-x}Se_x$ plates during the PT process: V – local vacancy concentration; n_e – concentration of free electrons; T – local temperature; D – average crystallite size; 1, 2, 3 – conditional zones differing in dispersion of the crystal structure

coming from the skin layer. These zones can significantly overlap each other, however, the gradient principle remains and forms a gradient grain structure, where the most dispersed crystallites are located near the surface of the material, and the largest ones - in the depth.

4. Conclusion

Thus, the nature of nanostructuring and formation of gradient layer in the surface layer of bismuth telluride at PT by incoherent radiation of xenon lamps is caused by a sequence of independent processes:

– growth of free electrons concentration;

– decrease of defect formation threshold;

– localization of a large temperature gradient in the skin layer;

– generation and propagation of sonic phonons;

– secondary recrystallization;

– formation of nanocrystalline phase in the Bi-Te-Se system.

As a result of PT by incoherent radiation of xenon lamps, a surface layer with a gradient of the average crystallite size grad *D* is formed. At the free surface the value of grad *D* in the direction of the volume of bismuth telluride reaches the maximum value. High rate of energy impact of broadband radiation of gas-discharge lamps causes nanostructuring of the surface region, changes in structural and morphological parameters and physicochemical properties of the massive semiconductor material $Bi_2Te_{3-x}Se_x$. Determining factors of photon activation of structural transformations: internal photoeffect, decrease of defect formation threshold.

Contribution of the authors

The authors contributed equally to this article.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

References

1. Belonogov E. K., Dybov V. A., Kostyuchenko A. V., Kushev S. B., Serikov D. V., Soldatenko S. A. The effect of pulsed photonic treatment on the mechanical properties of semiconductor thermoelectric branches (based on Bi_2Te_3–Bi_2Se_3 solid solutions) and adhesion of the switching layers. *Journal of Surface Investigation: X-ray, Synchrotron and Neutron Techniques*. 2019;5: 17–24. https://doi.org/10.1134/S0207352819050056

2. Grebennikov A. A., Bocharov A. I., Kushchev S. B., … Safonov I. A. Effect of pulsed photon treatment on electrophysical and thermal properties of *n*-type solid solution on the base of Bi_2Te_3–Bi_2Se_3. I. Electrophysical characteristics. *Physics and Chemistry of Materials Treatment*. 2019;5: 14–20. https://doi.org/10.30791/0015-3214-2019-5-14-20

3. Grebennikov A. A., Bocharov A. I., Kushchev S. B., … Safonov I. A. Effect of pulsed photon treatment on electrophysical and thermal properties of *n*-type solid solution on the base of Bi_2Te_3-Bi_2Se_3. II. Thermal conductivity and thermoelectric figure of merit. *Physics and Chemistry of Materials Treatment*. 2019;6: 22–27. https://doi.org/10.30791/0015-3214-2019-6-22-27

4. Belonogov E. K., Kuschev S. B., Sumets M. P., … Turaeva T. L. The effect of photonic processing on increasing the thermoelectric Q-factor of a solid solution Bi_2Te_3–Bi_2Se_3. *Inorganic Materials: Applied Research*. 2023;14(3): 595–603. https://doi.org/10.1134/s2075113323030061

5. Kapustin Yu. A., Kolokolnikov B. M., Sveshnikov A. A. Photostimulated gold diffusion during pulsed photon processing*. *Semiconductors*. 1990;24(2): 318–322. Available at: http://journals.ioffe.ru/articles/viewPDF/22840

6. Vavilova V. V., Kovneristyi Yu. K., Palii N. A., Timofeev V. N., Ievlev V. M., Isaenko A. P. Effects of thermal annealing and pulsed photon processing on the relaxation and crystallization of amorphous Fe-P-Si alloys. *Inorganic Materials*. 2004;40(2): 152–160. https://doi.org/10.1023/B:INMA.0000016090.36608.2f

7. Ievlev V. M., Soldatenko S. A., Kushev S. B., Gorozhankin Yu. V., Vakhtel V. M. Effect of photon activation during the synthesis of silicide films in the heterosystem (111) Si-Ni-Pt. *Condensed Matter and Interphases*. 2007;9(3): 216–227. (In Russ., abstract in Eng.). Available at: https://elibrary.ru/download/elibrary_9596050_91117226.pdf

