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Optics

Ellipsometric studies of $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals

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Abstract. $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals were grown using a direct crystallization technique from the melt. Refractive indices and extinction coefficients for mixed crystals were obtained from the spectral ellipsometry measurements. A nonlinear increase of the refractive indices is revealed with increase of Cu_7PS_6 content. The dispersion of refractive indices is described in the framework of Wemple–DiDomenico model. The compositional dependences of optical parameters for $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals are analyzed.

Keywords: superionic conductors, mixed crystals, spectral ellipsometry, refractive index, extinction coefficient.

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1. Introduction

$Cu_6PS_5I(Br)$ compounds belong to the argyrodite-type superionic conductors [1]. They are promising materials for applications in solid state ionics as the materials for solid state batteries, supercapacitors and electrochemical sensors. At room temperature $Cu_6PS_5I(Br)$ and Cu_7PS_6 crystallize in the cubic crystal system ($F\bar{4}3m$ and $P2_13$ space groups, respectively) [1, 2]. The most investigated in this family are $Cu_6PS_5I(Br)$ crystals that show a high value of electric conductivity at room temperature, comparable with the conductivity of the best solid electrolytes [1]. At low temperatures Cu_6PS_5I crystal undergoes two phase transitions (PTs), one of them being a first-order superionic and ferroelastic PT at $T_I = 144…169$ K, the other is a second-order structural PT at $T_{II} = (269\pm2)$ K [3]. Another situation is realized in Cu_6PS_5Br crystal: with decreasing temperature it undergoes two phase transitions – the ferroelastic one at $T_{II} = (268\pm2)$ K and superionic transition at $T_I = (166…180)$ K [4, 5].

It is shown that Cu_7PS_6 compound is formed with a large excess of S^{2-} anions and in a simplified case its structure can be viewed as a Cu_2S matrix containing isolated $[PS_4]^{3-}$ ions [2]. In Cu_7PS_6 the PT is observed at 515 K from the high-temperature phase with $F\bar{4}3m$ symmetry to the low-temperature phase with $P2_13$ symmetry. Calorimetric studies of Cu_7PS_6 showed no phase transitions within the temperature range of 100 to 400 K [6]. Electrical properties of Cu_7PS_6 crystal grown using direct crystallization were studied in the frequency range $10…10^{10}$ Hz and temperature interval 296…351 K in Ref. [7]. The main feature of argyrodites is ability to create solid solution raws on their base [8, 9]. The halogen-substituted $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals were investigated in Refs. [10, 11]. In Ref. [10], the structural peculiarities of $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ are studied and discussed. The crystal structure, as being based on the X-ray diffraction data, shows the face-centred cubic lattice for Cu_6PS_5I-rich solid solutions ($x < 0.12$) and primitive cubic lattice for Cu_7PS_6-rich ($0.84 < x < 1$) solid solutions [10]. Structural studies of $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals reveal a face-centred cubic lattice ($F\bar{4}3m$ space group) for Cu_6PS_5Br-rich crystals ($0 < x < 0.4$) and a primitive cubic lattice ($P2_13$ space group) for Cu_7PS_6-rich ($0.4 < x < 1$) crystals [11]. These structural data correlate with the Raman spectra and compositional dependence of the energy gap in the mixed crystals under investigations [10, 11].

