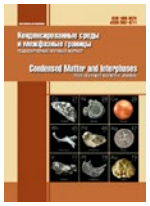

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The solid-phase equilibria in the $GeBi_2Te_4$-$SnBi_2Te_4$-Bi_2Te_3 system at 300 K and the characterization of tetradymite-type layered solid solutions

E. R. Nabiyev[1], E. N. Orujlu[2]✉, A. I. Aghazade[3], A. A. Hasanov[4], M. B. Babanly[3,4]

[1]*Ganja State University,*
429 Heydar Aliyev ave., Ganja AZ-2001, Azerbaijan

[2]*Azerbaijan State Oil and Industry University,*
6/2,1 Azadlıq ave., Baku AZ-1010, Azerbaijan

[3]*Institute of Catalysis and Inorganic Chemistry,*
113 H. Javid ave., Baku, AZ-1143, Azerbaijan

[4]*Baku State University,*
23 Z. Khalilov, Baku Az-1048, Azerbaijan

Abstract

The GeTe-SnTe-Bi_2Te_3 system is of great interest due to the potential formation of a series of cation-substituted solid solutions based on ternary layered compounds with a tetradymite-type structure, which have significant potential as valuable thermoelectric materials and topological insulators. This study presents the results of investigating this system in the composition range of $GeBi_2Te_4$-$SnBi_2Te_4$-Bi_2Te_3 using powder X-ray diffraction analysis. Particular attention is given to obtaining equilibrium alloys.

An isothermal section of the phase diagram at 300 K has been constructed, consisting of four single-phase regions separated by three two-phase regions. The X-ray diffraction patterns of the equilibrium alloys were refined using the Rietveld method. The obtained diffraction results clearly indicate the presence of continuous series of solid solutions along the sections $GeBi_2Te_4$-$SnBi_2Te_4$, $GeBi_4Te_7$-$SnBi_4Te_7$, and $GeBi_6Te_{10}$-$SnBi_6Te_{10}$. The lattice parameters for all the solid solution series were determined, showing a linear increase with the rise in Sn concentration.

Keywords: Solid solutions, Germanium bismuth tellurides, Tin bismuth tellurides, Topological insulators, Isothermal section, XRD

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✉ Elnur N. Orujlu, e-mail: elnur.oruclu@yahoo.com

1. Introduction

The quest for advanced materials with enhanced properties has led to extensive research in the field of multi-component chalcogenides, particularly those based on *M*-Bi-Te (*M* – Ge, Sn, Pb, and Mn) systems [1–8]. These materials, which have attracted great interest due to their thermoelectric properties, have been intensively studied in recent years again as materials exhibiting properties of a new quantum state of matter – topological insulators [9–14]. Topological insulators (TIs) are a class of materials that have garnered significant interest due to their ability to conduct electricity on their surfaces while remaining insulating in their bulk [15–18].

Recently, a homologues series of layered ternary compounds with a general formula of $n\mathrm{A^{IV}Te}{\cdot}m\mathrm{Bi_2Te_3}$ have gained great attention for their unique electronic structures. Systhematic investigations into ternary compounds in these chalcogenides systems show that these tetradymite-type layered van der Waals phases are 3D Tls and hold potential for revolutionary applications in spintronics, quantum computing, and low-power electronics [19–24]. All these compounds share a structural similarity as they belong to the tetradymite-type layered structure which is composed of repeating units of quintuple or septuple layers, typically consisting of alternating atomic layers such as chalcogenides (e.g., Se or Te) and metals (e.g., Bi or Sb with *M* – Ge, Sn, Pb, and Mn) [1–4; 14]. Research on existing layered topological insulator phases indicates that addressing the limitations of their applicability across various fields necessitates the precise tuning of their bulk band structure. An effective approach to promoting electron transport dominated by topologically protected states is through targeted chemical substitution, whereby specific atomic sites in the material's crystal lattice are replaced to modify its electronic structure and enhance the prevalence of these states. This type of topological engineering has been previously studied in numerous works and has demonstrated significant potential for tuning material properties and improving performance for application prospects [25–30].

