UDC 546 (72.681.682.22)

FeS- $FeGa_2S_4$- $FeGaInS_4$ SYSTEM

F.M. Mammadov

Institute of Catalysis and Inorganic Chemistry
National academy of Sciences of Azerbaijan
H. Javid ave., 113, AZ-1143, Baku, Azerbaijan
e-mail: faikmamadov@mail.ru

Received 22.01.2020
Accepted 01.04.2020

Abstract: *The phase equilibria in the FeS-$FeGa_2S_4$-$FeGaInS_4$ system were studied using the differential thermal and X-ray diffraction phase analysis. The projection of the liquidus surface and the isothermal sections of the phase diagram at 1200 and 900 K were constructed. It revealed that it belongs to quasi-ternary systems with monovariant eutectic and peritectoid equilibria. At 1200 K, the system was characterized by the presence of a continuous series of solid solutions along the boundary system $FeGa_2S_4$-$FeGaInS_4$ (β-phase) as well as solid solutions based on the high-temperature modification FeS (α-phase) which formed a wide two-phase region α + β. The FeS-$FeGa_2S_4$ boundary system was characterized by the formation of the $Fe_2Ga_2S_5$ ternary compound at 900 K. This compound formed $Fe_2Ga_2S_5$+β and $Fe_2Ga_2S_5$+ α+β heterogeneous regions below this temperature which significantly narrowed the two-phase region α + β.*

Keywords: *$FeGa_2S_4$, FeS, $FeGaInS_4$, phase diagram, liquidus, solid solutions*
DOI: 10.32737/2221-8688-2020-2-214-221

Introduction

Compounds of AB_2X_4- type (A-Mn, Fe, Co, Ni, Ge, Sn, Pb, B-p^1 or p^3-element, X-chalcogen) and phases based on them are valuable functional materials with thermoelectric, photoelectric, optical, magnetic and other properties [1-8]. In recent years, it has been established that some compounds of this type with a layered structure such as tetradimite are topological insulators and extremely promising for practical applications, ranging from spintronics to safety systems and medicine [9-13]. It is known that the intensive development of a new scientific field - spintronics is associated with the possibility of transferring the oriented electron spin from a ferromagnet to a semiconductor. The above compounds also apply to materials promising for the specified area [14-16]. In [17, 18] published recently, the $MnBi_2Te_4$ compound, the first antiferromagnetic topological insulator, was described.

The development and optimization of the synthesis of new complex phases are based on data on phase equilibria and thermodynamic characteristics of the corresponding systems [19-24].

The paper explores phase relations in the FeS– $FeGa_2S_4$-$FeGaInS_4$ system. The initial compounds of this system were studied thoroughly.

The FeS compound melt congruently at 1461 K and undergo polymorphic transitions at 411 and 588 K [25]. The high-temperature modification of FeS crystallized in a tetragonal structure (Sp.gr.P4/nmm) with lattice parameters a = 0.3768 nm, c = 0.5039 nm [26] or a = 0.36735 nm, c = 0.50328 nm [27], while the low-temperature modification has a hexagonal structure: a = 0.34436 (1) nm, c = 0.57262 (2) nm [28].

According to [29], the ternary compound $FeGa_2S_4$ melts congruently at 1418 K. According to [30], it is formed by the peritectic reaction at 1343 K and undergoes a polymorphic transformation at 1283 K. In [31] it was shown that $FeGa_2S_4$ crystallizes in a rhombic structure of the $ZnAl_2S_4$ type with lattice parameters a = 1.289 nm; b = 0.751; c =

0.609 nm. According to [32], this compound exists in two crystalline modifications: the low-temperature compound has a trigonal one (Sp.gr. P3ml, a = 0.3654 (2) nm; c = 1.20556 nm), and the high-temperature - rhombic (a = 1.289; b = 0.751; c = 0.609 nm) structure.

The $FeGaInS_4$ compound also melts congruently (1375 K) and has a trigonal structure of the $ZnAl_2S_4$ type (Sp.gr.P-3m1) with parameters: a = 0.37765, c = 1.22257 nm [33, 34].