8. Belyavskij V. I., Kapustin Yu. A., Sviridov V. V. Subthreshold defect formation during high-power pulse processing of silicon*. *Semiconductors*. 1991;25(7): 1204–1208. (In Russ.). Available at: http://journals.ioffe.ru/articles/viewPDF/23492

9. Kushchev S. B. *Study of the phase composition and substructure of silicides formed during pulsed photon processing of metal films on silicon by incoherent radiation**. Doct. phys. math. sci. diss. Abstr. Voronezh: 2000. 35 p. (In Russ.). Available at: https://viewer.rsl.ru/ru/rsl01000244921?page=1&rotate= 0&theme=white

10. Ievlev V. M., Latyshev A. N., Selivanov V. N., Turaeva T. L., Sinel'Nikov A. A. Effect of photon irradiation on the process of recrystallization of thin metallic films. *Physics of Metals and Metallography*. 2007;103(1): 58–63. https://doi.org/10.1134/s0031918x07010073

11. Ievlev V. M. Activation of solid-phase processes by radiation of gas-discharge lamps. *Russian Chemical Reviews*. 2013;82(9): 815–834. https://doi.org/10.1070/rc2013v082n09abeh004357

12. Serbin O. V. *Synthesis of nanodispersed films of lead titanate and tungsten carbide using pulsed photon processing*. Cand. phys. math. sci. diss. Voronezh: 2003. 119 p. (In Russ.). Available at: https://www.dissercat.com/content/sintez-

nanodispersnykh-plenok-titanata-svintsa-i-karbida-volframa-metodom-impulsnoi-fotonnoi

13. Marshak I. S. *Pulsed light sources**. Moscow – Leningrad: Gosenergoizdat Publ.; 1963. 336 p. (In Russ.)

14. Veis A. N., Zhitinskaya M. K., Lukyanova L. N., Kutasov V. A. Peculiarities of bismuth telluride energy spectrum from optical measurements data. *SPbPU Journal - Physics and Mathematics*. 2013;3(177): 29–41. (In Russ.). Available at: https://physmath.spbstu.ru/userfiles/files/articles/2013/3/03.pdf

15. Fleurial J. P., Gailiard L., Triboulet R., Scherrer H., Scherrer S. Thermal properties of high quality single crystals of bismuth telluride – part I: Experimental characterization. *Journal of Physics and Chemistry of Solids*. 1988;49(10): 1237–1247. https://doi.org/10.1016/0022-3697(88)90182-5

16. Gurevich M. M. *Photometry (theory, methods and instruments)**. Leningrad: Energoatomizdat Publ.; 1983. 272 p. (In Russ.)

17. Saberi Y., Sajjadi S. A., Mansouri H. Comparison of thermoelectric properties of Bi_2Te_3 and $Bi_2Se_{0,3}Te_{2,7}$ thin film materials synthesized by hydrothermal process and thermal evaporation. *Ceramics International*. 2021;47: 11547–11559. https://doi.org/10.1016/j.ceramint.2020.12.285

18. Adam A. M., Tolan M., Refaat A.A., Nafady A., Petkov P., Ataalla M. Optical properties of thin Bi_2Te_3 films synthesized by different techniques. *Superlattices and Microstructures*. 2021;155: 106909. https://doi.org/10.1016/j.spmi.2021.106909

19. Newell D. B., Tiesinga E. The International System of Units (SI). *National Institute of Standards and Technology Special Publication 330*. 2019: 122. https://doi.org/10.6028/NIST.SP.330-2019

20. Ivanov O., Yaprintsev M., Lyubushkin R., Soklakova O. Enhancement of thermoelectric efficiency in Bi2Te3 via rare earth element doping. *Scripta Materialia*. 2018;146: 91–94. https://doi.org/10.1016/j.scriptamat.2017.11.031

21. Carterb M. J., El-Desoukyc A., Matthieu A. A., Philippe B., LeBlanca S. Pulsed laser melting of bismuth telluride thermoelectric materials. *Journal of Manufacturing Processes*. 2019;43: 35–46. https://doi.org/10.1016/j.jmapro.2019.04.021