In this study, by means of differential thermal analysis (DTA) and powder X-ray diffraction (XRD) methods, we studied solid-phase equilibria diagram in the $GeBi_2Te_4$-$SnBi_2Te_4$-Bi_2Te_3 system at 300 K and characterized the $Ge_{1-x}Sn_xBi_2Te_4$, $Ge_{1-x}Sn_xBi_4Te_7$, and $Ge_{1-x}Sn_xBi_6Te_{10}$ continuous series of solid solutions with examining compositional effects on the material's crystalline behaviours. Our findings provide insights into the phase diagrams of the GeTe-SnTe-Bi_2Te_3 pseudoternary system and contribute to understanding the influence of Ge↔Sn substitution on the thermodynamic and structural properties of these topological insulator compounds. Data on phase equilibria in the boundary systems GeTe-Bi_2Te_3 and SnTe-Bi_2Te_3 are taken from [2, 5].

2. Experimental

The starting materials for the preparation of alloys were high-purity germanium pieces (Alfa Aesar, CAS 7440-56-4), tin lump (Alfa Aesar, CAS 7440-31-5), bismuth shots (Alfa Aesar, CAS 7440-69-9), and tellurium lump (Alfa Aesar, CAS 13494-80-9). During the first stage, GeTe, SnTe, and Bi_2Te_3 binary compounds were synthesized. The phase purity of the synthesized binary compounds was checked via DTA and powder XRD methods. Alloys of the studied systems with different compositions were prepared using presynthesized binary compounds. The weighed three components were sealed in quartz ampoules, then melted at 1050 K for 6 h, followed by rapid quenching in ice water. All the ampoules were then placed in a muffle furnace at a temperature of 770 K for 720 hours to achieve a state close to equilibrium. After heat treatment, the alloys were cooled in a switched off furnace.

Powder XRD and DTA techniques were used to characterize the products. The temperatures of the phase transformations were determined by DTA using the LINSEIS HDSC PT1600 system (heating rate of 10 °C/min) and a multichannel DTA device based on a TC-08 Thermocouple Data Logger. Powder X-ray diffraction (XRD) was examined on Bruker D2 PHASER diffractometer using $\mathrm{Cu}K\alpha_1$ radiation within a scanning range of $2\theta = 5\div75$. COD and PDF-2 databases were used for the interpretation of the powder diffraction patterns. Both qualitative and quantitative assessments of the XRD patterns were carried out using Rietveld analysis with FullProf and HighScore Plus software package.

3. Results and discussion

The powder XRD patterns of annealed alloys of $Ge_{1-x}Sn_xBi_2Te_4$ systems are shown in Fig. 1. The observed peaks of the XRD patterns indicate a trigonal symmetry with the *R*-3*m* space group. As can be seen, the diffraction peaks exhibit a systematic shift towards lower 2θ angles as the Sn content increases, indicating an expansion of the lattice due to the larger atomic radius of Sn compared to Ge. Additionally, the absence of any new peaks or the splitting of existing peaks suggests that no phase separation occurs, confirming the formation of a continuous solid solution. The broadening of peaks with increasing Sn content may also be attributed to microstrains or slight variations in crystallite size as the alloy composition changes. Overall, these patterns confirm the successful incorporation of Sn into the Ge-Bi-Te matrix, leading to a tunable modification of the crystal structure without disrupting the overall phase stability.

Similarly, the XRD patterns of $Ge_{1-x}Sn_xBi_4Te_7$ exhibit a comparable trend (see Fig. 2) with a systematic shift of diffraction peaks towards lower 2θ angles as the Sn concentration increases. This shift, like in the $Ge_{1-x}Sn_xBi_2Te_4$ system, indicates an expansion of the lattice due to the substitution of Sn for Ge. The consistency of this shift across the entire compositional range supports the formation of a continuous solid solution along the $GeBi_4Te_7$-$SnBi_4Te_7$ section.

The XRD patterns of alloys of the $GeBi_6Te_{10}$-$SnBi_6Te_{10}$ section also show a similar shift towards lower 2θ angles with increasing Sn content, indicating lattice expansion and the formation of a continuous solid solution without

