Experimental Study of the Tl$_4$PbTe$_3$-Tl$_9$TbTe$_6$-Tl$_9$BiTe$_6$ Section of the Tl-Pb-Bi-Tb-Te System

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The aim of the present study was to determine the phase relations in the Tl$_4$PbTe$_3$-Tl$_9$TbTe$_6$-Tl$_9$BiTe$_6$ section of the Tl-Pb-Bi-Tb-Te system. Based on a set of the methods of the physicochemical analysis (differential thermal analysis, powder X-ray diffraction method as well as microhardness measurements), the phase diagram of the Tl$_4$PbTe$_3$-Tl$_9$TbTe$_6$ boundary system, some isopleth sections, liquidus and solidus surfaces projections, as well as isothermal sections at 840 and 860 K, were plotted. Unlimited solid solutions with the Tl$_5$Te$_3$ structure (δ-phase) were found in the system, which are of interest as a thermoelectric materials.

Keywords: thallium-lead telluride, thallium-terbium tellurides, thallium-bismuth tellurides, phase equilibria, liquidus and solidus surfaces, solid solutions.

1. Introduction

Presently, great interest has devoted to the chalcogenides of heavy metals as prospective functional materials which found applications in the wide range of devices such as computer memories, chemical sensors, photo-detectors, solar cells, thermoelectric and optical devices, and ionic sensors1-4. Some of them expected as a good candidates for use in the spintronic devices5,6. The rare-earth materials, including chalcogenides, have been intensively investigated owing to their promising functional properties7-11.

Tl$_5$Te$_3$ compound crystallizes in tetragonal structure (Sp. gr.I4/mcm, a = 8.930; c = 12.598 Å, z=4)12,13. The formula Tl$_5$Te$_3$ can thus be rewritten as Tl$_{16}$[TlTe$_3$]$_4$. The thallium atoms on the 4c site can be partially or fully replaced by other elements, resulting in a group of ternary compounds: Tl$_4$AVTe$_3$ and Tl$_9$BVTe$_6$ -type (A IV-Sn, Pb; B V-Sb, Bi)14-17. Above-stated compounds possess a good thermoelectric performance18-21 whereas Tl$_9$BiTe$_6$ found to have excellent thermoelectric properties with extremely low thermal conductivity at room temperature19. As it was shown by authors of the Ref.21, the bulk superconductor Tl$_5$Te$_3$ and its tin-doped derivative [Tl$_{1-x}$Sn$_x$]Te$_3$ have Dirac-like surface states. Moreover, Tl$_5$SnS$_3$, Tl$_5$SnSe$_3$, Tl$_5$SnTe$_6$ compounds may be used for fabrication of IR induced electrooptically operated gratings22.

New structural analogs of Tl$_5$Te$_3$ with common formula Tl$_5$LnTe$_6$ (Ln-Ce, Nd, Sm, Gd, Tb, Tm) were found in the23,24. Later, the crystal structure, thermoelectric and magnetic properties of a number Tl$_5$LnTe$_6$-type compounds were determined by H.Kleinke and co-workers25,27.

The design and development of novel methods for controlled synthesis and growth of large single crystals require detailed studies of respective phase diagrams28-30. On the other hand, the improvement of thermoelectric performance can be achieved by introduction of the heavy metals into the crystal lattice31. With this aim, we presented the results of the study of phase relations for a number of systems including the Tl$_5$Te$_3$ compound and its structural analogs32-35. The formation of unlimited solid solutions was found for all these systems.

In this paper, we continued to study similar systems and presented the results of the study of the phase relations in the Tl$_4$PbTe$_3$-Tl$_9$TbTe$_6$-Tl$_9$BiTe$_6$ section of the Tl-Pb-Bi-Tb-Te system.

The initial compounds of above-mentioned system were studied in a number of papers. Tl$_4$PbTe$_3$ and Tl$_9$BiTe$_6$ melt congruently at 893 K15 and 830 K17 respectively, while Tl$_9$TbTe$_6$ is formed incongruently at 780 K36. The tetragonal lattice constants are following: a=8.841, c=13.056Å, z=4 (Tl$_4$PbTe$_3$)36; a=8.871; c=12.973 Å, z=2 Tl$_9$TbTe$_6$35; a = 8.855, c = 13.048 Å, z=2 (Tl$_9$BiTe$_6$)37.

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According to Ref. 38, the boundary system Tl₄PbTe₃-Tl₆BiTe₆ is quasi-binary and characterized by the formation of unlimited solid solutions (δ-phase) with Tl₅Te₃-structure.