The boundary quasi-binary components of the FeS-$FeGa_2S_4$-$FeGaInS_4$ system were studied in [29, 33]. According to [29], the 2FeS – $FeGa_2S_4$ system is eutectic type. The eutectic had a composition of ~ 53 mol% $FeGa_2S_4$ and crystallized at 1328 K. The $Fe_2Ga_2S_5$ compound is formed by a solid-phase reaction at 1043 K. According to [33], the 2FeS – $FeGaInS_4$ system also has a eutectic type phase diagram. The eutectic coordinates are 63 mol% $FeGaInS_4$ and 1310 K. The $FeGa_2S_4$-$FeGaInS_4$ system is characterized by the formation of a continuous series of solid solutions between $FeGaInS_4$ and the low-temperature modification of $FeGa_2S_4$ [33]. It is assumed that the formation of solid solutions leads to a sharp increase in the temperature of the polymorphic transition $FeGa_2S_4$ (1327 K) and the establishment of peritectic equilibrium at ~ 1410 K.

Experimental part

2.1. Materials and synthesis

The initial compounds FeS, $FeGa_2S_4$ and $FeGaInS_4$ were synthesized using high-purity iron (99.995%), indium (99.999%), gallium (99.999%) and sulfur (99.99%) purchased from Alfa Aesar.

Stoichiometric mixtures of elements were placed in a quartz ampoule which was evacuated to a residual pressure of ~ 10^{-2} Pa. The syntheses were carried out in a two-zone furnace. In the case of FeS, the lower “hot” zone was slowly heated from a room temperature to a temperature of 1400 K, and for $FeGa_2S_4$ and $FeGaInS_4$ compounds it was 30–50 K above their melting points, and part of the ampoule outside the furnace was cooled with water (“cold” zone). The interaction of the components occurrs in the “hot” zone, and in the “cold” zone, the chalcogen condenses and returns to the interaction zone. As a result of the reaction in the "cold" zone, the mass of chalcogen gradually decreased and within 1-2 hours it is consumed almost completely. After that, the ampoule was completely placed in the oven and kept at the indicated temperature for 2-3 hours. The obtained samples were subjected to heat treatment at 800 K for 100 hours in order to increase the crystallinity of the synthesized compounds.

The alloys of the studied system were prepared through melting pre-synthesized compounds in evacuated quartz ampoules. The alloys were first annealed at 1000 K (100 h), then at 900 K (300 h) and cooled in a switched off the furnace. Some alloys, after heat treatment at 1200 K or 900 K, were quenched in cold water.

2.2. Methods

The differential thermal analysis (DTA) and X-ray powder diffraction technique (XRD) were used for the analysis of samples. DTA was carried out using the NETZSCH 404 F1 Pegasus system from room temperature to ~ 1450 K, depending on the composition of the alloys at a heating rate of 10 $K{\cdot}min^{-1}$. Thermal effects temperatures were determined mainly from heating curves. The temperature accuracy was ± 2 K.

Powder X-ray diffraction patterns were recorded on a Bruker D2 Phaser diffractometer using Cu $K\alpha_1$ radiation at room temperature.

According to DTA, the synthesized compounds melt at 1460 K (FeS), 1420 K ($FeGa_2S_4$) and 1375 K ($FeGaInS_4$). Our data are consistent with published data [25, 29, 33]

X-ray diffraction patterns of the synthesized compounds also showed the formation of single-phase materials. The calculated lattice parameters of hexagonal FeS (a = 0.34440 nm, c = 0.57260 nm), trigonal $FeGa_2S_4$ (a = 0.36543; c = 1.20558 nm) and $FeGaInS_4$ (a = 0.37765, c = 1.22257 nm) are good consistent with published data [28, 30, 34].