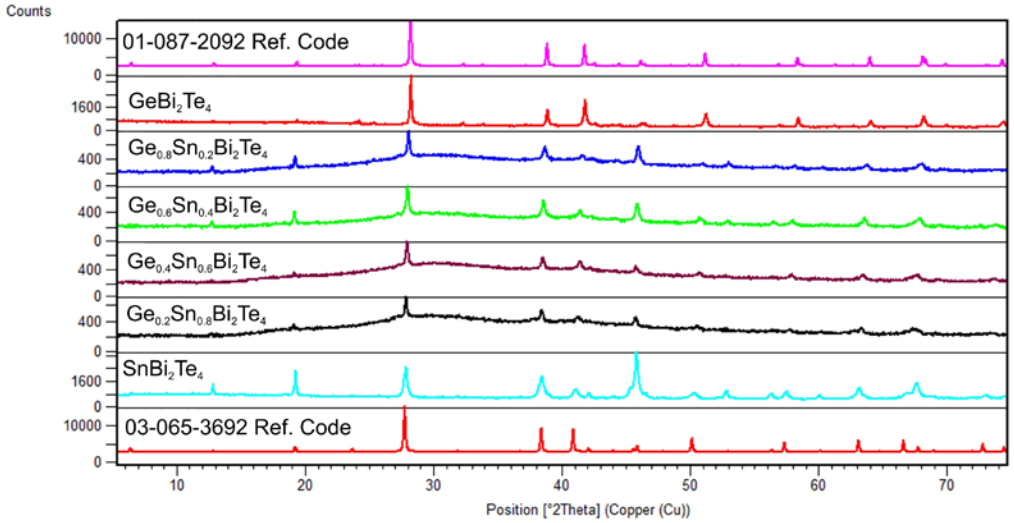

Fig. 1. Powder XRD patterns of $Ge_{1-x}Sn_xBi_2Te_4$ alloys

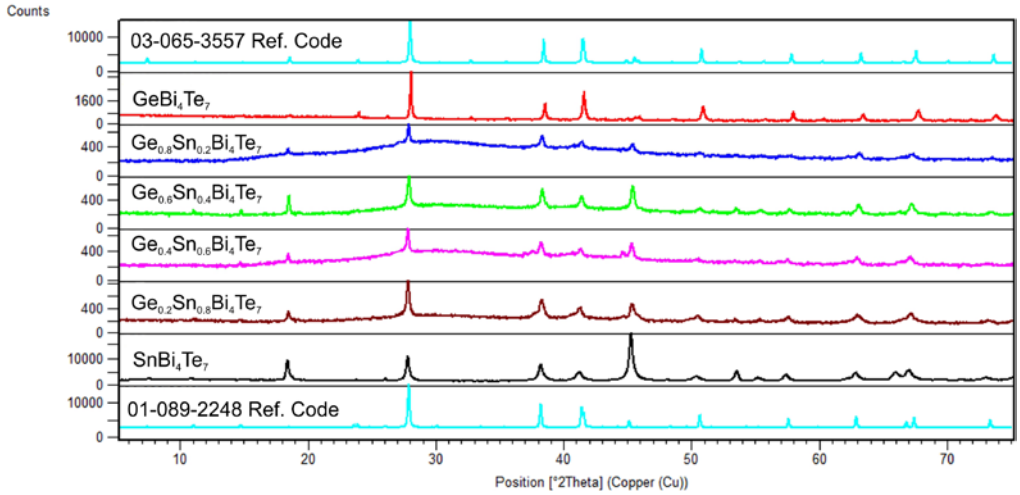

Fig. 2. Powder XRD patterns of $Ge_{1-x}Sn_xBi_4Te_7$ alloys

phase separation, as seen in Fig. 3. Thus, based on the obtained results, it can be stated that the $GeBi_2Te_4$-$SnBi_2Te_4$, $GeBi_4Te_7$-$SnBi_4Te_7$, and $GeBi_6Te_{10}$-$SnBi_6Te_{10}$ sections of the GeTe-SnTe-Bi_2Te_3 system are characterized by the formation of continuous series of solid solutions below the subsolidus temperature.