22. Zimmer A., Stchakovsky M., Stein N., Johann L., Eypert C., Boulanger C. Optical constants of electroplated Bi_2Te_3 films by Mueller matrix spectroscopic ellipsometry. *Thin Solid Films*. 2008;516(10): 2922–2927. https://doi.org/10.1016/j.tsf.2007.06.011

23. Srinivasan R., McReynolds K., Gothard N. W., Spowart J. E. Texture development during deformation processing of the *n*-type bismuth telluride alloy $Bi_2Se_{0.3}Te_{2.7}$. *Materials Science and Engineering: A*. 2013;588(A): 376–387. https://doi.org/10.1016/j.msea.2013.09.044.

24. Markevich M. I., Tochizki I. I., Chaplanov A. M. On the kinetics of redistribution of vacancies in f.c.c. metals films under high rate heating. *Thin Solid Films*. 1989;168(3): 363–368. https://doi.org/10.1016/0040-6090(89)90020-5

25. Markevich M. I., Chaplanov A. M. Structural transformations in thin metal films under pulsed laser irradiation. *Proceedings of the National Academy of Sciences of Belarus. Physical-technical series (Vestsi Natsyyanal'nai akademii navuk Belarusi. Seryya fizika-tekhnichnykh navuk)*. 2016;1: 28–35. (In Russ.) Available at: https://vestift.belnauka.by/jour/article/view/151/152

26. Honeycomb R. *Plastic deformation of metals**. Moscow: Mir; 1972. 408 p. (In Russ.)

27. Vavilova V. V., Ievlev V. M., Isaenko A. P., … Selivanov V. N. Hypersonic mechanism of photon activation of solid-phase processes*. In: *The effect of electromagnetic fields on the plasticity and strength of materials. Materials of the 5th international conference, February 14–15, 2003*. Voronezh: VSTU Publ.; 2003. p. 31–33. (In Russ.)

28. Medvedev E. S., Osherov V. I. *Theory of non-radiative transitions in polyatomic molecules**. Moscow: Nauka Publ.; 1983. 280 p. (In Russ.)

29. Belonogov E. K., Dybov V. A., Kostyuchenko A. V., … Soldatenko S. A. Modification of the surface of thermoelectric branches based on a Bi_2Te_3–Bi_2Se_3 solid solution by pulse photon treatment method. *Condensed Matter and Interphases*. 2017;19(4): 479–488. (In Russ., abstract in Eng.). Available at: https://elibrary.ru/download/elibrary_32322272_25557687.pdf

** Translated by author of the article*

Information about the authors

Belonogov Evgeniy Konstantinovich, Dr. Sci. (Phys.-Math.), Associate Professor, Professor at the Department of Physics, Voronezh State Technical University (Voronezh, Russian Federation).

https://orcid.org/0000-0002-0216-0986
ekbelonogov@mail.ru

Kushchev Sergey Borisovich, Dr. Sci. (Phys.-Math.), Professor, Professor at the Department of Physics, Voronezh State Technical University (Voronezh, Russian Federation).

https://orcid.org/0000-0003-1263-1806
kushev_sb@mail.ru

Serikov Dmitry Vladimirovich, Cand. Sci. (Phys.-Math.), Research Engineer, Voronezh Design Bureau of Communications (Voronezh, Russian Federation).

https://orcid.org/0000-0002-0464-3500
dmitriy.tut@mail.ru

Soldatenko Sergey Anatolievich, Cand. Sci. (Phys.-Math.), Research Fellow, Associated Professor at the Department of Physics, Voronezh State Technical University (Voronezh, Russian Federation).

https://orcid.org/0000-0002-3927-2738
cossack408@mail.ru

Turaeva Tatyana Leonidovna, Cand. Sci. (Phys.-Math.), Associate Professor, Head of the Department of Physics, Voronezh State Technical University (Voronezh, Russian Federation).

https://orcid.org/0000-0002-6126-1605
tlturaeva@mail.ru

Received 10.01.2025; approved after reviewing 13.02.2025; accepted for publication 17.02.2025; published online 25.06.2025.