Results

Combined analysis of the obtained experimental data allowed us to obtain a general scheme of the phase equilibria, including isothermal sections at 1200 K and 900 K, polythermal sections 2FeS- [A], $FeGa_2S_4$- [B] ([A] and [B] alloys with "$FeGa_{1.5}In_{0.5}S_4$" and "$Fe_{1,5}\ Ga_{0.5}In_{0.5}S_3$" compositions, respectively) of the phase diagram as well as the projection of the liquidus surface (Figs. 1–4).

According to the data obtained, the FeS-$FeGa_2S_4$-$FeGaInS_4$ system referrs to quasi-ternary systems with monovariant eutectic and peritectoid equilibria.

Isothermal sections at 1200 K and 900 K. Continuous solid solutions along the boundary system $FeGa_2S_4$-$FeGaInS_4$ (β-phase) are in connod tie with solid (α) solutions based on the high-temperature modification of FeS and form a two-phase region α+β, which at 1200 K covers the entire area of the concentration triangle (Fig. 1a).

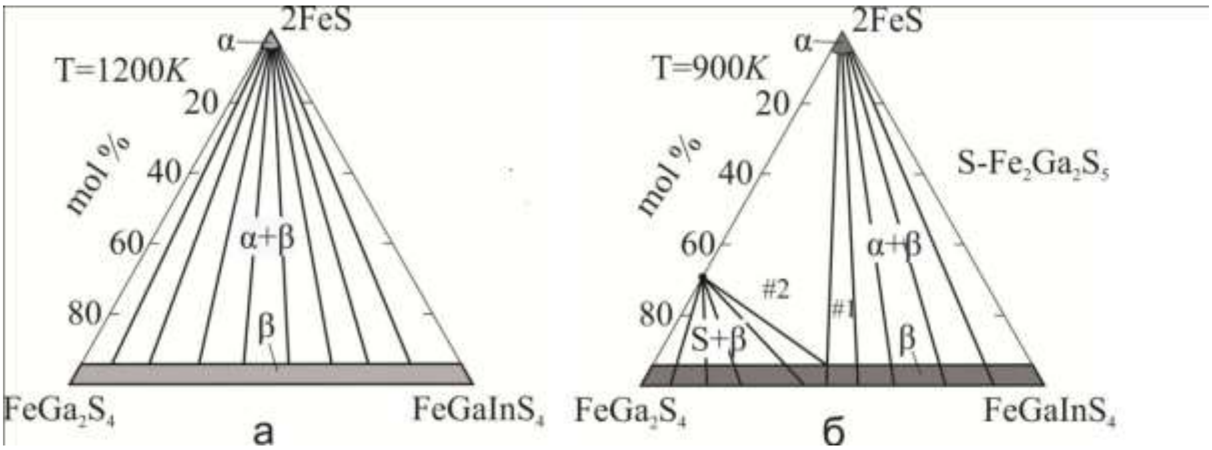

Fig.1. Isothermal sections of the FeS-$FeGa_2S_4$-$FeGaInS_4$ system at 1200 K (a) and 900 K(b).

Below 900 K, in the FeS-$FeGa_2S_4$ boundary system, there is a ternary compound $Fe_2Ga_2S_5$ formed by the solid-phase reaction between FeS and $FeGa_2S_4$. This leads to the formation of $Fe_2Ga_2S_5$+β and α+β+$Fe_2Ga_2S_5$ phase regions. The isothermal section at 900 K clearly demonstrates this (Fig. 1b).

Phase fields on both isothermal sections are confirmed by powder XRD analysis. As an example, Fig. 2 presents powder diffraction patterns of two annealed alloys (Fig. 1b, samples # 1 and # 2) with the reflection lines of the phases coexisting in them. As can be seen, alloy # 1 consists of a two-phase mixture of FeS (low-temperature modification) and the β-phase. Sample # 2 is three-phase - FeS + $Fe_2Ga_2S_5$+β. A comparison of the reflection angles with the diffraction patterns of alloys of the $FeGa_2S_4$- $FeGaInS_4$ side system showed that the β- phase in both samples has a composition of ~50 mol% FeGaInS4, which is in accordance with Fig. 1b.