The structural parameters of all the alloys were refined by the Rietveld technique. Powder XRD-based Rietveld refinements yield the final lattice parameter values by showing good agreement between the experimental and calculated profiles across all compositions. Calculated lattice parameters for the $Ge_{1-x}Sn_xBi_2Te_4$, $Ge_{1-x}Sn_xBi_4Te_7$, and $Ge_{1-x}Sn_xBi_6Te_{10}$ solid solutions were listed in Table 1. It can been seen that the values obtained by our refinements for all ternary end-member compounds are in good agreement with the values of the literature [2, 5]. Results for intermediate compositions are consistent with Vegard's law, which describes the linear relationship between lattice parameters and composition in solid solutions. The variation of lattice parameters *a*, and *c* with the Sn content is presented in Fig. 4 (a), (b), and (c). As expected,

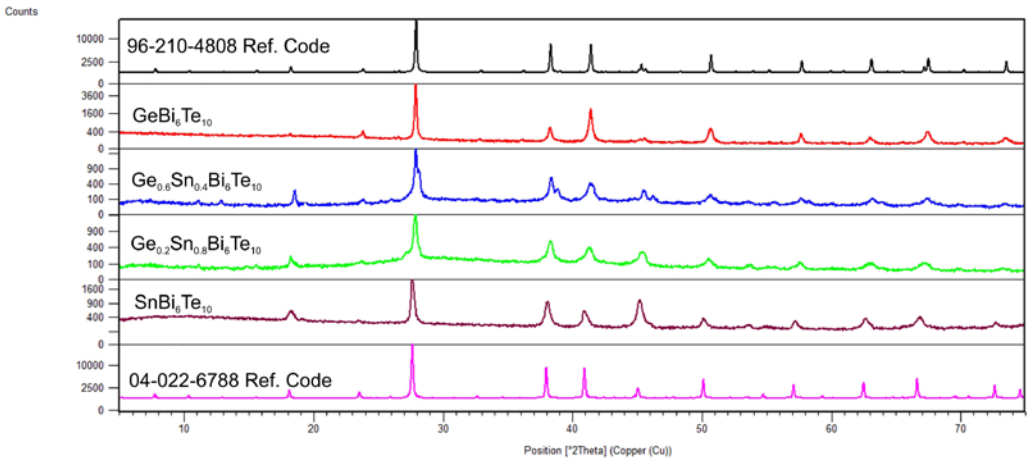

Fig. 3. Powder XRD patterns of $Ge_{1-x}Sn_xBi_6Te_{10}$ alloys

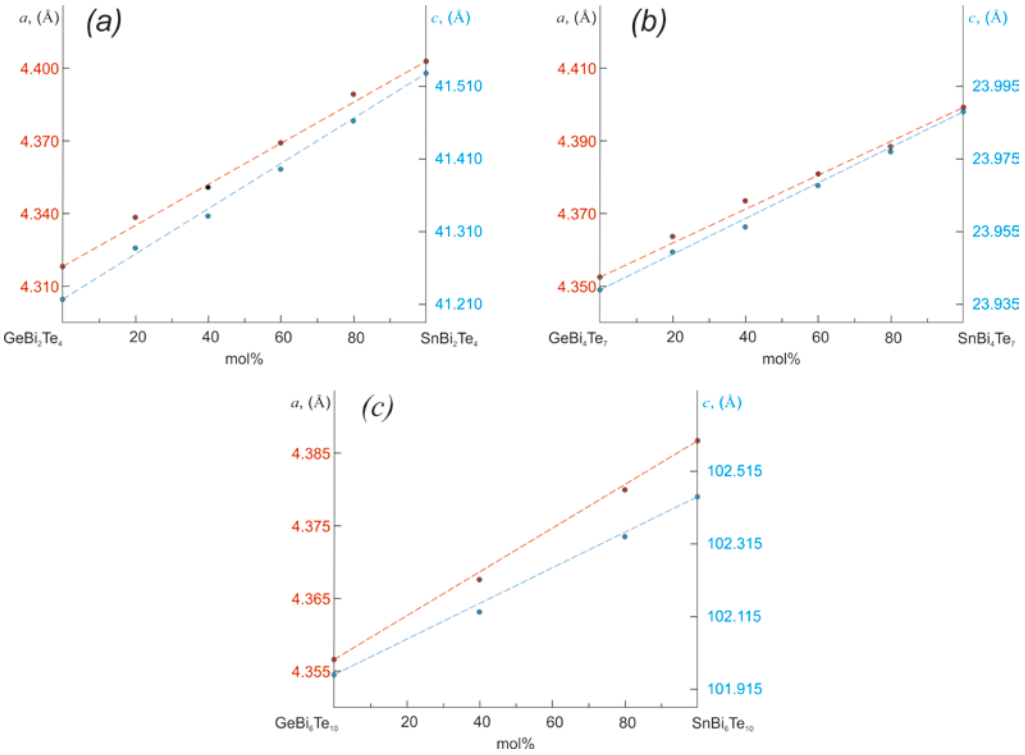

Fig. 4. Dependence of lattice parameters *a* and *c* for alloys of $Ge_{1-x}Sn_xBi_2Te_4$ (a), $Ge_{1-x}Sn_xBi_4Te_7$ (b), and $Ge_{1-x}Sn_xBi_6Te_{10}$ (a) systems versus Sn content