Other boundary system Tl₉TbTe₆-Tl₉BiTe₆ was shown to contain a continuous series of solid solutions with a Tl₅Te₃ tetragonal structure, but not quasi-binary due to the incongruent melting of Tl₉TbTe₆ compound 32.

2. Experimental

2.1. Materials and syntheses

The ternaries synthesized from the high purity elements (Tl-99.999%, Pb-99.99%, Tb-99.9%, Bi-99.999%, Te-99.999%). All synthesis were carried out in previously cleaned and dried quartz ampoules. Taking into account the high toxicity of thallium and its compounds, we used protective gloves at all times when working.

Stoichiometric amounts of the starting components were put into silica tubes of about 20 cm in length and diameter of about 1.5 cm and sealed under a pressure of 10⁻² Pa. Tl₄PbTe₃ and Tl₉BiTe₆ were synthesized by direct synthesis of elemental components in a resistance furnace at 920 K followed by cooling in the switched-off furnace.

The synthesis of Tl₉TbTe₆ was carried out at 1000 K in the graphitized ampoule in order to avoid the interaction between the terbium and quartz. Then the intermediate ingot of Tl₉TbTe₆ was powdered in an agate mortar, thoroughly mixed, pressed into a pellet and annealed at 750 K during ~700 h.

The ampoules were shaken during all the heating process in order to help the complete mixing of all the elements.

We used the differential thermal analysis (DTA) and X-ray diffraction (XRD) methods, as well as microhardness measurements to analyze the samples of the Tl₄PbTe₃-Tl₉TbTe₆-Tl₉BiTe₆ section.

The temperatures of the thermal effects were determined using a NETZSCH 404 F1 Pegasus differential scanning calorimeter within room temperature and ~1400 K at a heating rate of 10 K.min⁻¹ and accuracy of ±2 K. The phase composition of the powdered samples was identified by powder X-ray diffraction Bruker D8 diffractometer with CuKα radiation within 10°≤ 2θ ≤ 70° at room temperature. The unit cell parameters of intermediate alloys were calculated by indexing of powder patterns using Topas V3.0 software. An accuracy of the crystal lattice parameters is shown in parentheses (Table 1). Microhardness measurements were done with a microhardness tester PMT-3, the typical loading being 20 g and accuracy about 20 MPa.

3. Results and Discussion

The character of the phase relations along the Tl₄PbTe₃-Tl₉TbTe₆-Tl₉BiTe₆ section is established based on combined analysis of experimental results and literature data on boundary systems Tl₄PbTe₃-Tl₉BiTe₆ 38 and Tl₉TbTe₆-Tl₉BiTe₆ 33 (Fig.1-6).

3.1. Tl₄PbTe₃-Tl₉TbTe₆ boundary section

The results of DTA, XRD and microhardness measurements for starting compounds and some intermediate alloys of the Tl₄PbTe₃-Tl₉TbTe₆ section are presented in Table 1.

Table 1. Dependence of the properties of the alloys annealed at the 750 K (1000 h) on the composition for the Tl₄PbTe₃-Tl₉TbTe₆ section of the Tl-Pb-Bi-Tb-Te system

| Solid phase compositions | Thermal effects, K | Microhardness, MPa | Tetragonal lattice parameters, Å |
|-------------------------|--------------------|---------------------|---------------------------------|
|                         |                    |                     | a                               | c                              |
| Tl₄PbTe₃                | 893                | 1120                | 8.8409(9)                       | 13.0556(12)                    |
| Tl₄Pb₁₋₄Tb₂₋₄Te₆       | 860-885            | 1145                | 8.8470(8)                       | 13.0390(11)                    |
| Tl₄Pb₁₋₃Tb₀₋₃Te₆       | 835-865            | 1155                | 8.8530(7)                       | 13.0226(10)                    |
| Tl₄Pb₀₋₄Tb₁₋₄Te₆       | 825-853            | -                   | -                               | -                              |
| Tl₄Pb₀₋₃Tb₂₋₄Te₆       | 815-845            | 1145                | 8.8590(8)                       | 13.0606(10)                    |
| Tl₄Pb₀₋₂Tb₀₋₂Te₆       | 800-815; 1030      | 1125                | 8.8650(9)                       | 12.9895(12)                    |
| Tl₄Pb₀₋₀Tb₀₋₀Te₆       | 790-800; 1080      | -                   | -                               | -                              |
| Tl₄TbTe₆                | 780; 1110          | 1100                | 8.871(10)                       | 12.9730(14)                    |
Experimental Study of the Tl<sub>4</sub>PbTe<sub>3</sub>-Tl<sub>9</sub>TbTe<sub>6</sub>-Tl<sub>9</sub>BiTe<sub>6</sub> Section of the Tl-Pb-Bi-Tb-Te System