The liquidus surface (Fig. 3) consists of three areas corresponding to the primary crystallization of the α, β and β′- phases (β′ - solid solutions based on the high-temperature modification of $FeGa_2S_4$). The last two areas are delimited by us conditionally (P_1P_2 dashed line). P_1P_2 curve refers to monovariant peritectic equilibrium

$$L+\beta' \leftrightarrow \beta \qquad (1)$$

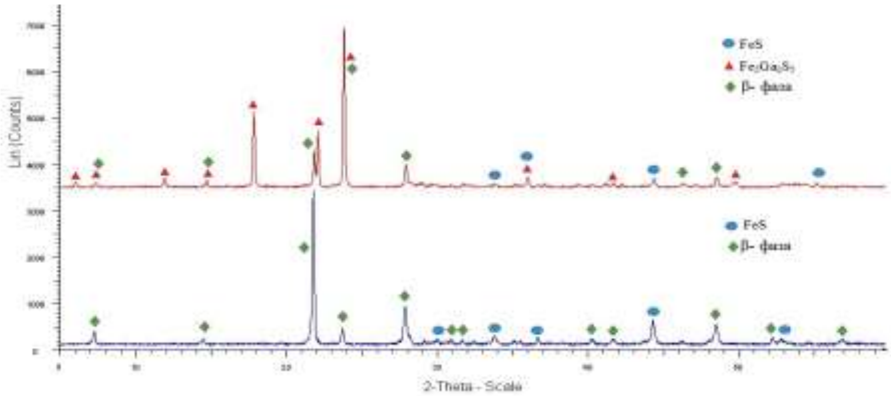

Fig. 2. Powder diffraction patterns of alloys # 1 and # 2 showed on Fig.1

The fields of primary crystallization of α- and β- phases are separated by the e_1e_2 eutectic curve with the monovariant equilibrium

L ↔ α+β (2)

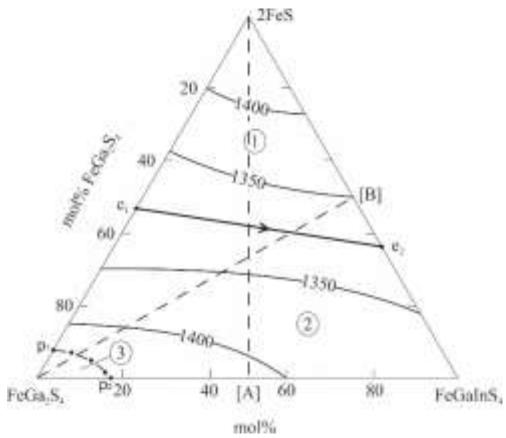

Fig.3. Liquidus surfaces projection of the FeS- $FeGa_2S_4$- $FeGaInS_4$ system

Polythermal section $FeGa_2S_4$ - [B] (Fig. 5). The liquidus of this section consists of three curves, which from left to right correspond to the primary crystallization of β′-, β- and α- solid solutions. The formation of β′-and β- phases is accompanied by a sharp increase in the temperature of the polymorphic transition $FeGa_2S_4$ (from 1330 K to ~ 1410 K) and the establishment of peritectoid equilibrium (1).

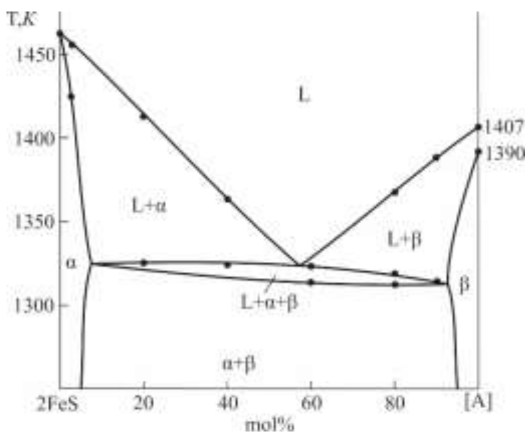

Fig. 4. Polythermal section 2FeS- [A] of the FeS- $FeGa_2S_4$- $FeGaInS_4$ system

Polythermal section $FeGa_2S_4$- [B] (Fig. 5). The liquidus of this section consists of three curves, which from left to right correspond to the primary crystallization of β′-, β- and α- solid solutions. The formation of β′-and β- phases is accompanied by a sharp increase in the temperature of the polymorphic transition $FeGa_2S_4$ (from 1330 K to ~ 1410 K) and the establishment of peritectoid equilibrium (1).