Table 1. Crystal structure parameters of some phases

Composition, mol%	Lattice parameters, Å		Ref.
	a	*c*	
$Ge_{1-x}Sn_xBi_2Te_4$			
x = 0.0	4.3176(3)	41.259(5)	[5]
	4.3181(4)	41.217(5)	This work
x = 0.2	4.3384(2)	41.288(3)	This work
x = 0.4	4.3508(7)	41.332(5)	This work
x = 0.6	4.3691(4)	41.396(4)	This work
x = 0.8	4.3892(3)	41.462(5)	This work
x = 1.0	4.4035(3)	41.511(2)	[25]
	4.4029(3)	41.528(5)	This work
$Ge_{1-x}Sn_xBi_4Te_7$			
x = 0.0	4.3556(2)	23.928(4)	[5]
	4.3525(4)	23.939(2)	This work
x = 0.2	4.3637(2)	23.949(4)	This work
x = 0.4	4.3735(5)	23.956(3)	This work
x = 0.6	4.3809(7)	23.967(7)	This work
x = 0.8	4.3884(1)	23.977(1)	This work
x = 1.0	4.3998(2)	23.981(3)	[31]
	4.3992(5)	23.988(6)	This work
$Ge_{1-x}Sn_xBi_6Te_{10}$			
x = 0.0	4.3572(3)	101.911(2)	[5]
	4.3566(1)	101.918(4)	This work
x = 0.4	4.3676(8)	102.128(3)	This work
x = 0.8	4.3799(5)	102.335(1)	This work
x = 1.0	4.3873(8)	102.431(1)	[32]
	4.3867(2)	102.438(4)	This work

both lattice parameters increase with increasing concentration of Sn content due to the larger ionic radius of Sn^{2+} compared to Ge^{2+}.

Fig. 5 shows the solid-phase equilibrium diagram of the $GeBi_2Te_4$-$SnBi_2Te_4$-Bi_2Te_3 system at 300 K constructed using the above experimental results and literature data. The isothermal section consists of four monophasic and three two-phase regions. As mentioned above, three out of four single-phase regions belong to a continuous series of solid solutions which are the ε-, φ-, and χ-phases. The β-phase corresponds to the homogeneity region of Bi_2Te_3, which we delimited taking into account the data from [2, 5]. The formation of biphasic areas is confirmed with XRD. Alloy #1 clearly demonstrated that the ε-phase is in equilibrium with the φ-phase, as shown in Fig. 6 (a). Similarly, alloy #2 (Fig. 2(b)) had two equilibrium phases, which were identified as the φ- and χ- phases. Since both alloy compositions located on the Ge-rich side of the diagram (see Fig. 5), reference XRD lines shown in Fig. 6 (a) and (b) were chosen for comparison from germanium ternary compounds.

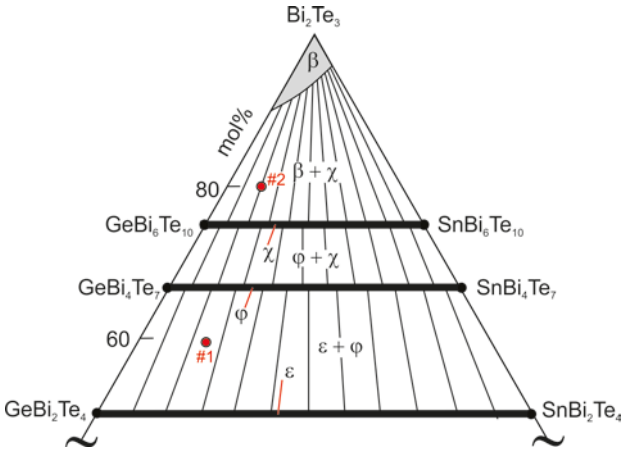

Fig. 5. The solid-phase equilibrium diagram of the $GeBi_2Te_4$-$SnBi_2Te_4$-Bi_2Te_3 system at 300 K. Red circles show alloy compositions for XRD in Fig. 6