Figure 1. Phase diagram (a), concentration dependencies of microhardness (b), and lattice parameters (c) for the alloys of the Tl<sub>9</sub>TbTe<sub>6</sub>-2Tl<sub>4</sub>PbTe<sub>3</sub> section.

Figure 2. XRD powder patterns for Tl<sub>5</sub>Te<sub>3</sub> (a), as well as Tl<sub>4</sub>PbTe<sub>3</sub>, Tl<sub>9</sub>TbTe<sub>6</sub> and some alloys of the Tl<sub>4</sub>PbTe<sub>3</sub>-Tl<sub>9</sub>TbTe<sub>6</sub> section (b). 1- Tl<sub>4</sub>PbTe<sub>3</sub>; 2-20 mol% Tl<sub>9</sub>TbTe<sub>6</sub>; 3-50 mol% Tl<sub>9</sub>TbTe<sub>6</sub>; 4-80 mol% Tl<sub>9</sub>TbTe<sub>6</sub>; 5-Tl<sub>9</sub>TbTe<sub>6</sub>.

Figure 3. Polythermal sections Tl<sub>9</sub>TbTe<sub>6</sub>-[A], Tl<sub>9</sub>BiTe<sub>6</sub>-[B] and Tl<sub>4</sub>PbTe<sub>3</sub>-[C] of the Tl<sub>4</sub>PbTe<sub>3</sub>-Tl<sub>9</sub>TbTe<sub>6</sub>-Tl<sub>9</sub>BiTe<sub>6</sub> concentration area of the phase diagram of the Tl-Pb-Bi-Tb-Te system. A, B, and C are equimolar alloys from the respective boundary system as shown in Fig.4.

unlimited solid solutions (δ-phase) with Tl<sub>5</sub>Te<sub>3</sub>-structure. However, it is a non-quasi-binary section of the Tl-Pb-Tb-Te quaternary system due to the peritectic character of melting of the Tl<sub>9</sub>TbTe<sub>6</sub> compound. This leads to the crystallization of TlTbTe<sub>2</sub> compound in a wide composition interval and to the formation of L+TlTbTe<sub>2</sub>+δ three-phase area. Due to a narrow interval of temperatures, the area L+TlTbTe<sub>2</sub>+δ is not fixed experimentally and shown by a dashed line.

The dependences of microhardness on composition have a flat maximum which is typical for systems with unlimited solid solutions (Fig.1b).
The XRD powder patterns for some alloys of the Tl₄PbTe₃-Tl₉TbTe₆ section as well as Tl₅Te₃, are presented in Fig.2. Powder diffraction patterns of Tl₄PbTe₃, Tl₉TbTe₆, and also intermediate alloys are single-phase and have the diffraction patterns qualitatively similar to Tl₅Te₃ with slight reflections displacement from one compound to another. For example, we present the powder diffraction patterns of alloys with composition 20, 50 and 80 mol% Tl₉TbTe₆. Parameters of the tetragonal lattice of solid solutions obey the Vegard's law (Table 1, Fig.1c).40

3.2. Isopleth sections of the phase diagram

We plotted some isopleth sections, in order to construct a complete T-x-y diagram. Figs.3a-c present the isopleth sections Tl₉TbTe₆-[A], Tl₉BiTe₆-[B] and Tl₄PbTe₃-[C] of the Tl₄PbTe₃-Tl₉TbTe₆-Tl₉BiTe₆ concentrations area, where A, B, and C are equimolar alloys from the respective boundary system as shown in Fig.4.

According to Fig.3a, b, the Tl₄PbTe₃-[C] and Tl₉BiTe₆-[B] sections are characterized by primary crystallization of the δ-phase from the melt over the entire concentration interval.