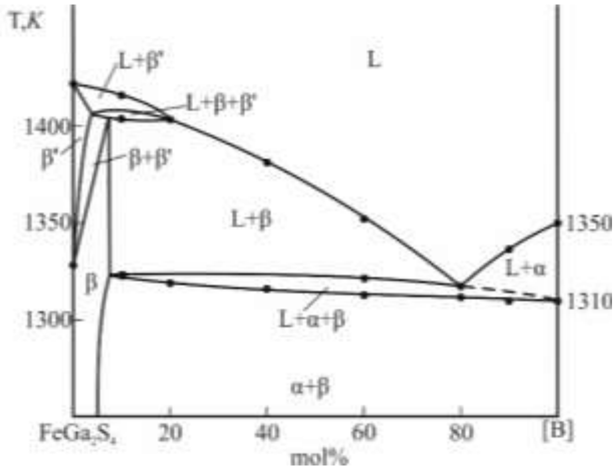

Fig. 4. Polythermal section $FeGa_2S_4$- [B] of the FeS- $FeGa_2S_4$- $FeGaInS_4$ system

The intersection point of liquidus curves of α and β- phases corresponds to the beginning of a monovariant eutectic reaction (2). During this reaction, a three-phase region L+α+β is formed, and upon its completion, a two-phase region α+β is formed.

According to our data (Figs. 1, 4, 5), the homogeneity regions of the α and β- phases of the above sections are maximum at the eutectic temperature (1310–1330 K) and amount to 6–7 mol%.

Conclusion

Based on the experimental data, we obtained a general scheme of phase equilibria in the FeS-$FeGa_2S_4$-$FeGaInS_4$ system, including the projection of the liquidus surface, two polythermal sections, and isothermal sections of the phase diagram at 1200 and 900 K. At 1200 K, the system is characterized by the presence of a continuous series of solid solutions along the side system $FeGa_2S_4$-$FeGaInS_4$ (β-phase) and α-solid solutions based on the high-temperature modification of FeS, which form a wide two-phase region α + β. At 900 K, the $Fe_2Ga_2S_5$ compound is involved in phase equilibria, which leads to the formation of heterogeneous regions $Fe_2Ga_2S_5$+β и FeS+$Fe_2Ga_2S_5$+β. The results can be used to develop new magnetic materials based on β-solid solutions.

References

1. Hyunjung Kim, Anand P. Tiwari, Eunhee Hwang, Yunhee Cho, Heemin Hwang, SoraBak, Yeseul Hong, and Hyoyoung Lee. FeIn2S4 Nanocrystals: A Ternary Metal Chalcogenide Material for Ambipolar Field-Effect Transistors. *Adv. Sci*. 2018, 5, 1800068 DOI: 10.1002/advs.201800068
2. Gao, M.-R., Xu, Y.-F., Jiang, J., & Yu, S.-H. Nanostructured metal chalcogenides: synthesis, modification, and applications in energy conversion and storage devices. *Chemical Society Reviews*, 2013, vol. 42(7), pp. 2986-3017.
3. Ahluwalia G.K. (Ed.). *Applications of Chalcogenides: S, Se, and Te,* Springer, 2016.
4. Shevelkov A.V. Chemical aspects of thermoelectric materials engineering. *Russ. Chem. Rev*. 2008, vol. 77, pp.1-19.