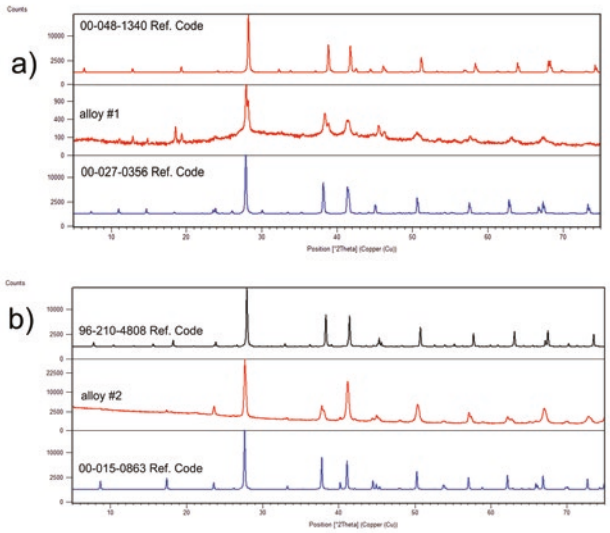

Fig. 6. Powder XRD patterns of alloys #1 and #2 in Fig. 5

4. Conclusions

In this work, based on the results of XRD of equilibrium alloys, a solid-phase equilibrium diagram of the GeTe-SnTe-Bi_2Te_3 system in the composition range of $GeBi_2Te_4$-$SnBi_2Te_4$-Bi_2Te_3 at 300 K was constructed. It was established that this subsystem is characterized by the formation of continuous series of substitution solid solutions with the general formula $Ge_{1-x}Sn_xBi_2Te_4$, $Ge_{1-x}Sn_xBi_4Te_7$ and $Ge_{1-x}Sn_xBi_6Te_{10}$ with a layered tetradymite-type structure and a wide homogeneity region based on Bi_2Te_3. The lattice parameters of the above-mentioned series of solid solutions were refined based on powder diffraction patterns using the Rietveld method. It is shown that their concentration dependences are in good agreement with Vegard's law. The solid solutions obtained in this work are of practical interest from the point of view of developing new topological insulators and thermoelectric materials with adjustable properties.

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.

Contribution of the authors

The authors contributed equally to this article.

References

1. Aliev Z. S., Amiraslanov I. R., Nasonova D. I., ... Chulkov E. V. Novel ternary layered manganese bismuth tellurides of the MnTe-Bi_2Te_3 system: synthesis and crystal structure. *Journal of Alloys and Compounds*. 2019;789: 443–450. https://doi.org/10.1016/j.jallcom.2019.03.030

2. Orujlu E. N., Seidzade A .E., Babanly D. M., Amiraslanov I. R., Babanly M. B. New insights into phase equilibria of the SnTe–Bi_2Te_3 pseudo-binary system: synthesis and crystal structure of new tetradymite-type compound $Sn_3Bi_2Te_6$. *Journal of Solid State Chemistry*. 2024;330: 124494. https://doi.org/10.1016/j.jssc.2023.124494

3. Seidzade A. E., Orujlu E. N., Doert T., Amiraslanov I. R., Aliev Z. S., Babanly M. B. An updated phase diagram of the SnTe-Sb_2Te_3 system and the crystal structure of the new compound $SnSb_4Te_7$. *Journal of Phase Equilibria and Diffusion*. 2021;42: 373–8. https://doi.org/10.1007/s11669-021-00888-8

4. Alakbarova T. M., Meyer H.-J., Orujlu E. N., Amiraslanov I. R., Babanly M. B. Phase equilibria of the GeTe–Bi_2Te_3 quasi-binary system in the range 0–50 mol% Bi_2Te_3. *Phase Transitions*. 2021;94: 366–75. https://doi.org/10.1080/01411594.2021.1937625

5. Alakbarova T. M., Meyer H.-J., Orujlu E. N., Babanly M. B. A refined phase diagram of the GeTe-Bi_2Te_3 system. *Kondensirovannye Sredy I Mezhfaznye Granitsy = Condensed Matter and Interphases*. 2022;24: 11–18. https://doi.org/10.17308/kcmf.2022.24/9050