In contrast to the above-mentioned sections, along the Tl₉TbTe₆-[A] section, the direct crystallization of the δ-phase from the melt occurs only in the interval <60 mol% Tl₉TbTe₆. In the Tl₉TbTe₆-rich concentration area, the more refractory phase of TlTbTe₂ first crystallizes from the melt. Then a monovariant peritectic process L+TlTbTe₂↔δ occurs (Fig.3c), as a result of which a three-phase region L+TlTbTe₂+δ should form on the phase diagram. However, according to DTA data, we were unable to fix this region, which is apparently associated with the narrowness of the temperature interval of the above-stated peritectic reaction. Therefore, this region is indicated by the dotted line (Fig. 3b). The crystallization of all alloys is completed by the formation of δ-phase. The TlTbTe₂ phase is completely consumed in the peritectic reaction L+TlTbTe₂↔δ, and the remaining excess of the melt crystallizes into the δ-phase.

The XRD powder patterns for selective alloys on polythermal sections confirmed the formation of continuous solid solutions with the Tl₅Te₃-structure.
3.3. The liquidus and solids surfaces projections

Projection of liquidus of the $\text{Tl}_4\text{PbTe}_3$-$\text{Tl}_9\text{TbTe}_6$-$\text{Tl}_9\text{BiTe}_6$ section consists of two fields of the primary crystallization of $\text{TlTbTe}_6$ and $\delta$-solid solutions. These fields are separated by a monovariant peritectic curve $L+\text{TlTbTe}_2\leftrightarrow\delta$ (ab curve). The solidus projection (dashed lines) consist of one surface corresponding to the completion of the crystallization of the $\delta$-phase.

3.4. Isothermal sections at 860 and 840 K

Both sections are consist of areas of $L$, $\text{TlTbTe}_6$, and $\delta$-phases (Fig.5). In alloys with composition <60 mol\% $\text{Tl}_5\text{Te}_3$ in the two-phase region $L+\delta$ region the directions of the tie-lines on the studied composition plane. It should be noted that comparison of the isopleth sections (Fig.3) and isothermal sections (Fig.5) shows that the directions of the connodes in the two-phase region $L+\delta$ deviate from the $T-x$ plane and constantly vary with temperature. Isothermal sections at 860 and 840 K clearly confirm this.

4. Conclusion

At the first time, a self-consistent scheme of the phase relations in the $\text{Tl}_4\text{PbTe}_3$-$\text{Tl}_9\text{TbTe}_6$-$\text{Tl}_9\text{BiTe}_6$ section of the $\text{Tl-Pb-Bi-Tb-Te}$ system is obtained. The $T-x$ diagrams of boundary system $\text{Tl}_4\text{PbTe}_3$-$\text{Tl}_9\text{TbTe}_6$, some isopleth sections, an isothermal section at 860 and 840 K, as well as liquidus and solidus surface projections, are plotted. It was shown, that studied system is characterized by the formation of the continuous field of $\delta$-solid solutions with the $\text{Tl}_5\text{Te}_3$ structure. Obtained experimental results can be used for choosing the composition of solution-melt for the growth of the high-quality crystals of $\delta$-phase which are of interest as thermoelectric materials.