5. *Xia C., Li J.* Recent advances in optoelectronic properties and applications of two-dimensional metal chalcogenides. *Journal of Semiconductors*, 2016, vol. 37, issue 5, pp. 051001-1 051001-9
6. Ranmohotti K.G.S., Djieutedjeu H., Lopez J., Page A., Haldolaarachchige N., Chi H., Sahoo P., Uher C., Young D., Poudeu P.F.P. Coexistence of High-T c Ferromagnetism and n-Type Electrical Conductivity in $FeBi_2Se_4$. *J. of the American Chemical Society*, 2015, vol.137, no.2, pp.691-698.
7. Songrui Zhao, P. Dalmas de Reotier, Yaouanc A., MacLaughlin D.E., Mackie J.M., Bernal O.O., Nambu Y., Higo T, and Nakatsuji S. Spin dynamics and spin freezing in the triangular lattice antiferromagnets $FeGa_2S_4$ and $NiGa_2S_4$. *Physical Review B*. 2012, vol. 86, 064435 (1-11).
8. Djieutedjeu H., Makongo J.P.A., Rotaru A., Palasyuk A., Takas N.J, Zhou X., Ranmohotti K.G.S., Spinu L., Uher C., Poudeu P.F.P. Crystal Structure, Charge Transport, and Magnetic Properties of $MnSb_2Se_4$. *European Journal of Inorganic Chemistry*. 2011, vol. 26, pp.3969-3977. DOI: 10.1002/ejic.201100364
9. Niesner D., Otto S., Hermann V., Fauster Th., Menshchikova T.V., Eremeev S.V., Aliev Z.S., Amiraslanov I.R., Echenique P.M., Babanly M.B., Chulkov E.V. Bulk and surface electron dynamics in a p-type topological insulator $SnSb_2Te_4$. *Physical Review* B, 2014, vol. 89, pp. 081404-081404-5.
10. Shvets I.A., Klimovskikh I.I., Aliev Z.S., Babanly M.B., Sánchez-Barriga J., Krivenkov M., Shikin A.M., Chulkov E.V. Impact of stoichiometry and disorder on the electronic structure of the $PbBi_2Te_{4-x}Se_x$ topological insulator. *Physical Review* B, 2017, vol. 96, issue 23, p. 235124.
11. Eremeev S.V., Landolt G., Aliyev Z.S., Babanly M.B., Amiraslanov I.R. et al. Atom-specifik spin mapping and buried topological states in a homologous series of topological insulators. *Nature Commun*. 2012, vol. 3, pp. 635-639. Doi: 10.1038/ncomms1638 .
12. Viti L., Coquillat D., Politano A., Kokh K.A., Aliev Z.S., Babanly M.B., Tereshchenko O.E., Knap W., Chulkov E.V., Vitiello M.S. Plasma-Wave Terahertz Detection Mediated by Topological Insulators Surface States. *Nano Letters,* 2016, vol.16, pp. 80−87.
13. Politano A., Caputo M., Nappini S., Bondino F., Aliev Z.S., Babanly M.B., Chulkov E Exploring the surface chemical reactivity of single crystals of binary and ternary bismuth chalcogenides. *Journal of Physical Chemistry C*, 2014, vol.118, pp. 21517-21522.
14. Niftiyev N.N., Mamedov F.M., Quseynov V. I., Kurbanov S.Sh. AC Electrical Conductivity of $FeIn_2Se_4$ Single Crystals. *Semiconductors*. 2018, vol. 52, issue 6, pp. 683–685.
15. Niftiev N.N , Tagiev O.B., Muradov M.B., Mamedov F.M. AC electrical properties of $FeIn_2S_4$. *Technical Physics,* 2012, vol. 57, issue 4, pp. 572–574.
16. Mammadov F.M., Niftiyev N.N. Dielectric properties of layered FeGaInS4 single crystals in an alternating electric field. *Semiconductors*. 2016, vol. 50, issue 9, pp. 1203–1207.
17. Otrokov M.M., Klimovskikh I.I., Bentmann H., Zeugner A. and others. Prediction and observation of the first antiferromagnetic topological insulator. *Nature, 2019, vol. 576, pp. 416-422*. arXiv:1809.07389[cond-mat.mtrl-sci]. DOI: 10.1038/s41586-019-1840-9.
18. Ziya S. Aliev, Imamaddin R. Amiraslanov, Daria I. Nasonova, Andrei V. Shevelkov, Nadir A. Abdullayev, Zakir A. Jahangirli, Elnur N. Orujlu, Mikhail M. Otrokov, Nazim T. Mamedov, Mahammad B. Babanly, Evgueni V. Chulkov. Novel ternary layered manganese bismuth tellurides of the MnTe- Bi_2Te_3 system: Synthesis and crystal structure. *Journal of Alloys and Compounds*. 2019 , vol. 789, pp. 443-450.
19. Zlomanov V.P., Khoviv A.M. and Zavrazhnov A.Yu. Physicochemical Analysis and Synthesis of Nonstoichiometric Solids. In: InTech. *Materials Science - Advanced Topics* 2013, pp.103-128
20. Babanly M.B., Chulkov E.V., Aliev Z.S.,