6. Huang D., Xia D., Ye T., Fujita T. New experimental studies on the phase relationship of the Bi–Pb–Te system. *Materials & Design*. 2022;224: 111384. https://doi.org/10.1016/j.matdes.2022.111384

7. Omoto T., Kanaya H., Ishibashi H., Kubota Y., Kifune K., Kosuga A. Formation phases and electrical properties of Ge-Bi-Te compounds with homologous structures. *Journal of Electronic Materials*. 2015;45: 1478–83. https://doi.org/10.1007/s11664-015-4083-z

8. Gojayeva I. M., Babanly V. I., Aghazade A. I., Orujlu E. N. Experimental reinvestigation of the PbTe–Bi_2Te_3 pseudo-binary system. *Azerbaijan Chemical Journal*. 2022;0: 47–53. https://doi.org/10.32737/0005-2531-2022-2-47-53

9. Heremans J. P., Cava R. J., Samarth N. Tetradymites as thermoelectrics and topological insulators. *Nature Review Materials*. 2017;2: 17049. https://doi.org/10.1038/natrevmats.2017.49

10. Banik A., Roychowdhury S., Biswas K. The journey of tin chalcogenides towards high-performance thermoelectrics and topological materials. *Chemical Communications*. 2018;54: 6573–6590. https://doi.org/10.1039/c8cc02230e

11. Lukyanova L. N., Usov O. A., Volkov M. P., Makarenko I. V. Topological thermoelectric materials based on bismuth telluride. *Nanotechnologly Reports*. 2021;16: 282–293. https://doi.org/10.1134/s2635167621030125

12. Xu N., Xu Y., Zhu J. Topological insulators for thermoelectrics. *Npj Quantum Materials*. 2017;2(1). https://doi.org/10.1038/s41535-017-0054-3

13. Yang T., Yang Y., Wang X., Zhang G., Cheng Z. Topological thermoelectrics: new opportunities and challenges. *Materials Today Chemistry*. 2023;30: 101488. https://doi.org/10.1016/j.mtchem.2023.101488

14. Babanly M. B., Chulkov E. V., Aliev Z. S., Shevelkov A. V., Amiraslanov I. R. Phase diagrams in materials science of topological insulators based on metal chalcogenides. *Russian Journal of Inorganic Chemistry*. 2017;62: 1703–1729. https://doi.org/10.1134/S0036023617130034

15. Hasan M. Z., Kane C. L. Colloquium: topological insulators. *Review of Modern Physics*. 2010;82: 3045–3067. https://doi.org/10.1103/revmodphys.82.3045

16. Qi X.-L., Zhang S.-C. Topological insulators and superconductors. *Review of Modern Physics*. 2011;83: 1057–1110. https://doi.org/10.1103/revmodphys.83.1057

17. Zhang H., Liu C.-X., Qi X.-L., Dai X., Fang Z., Zhang S.-C. Topological insulators in $BiSe_3$, Bi_2Te_3 and Sb_2Te_3 with a single Dirac cone on the surface. *Nature Physics*. 2009;5: 438–442. https://doi.org/10.1038/nphys1270

18. Rachel S. Interacting topological insulators: a review. *Reports on Progress in Physics*. 2018;81: 116501. https://doi.org/10.1088/1361-6633/aad6a6

19. McGuire M. A., Zhang H., May A. F., ... Yan J. Superconductivity by alloying the topological insulator $SnBi_2Te_4$. *Physical Review Materials*. 2023;7. https://doi.org/10.1103/physrevmaterials.7.034802

20. Saxena A., Karn N. K., Sharma M. M., Awana V. P. S. Detailed structural and topological analysis of $SnBi_2Te_4$ single crystal. *Journal of Physics and Chemistry of Solids*. 2023;174: 111169. https://doi.org/10.1016/j.jpcs.2022.111169

21. Wang L-L. Highly tunable band inversion in AB_2X_4 (*A*=Ge, Sn, Pb; *B*=As, Sb, Bi; *X*=Se, Te) compounds. *Physical Review Materials*. 2022;6. https://doi.org/10.1103/physrevmaterials.6.094201

22. Marcinkova A., Wang J. K., Slavonic C., ... Morosan E. Topological metal behavior in $GeBi_2Te_4$ single crystals. *Physical Review B*. 2013;88. https://doi.org/10.1103/physrevb.88.165128