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6. References

1. Ahluwalia GK, ed. Applications of Chalcogenides: S, Se, and Te. New York: Springer; 2016.
2. Kolobov AV, Tominaga J. Chalcogenides. Metastability and Phase Change Phenomena. New York: Springer; 2012.
3. Shevelkov AV. Chemical aspects of thermoelectric materials engineering. Russian Chemical Reviews. 2008;77(1):1-20.
4. Cheng L, Li D, Dong X, Ma Q, Yu W, Wang X, et al. Synthesis, Characterization and Photocatalytic Performance of SnS Nanofibers and SnSe Nanofibers Derived from the Electrospinning-made SnO$_2$ Nanofibers. Materials Research. 2017;20(6):1748-1755.
5. Papagno M, Ereemeev S, Fujii J, Aliev ZS, Babanly MB, Mahatha SK, et al. Multiple Coexisting Dirac Surface States in Three-Dimensional Topological Insulator PbBi$_2$Te$_{2-x}$O$_x$. ACS Nano. 2016;10(3):3518-3524.
6. Caputo M, Panighel M, Lisi S, Khali L, DiSanto G, Papalazarou E, et al. Manipulating the Topological Interface by Molecular Adsorbates: Adsorption of Co-Phthalocyanine on Bi$_2$Se$_3$. Nano Letters. 2016;16(6):3409-3414.
7. Jha AR. Rare Earth Materials: Properties and Applications. Boca Raton: CRC Press; 2014.
8. Yaprintsev YM, Lyubushkin R, Soklakova O, Ivanov O. Effects of Lu and Tm Doping on Thermoelectric Properties of Bi$_2$Te$_3$. Compound. Journal of Electronic Materials. 2018;47(2):1362-1370.
9. Han F, Liu H, Malliakas CD, Staruz M, Wan X, Kanatzidis MG. La$_{1-x}$Bi$_x$S ($x \approx 0.08$): An n-Type Semiconductor. Inorganic Chemistry. 2016;55(7):3547-3552.
10. Alemi A, Klein A, Meyer G, Dolatyari M, Babalou A. Synthesis of New Ln$_2$Bi$_2$Se$_6$ (Ln: Sm$^{3+}$, Eu$^{3+}$, Gd$^{3+}$, Tb$^{3+}$) Nanomaterials and Investigation of Their Optical Properties. Zeitschrift für anorganische und allgemeine Chemie. 2011;637(1):87-93.
11. Bao L, Zhang Z, Le Q, Li Q, Cui G. Influence of Gd, Nd and Ce Additions on Microstructures and Mechanical Properties of Ultra-light Dual Phase Mg-9Li-0.4Zr Alloys. Materials Research. 2016;19(3):654-658.
12. Schewe I, Böttcher P, von Schmering HG. The crystal structure of $\text{Tl}_5\text{Te}_3$, and its relationship to the Cr$_5$B$_3$ type. Zeitschrift für Kristallographie. 1989;188(1-4):287-298.
13. Černý R, Joubert J, Filinchuk Y, Feutelais Y. $\text{Tl}_5\text{Te}_3$ and its relationship with $\text{Tl}_5\text{Te}_3$. Acta Crystallographica C. 2002;58(5):63-65.
14. Gotuk AA, Babanly MB, Kuliev AA. Phase equilibria in the $\text{Tl}_5\text{Sn}-\text{Te}$ system. Neorganic Materials. 1979;15(8):1356-1361.
15. Gotuk AA, Babanly MB, Kuliev AA. Phase equilibria in the systems $\text{Tl}_5\text{Te}-\text{SnTe}$ and $\text{Tl}_5\text{Te}-\text{PbTe}$. Uch. Zap. Azerb. Gos. Univ. Ser. Khim. 1978(3):50-56.
16. Babanly MB, Azizulla A, Kuliev AA. System $\text{Tl}_5\text{Sb-Te}$. Russian Journal of Inorganic Chemistry. 1985;30:1051-1059.
17. Babanly MB, Akhmadyar A, Kuliev AA. System $\text{Tl}_5\text{Te}-\text{Bi}_5\text{Te}_7$. Russian Journal of Inorganic Chemistry. 1985;30(9):2356-2359.
18. Wölfing B, Kloc C, Teubner J, Bucher E. High performance thermoelectric $\text{Tl}_5\text{BiTe}_6$ with an extremely low thermal conductivity. Physical Review Letters. 2001;86(19):4350-4353.
19. Guo Q, Chen M, Kuropatwa BA, Kleinke H. Enhanced Thermoelectric Properties of Variants of $\text{Tl}_5\text{SbTe}_5$ and $\text{Tl}_5\text{BiTe}_6$. Chemistry of Materials. 2013;25(20):4097-4104.
20. Kosuga A, Kurosaki K, Muta H, Yamanaka S. Thermoelectric properties of $\text{Tl}_5\text{X-Te}$ ($X = \text{Ge}$, $\text{Sn}$, and $\text{Pb}$) compounds with low lattice thermal conductivity. Journal of Applied Physics. 2006;99(6):063705.
21. Arpino KE, Wallace DC, Nie YF, Birol T, King PDC, Chatterjee S, et al. Evidence for Topologically Protected Surface States and a Superconducting Phase in [Tl₂₅] (Tl₁₋ₓ Snₓ)Te₃ Using Photoemission, Specific Heat, and Magnetization Measurements, and Density Functional Theory. *Physical Review Letters*. 2014;112(1):017002.

22. Barchij I, Sabov M, El-Naggar AM, Al Zayed NS, Albassam AA, Fedorchuk AO, et al. Tl₄ SnS₃, Tl₄ SnSe₃ and Tl₄ SnTe₃ crystals as novel IR induced optoelectronic materials. *Journal of Materials Science: Materials in Electronics*. 2016;27(4):3901-3905.