Shevel'kov A.V., and Amiraslanov I. R. Phase diagrams in materials science of topological insulators based on metal chalkogenides. *Russ. J. Inorg. Chem*., 2017, vol. 62, no. 13, pp. 1703–1729.

21. Babanly D.M., Tagiyev D.B. Physicochemical aspects of ternary and complex phases development based on thallium chalcohalides. *Chemical Problems*. 2018, no. 2 (16), pp. 153-177.
22. Imamaliyeva S.Z., Babanly D.M., Tagiev D.B., Babanly M.B. Physicochemical Aspects of Development of Multicomponent Chalcogenide Phases Having the Tl_5Te_3 Structure: A Review. *Russ.J.Inorg.Chem*., 2018, no.13, pp.1703-1027.
23. Mammadov Faig M., Amiraslanov Imamaddin R., Aliyeva Yegana R., Ragimov Sadiyar S., Mashadiyeva Leyla F., Babanly Mahammad B. Phase Equilibria in the $MnGa_2Te_4$-$MnIn_2Te_4$ System, Crystal Structure and Physical Properties of $MnGaInTe_4$. *Acta Chim. Slov*. 2019, vol. 66, pp. 466-472.
24. Mammadov F.M., Imamaliyeva S.Z., Amiraslanov I.R., Babanly M. B. The phase diagram of the $FeGa_2Se_4$-$FeIn_2Se_4$ system and the crystal structure of $FeGaInSe_4$.*Condensed Matter And Interphases***.** 2018, vol. 20, no. 4, pp. 604-610. DOI: https://doi.org/10.17308/kcmf.2018.20/633.
25. Binary alloy phase diagrams, Ed. T.B. Massalski, second edition. ASM International, Materials park, Ohio, 1990, 3875p.
26. Bertaut E.F., Burlet P., and Chappert J. On the absence of magnetic order in tetragonal FeS *Sol. State Comm.,* 1965, vol.3, pp. 335-338.
27. Lennie A.R., Redfern S.A., Schofield P.F. and Vaughan D.J. Synthesis and Rietveld crystal structure refinement of mackinawite, tetragonal FeS. *Mineralogical Magazine*.1995, vol..59, p. 677.
28. Kuhn S.J., Kidder M.K., Parker D.S., McGuire M.A., Chance W.M., Sefat A.S.Structure and property correlations in FeS. *Physica C: Superconductivity and Its Applications*, 2017, vol. 534, pp. 29–36.
29. Allazov M.R. The system of FeS-GaS-S. *Bulletin of Baku State University*. 2009, no. 2, pp. 42-47.
30. Dogguy-Smiri L., Nguyen Huy D., Pardo M.P. Structure crystalline du polytype $FeGa_2S_4$. *Mater. Res. Bull*. 1980, vol. 15, no. 7, pp. 861-866.
31. Hahn H., Klingler W. Unter such ungen uber ternare chalkogenide. I. Uber die, kristall structure iniger ternaerer sulfide, die sichvom In_2S_3 ableiten. *Zeitschrift fur Anorganische und Allgemeine Chemie*. 1950, vol. 263, pp. 177-190.
32. Pardo M.P., Dogguy-Smiri L., Flahaut J. Systeme FeS–Ga_2S_3 – diagramme de phase - etude cristallographique . *Mater. Res. Bull*. 1980, no. 7, vol. 16, pp.1375-1384.
33. Mammadov F.M., Amiraslanov I.R., Efendiyeva N.N., Imamaliyeva S.Z. Phase diagrams of the $FeGa_2S_4$- $FeIn_2S_4$ and FeS-$FeGaInS_4$ systems. *Chemical Problems*. 2019, no.1 (17). pp- 58-65.
34. Mammadov F.M., Niftiyev N.N., Mammadov F.I. Synthesis and crystal structure of the $FeGaInS_4$ compound. *Azerbaijan Chemical Journal*, 2017, no. 2, pp.135-138.