23. Klimovskikh I. I., Otrokov M. M., Estyunin D., ... Chulkov E. V. Tunable 3D/2D magnetism in the $(MnBi_2Te_4)(Bi_2Te_3)$m topological insulators family. *Npj Quantum Materials*. 2020;5. https://doi.org/10.1038/s41535-020-00255-9

24. Kuroda K., Miyahara H., Ye M., ... Kimura A. Experimental verification as a 3D topological insulator. *Physical Review Letters*. 2012;108. https://doi.org/10.1103/physrevlett.108.206803

25. Orujlu E. Phase equilibria in the $SnBi_2Te_4$–$MnBi_2Te_4$ system and characterization of the $Sn_{1-x}Mn_xBi_2Te_4$ solid solutions. *Physics and Chemistry of Solid State*. 2020;21: 113–116. https://doi.org/10.15330/pcss.21.1.113-116

26. Pan L., Li J., Berardan D., Dragoe N. Transport properties of the $SnBi_2Te_4$–$PbBi_2Te_4$ solid solution. *Journal of Solid State Chemistry*. 2015;225: 168–173. https://doi.org/10.1016/j.jssc.2014.12.016

27. Frolov A. S., Usachov D. Yu., Tarasov A. V., ... Yashina L. V. Magnetic Dirac semimetal state of $(Mn,Ge)Bi_2Te_4$. *Communications Physics*. 2024;7. https://doi.org/10.1038/s42005-024-01675-w

28. Wang S., Xing T., Hu P., ... Chen, L. Optimized carrier concentration and enhanced thermoelectric properties in $GeSb_{4-x}Bi_xTe_7$ materials. *Applied Physics Letters*. 2022;121. https://doi.org/10.1063/5.0123298

29. Qian T., Yao Y.-T., Hu C., ... Ni N. Magnetic dilution effect and topological phase transitions in $(Mn_{1-x}Pb_x)Bi_2Te_4$. *Physical Review B*. 2022;106. https://doi.org/10.1103/physrevb.106.045121

30. Tokumoto Y., Sugimoto K., Hattori Y., Edagawa K. Electronic transport properties of $Pb(Bi_{1-x}Sb_x)_2(Te_{1-y}Se_y)_4$ topological insulator. *Journal of Applied Physics*. 2022;131. https://doi.org/10.1063/5.0077002

31. Aghazade A. I. Phase relations and characterization of solid solutions in the $SnBi_2Te_4$–$PbBi_2Te_4$ and $SnBi_4Te_7$–$PbBi_4Te_7$ systems. *Azerbaijan Chemical Journal*. 2022;0(3): 75–80. https://doi.org/10.32737/0005-2531-2022-3-75-80

32. Aghazade A. I., Orujlu E. N., Salimov Z. E., Mammadov A. N., Babanly M. B. Experimental investigation of the solid phase equilibria at 300 K in the $SnBi_2Te_4$-$PbBi_2Te_4$-Bi_2Te_3 system. *Physics and Chemistry of Solid State*. 2023;24: 453–459. https://doi.org/10.15330/pcss.24.3.453-459

Information about the authors

Elnur R. Nabiyev, PhD student, Ganja State University (Ganja, Azerbaijan).

https://orcid.org/0009-0006-1907-3957

azechemist@gmail.com

Elnur N. Orujlu, PhD in Chemistry, Head of "Nanomaterials and nanotechnologies" science-research laboratory, Azerbajan State Oil and Industry University (Baku, Azerbaijan).

https://orcid.org/0000-0001-8955-7910

elnur.oruclu@yahoo.com

Aytan I. Aghazade, PhD student, Researcher at the Institute of Catalysis and Inorganic Chemistry (Baku, Azerbaijan).

https://orcid.org/0000-0002-6072-1075

aytenagazade94@gmail.com

Alakbar A. Hasanov, Dr. Sci. (Tech.), Professor, Azerbajan State Oil and Industry University (Baku, Azerbaijan).

https://orcid.org/0000-0001-7505-4925

alakbar48-48@mail.ru

Mahammad B. Babanly, Dr. Sci. (Chem.), Professor, Associate Member of the Azerbaijan National Academy of Sciences, Deputy-director of the Institute of Catalysis and Inorganic Chemistry (Baku, Azerbaijan).

https://orcid.org/0000-0001-5962-3710

babanlymb@gmail.com

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