23. Imamalieva SZ, Sadygov FM, Babanly MB. New thallium-neodymium tellurides. *Inorganic Materials*. 2008;44(9):935-938.

24. Babanly MB, Imamalieva SZ, Babanly DM. Tl₉ LnTe₆ (Ln=Ce, Sm, Gd) compounds - the new structural analogies of Tl₅ Te₃. *Azerbaijan Chemical Journal*. 2009;2:122-125. (In Russian).

25. Bangarigadu-Sanasy S, Sankar CR, Schlender P, Kleinke H. Thermoelectric properties of Tl₁₀₋ₓ Lnₓ Te₆ with Ln = Ce, Pr, Nd, Sm, Gd, Tb, Dy, Ho and Er, and 0.25≤x≤1.32. *Journal of Alloys and Compounds*. 2013;549:126-134.

26. Bangarigadu-Sanasy S, Sankar CR, Dube PA, Greedan JE, Kleinke H. Magnetic properties of Tl₁₀₋ₓ Lnₓ Te₆, with Ln = Ce, Pr, Tb and Sm. *Journal of Alloys and Compounds*. 2014;589:389-392.

27. Guo Q, Kleinke H. Thermoelectric properties of hot-pressed Tl₁₀₋ₓ Lnₓ Te₆ (Ln = La, Ce, Pr, Nd, Sm, Gd, Tb) and Tl₁₀₋ₓ Laₓ Te₆ (0.90 ≤ x ≤ 1.05). *Journal of Alloys and Compounds*. 2015;630:37-42.

28. Andreev OV, Bamburov VG, Monina LN, Razumkova IA, Ruseikina AV, Andreev VO. *Phase equilibria in the sulfide systems of the 3d, 4f-elements*. Ekaterinburg: Editorial Publication Department of the UR RAS; 2015.

29. Tomashik V, Feychuk P, Shcherbak L. Ternary Alloys Based on II-VI Semiconductor Compounds. Chernivtsi: Books-XX1; 2010.

30. Babanly MB, Chulkov EV, Aliyev ZS, Shevelkov AV, Amirzhanov IR. Phase diagrams in materials science of topological insulators based on metal chalcogenides. *Russian Journal of Inorganic Chemistry*. 2017;62(13):1703-1729.

31. Ioffe AF. *Semiconductor Thermoelements and Thermoelectric Cooling*. London: Infosearch Limited; 1957.

32. Imamalieva SZ, Gasanly TM, Gasymov VA, Babanly MB. Phase Equilibria and some Properties of Solid Solutions in the Tl₁₀₋ₓ Tlₓ BiTe₆-Tlₓ TbTe₆ System. *Acta Chimica Slovenica*. 2017;64(1):221-226.

33. Imamalieva SZ, Gasanly TM, Zlomanov VP, Babanly MB. Phase Equilibria in the Tl₁₀₋ₓ Tlₓ BiTe₆-Tlₓ TbTe₆ system. *Inorganic Materials*. 2017;53(7):685-689.

34. Imamalieva SZ, Firudin MI, Gasymov VA, Babanly MB. Phase equilibria in the Tl₁₀₋ₓ Tlₓ BiTe₆-Tlₓ TbTe₆ section of the Tl-Bi-Tm-Te Quaternary System. *Materials Research*. 2017;20(4):1057-1062.

35. Imamalieva SZ, Hasanly TM, Gasymov VA, Babanly MB, Sadygov FM. Phase relations in the Tl₁₀₋ₓ GdTe₆-Tlₓ SbTe₆ and Tl₁₀₋ₓ TbTe₆-Tlₓ SbTe₆ systems. *Chemical Problems*. 2017;3:241-247.

36. Bradtmöller S, Böttcher PZ. Darstellung und Kristallstruktur von SnTl₄ Te₃ und PbTl₄ Te₃. *Zeitschrift für anorganische und allgemeine Chemie*. 1993;619(7):1155-1160.

37. Doert T, Böttcher P. Crystal structure of bismuthnonathallium hexatelluride BiTl₉ Te₆. *Zeitschrift für Kristallographie*. 1994;209:95.

38. Andreev OV, Bamburov VG, Monina LN, Razumkova IA, Ruseikina AV, Andreev VO. *Phase equilibria in the sulfide systems of the 3d, 4f-elements*. Ekaterinburg: Editorial Publication Department of the UR RAS; 2015.

39. Glazov VM, Vigdorovich VN. *Mikrotverdost’ metallov i poluprovodnikov*. Moscow: Metallurgiya; 1969. (In Russian).

40. Ferey G. *Crystal Chemistry. From Basics to Tools for Materials Creation*. New Jersey: World Scientific; 2017.