FeS- $FeGa_2S_4$- $FeGaInS_4$ SİSTEMİ

F.M. Məmmədov

AMEA Kataliz və Qeyri-üzvi Kimya İnstitutu
Bakı şəhəri, H.Cavid pr.113, AZ-1143
e-mail: faikmamadov@mail.ru

Differensial termiki və rentgenfaza analiz metodları ilə FeS-$FeGa_2S_4$-$FeGaInS_4$ sistemində faza tarazlığı tədqiq edilmişdir. Sistemin likvidus səthinin proeksiyası, 1200 və 900 K temperaturlarda izotermik kəsiklərin faza diaqramları qurulmuşdur. Müəyyən edilmişdir ki, sistem monovariant evtektik və peritektoid tarazlığı olan kvaziüçlü sistemə aiddir. Sistem 1200 K-də $FeGa_2S_4$-$FeGaInS_4$

(β- faza) yan kəsiyi boyunca fasiləsiz bərk məhlulların mövcudluğu və FeS (α-) yüksək temperaturlu modifikasiyası əsasında həllolma sahəsinin olması ilə xarakterizə olunur. Üçlü sistemin FeS-$FeGa_2S_4$ yan kəsiyində 900 K temperaturda $Fe_2Ga_2S_5$ üçlü birləşməsi əmələ gəlir. Bu birləşmə $Fe_2Ga_2S_5$ + β və $Fe_2Ga_2S_5$ + α + β heterogen sahələri əmələ gətirir ki, bunun da təsirindən α + β iki fazalı sahə əhəmiyyətli dərəcədə kiçilir.

Açar sözlər: *$FeGa_2S_4$, FeS, $FeGaInS_4$, faza diaqramı, likvidus, bərk məhlullar.*

СИСТЕМА FeS- $FeGa_2S_4$- $FeGaInS_4$

Ф.М. Мамедов

Институт катализа и неорганической химии Национальной АН Азербайджана,
пр. Г. Джавида, 113, AZ-1143, Баку, Азербайджан
e-mail: faikmamadov@mail.ru

Методами дифференциально-термического и рентгенофазового анализов исследованы фазовые равновесия в системе FeS-$FeGa_2S_4$-$FeGaInS_4$. Построены проекция поверхности ликвидуса и изотермические сечения фазовой диаграммы при 1200 и 900 К. Установлено, что она относится к квазитройным системам с моновариантными эвтектическим и перитектоидным равновесиями. При 1200 К система характеризуется наличием непрерывного ряда твердых растворов вдоль боковой системы $FeGa_2S_4$-$FeGaInS_4$ (β-фаза) и твердых растворов на основе высокотемпературной модификации FeS (α-), которые образуют широкую двухфазную область α+β. При 900 К в боковой системе FeS-$FeGa_2S_4$ образуется тройное соединение $Fe_2Ga_2S_5$, которое формируя гетерогенные области $Fe_2Ga_2S_5$+ β и $Fe_2Ga_2S_5$+ α+β ниже этой температуры значительно сужает двухфазную область α+β.

Ключевые слова: *$FeGa_2S_4$, FeS, $FeGaInS_4$, фазовая диаграмма, ликвидус, твердые растворы.*