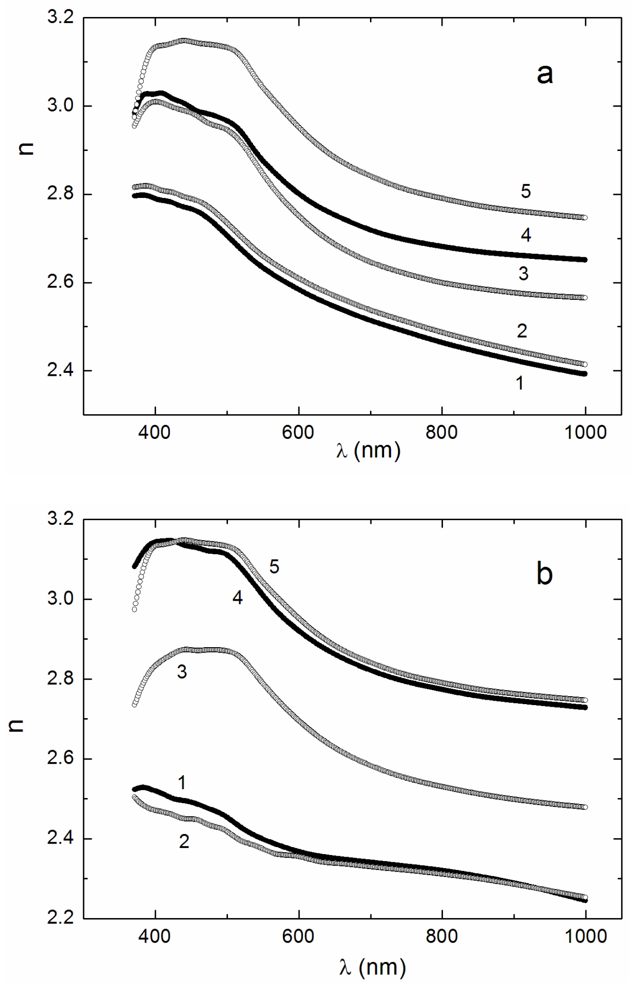

Fig. 1. Spectral dependences of the refractive index *n* for $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ (*a*) and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ (*b*) mixed crystals: a) Cu_6PS_5I (*1*), $(Cu_6PS_5I)_{0.9}(Cu_7PS_6)_{0.1}$ (*2*), $(Cu_6PS_5I)_{0.5}(Cu_7PS_6)_{0.5}$ (*3*), $(Cu_6PS_5I)_{0.2}(Cu_7PS_6)_{0.8}$ (*4*), Cu_7PS_6 (*5*); b) Cu_6PS_5Br (*1*), $(Cu_6PS_5Br)_{0.9}(Cu_7PS_6)_{0.1}$ (*2*), $(Cu_6PS_5Br)_{0.5}(Cu_7PS_6)_{0.5}$ (*3*), $(Cu_6PS_5Br)_{0.2}(Cu_7PS_6)_{0.8}$ (*4*), Cu_7PS_6 (*5*).

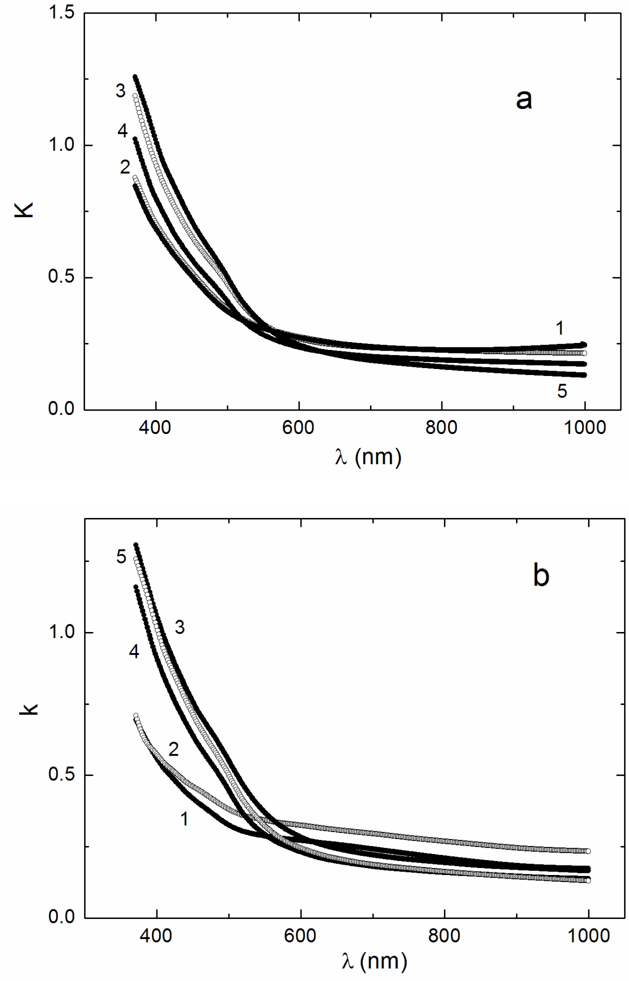

Fig. 2. Spectral dependences of the extinction coefficient *k* for $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ (*a*) and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ (*b*) mixed crystals: a) Cu_6PS_5I (*1*), $(Cu_6PS_5I)_{0.9}(Cu_7PS_6)_{0.1}$ (*2*), $(Cu_6PS_5I)_{0.5}(Cu_7PS_6)_{0.5}$ (*3*), $(Cu_6PS_5I)_{0.2}(Cu_7PS_6)_{0.8}$ (*4*), Cu_7PS_6 (*5*); b) Cu_6PS_5Br (*1*), $(Cu_6PS_5Br)_{0.9}(Cu_7PS_6)_{0.1}$ (*2*), $(Cu_6PS_5Br)_{0.5}(Cu_7PS_6)_{0.5}$ (*3*), $(Cu_6PS_5Br)_{0.2}(Cu_7PS_6)_{0.8}$ (*4*), Cu_7PS_6 (*5*).

In this paper, we report on the ellipsometric studies of $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals obtained by means of directed crystallization from the melt. Besides, the paper is aimed at the analysis of refractometric data in the framework of Wemple–DiDomenico model.

2. Experimental

$(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals were grown using a direct crystallization technique from the melt. Synthesis of $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ compounds was performed using the following procedure: heating at the rate close to 50 K/h up to (673 ± 5) K, ageing at this temperature for 24 h, then heating the "hot" zone to (1330 ± 5) K as well as the "cold" zone to (973 ± 5) K. At the temperature of (1330 ± 5) K the mixture was kept for 72 h and then the melting zone was heated up to (1380 ± 5) K (which is 50 K above the melting point) and kept at this temperature for 24 h. Seeding was performed for 48 h in the lower part of the container. The crystallization front rate was 3 mm/day. Subsequent annealing of the silica glass ampoule with the crystal was performed in the "cold" zone at (973±5) K for 48 h. The procedure resulted in $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals, 45…50 mm long with the diameter of 10…12 mm.

Spectroscopic ellipsometer M-2000V was used for the measurements of the optical constants of $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals. Measurements were carried out in the spectral range 370…1000 nm at the angle of incidence close to 70°.

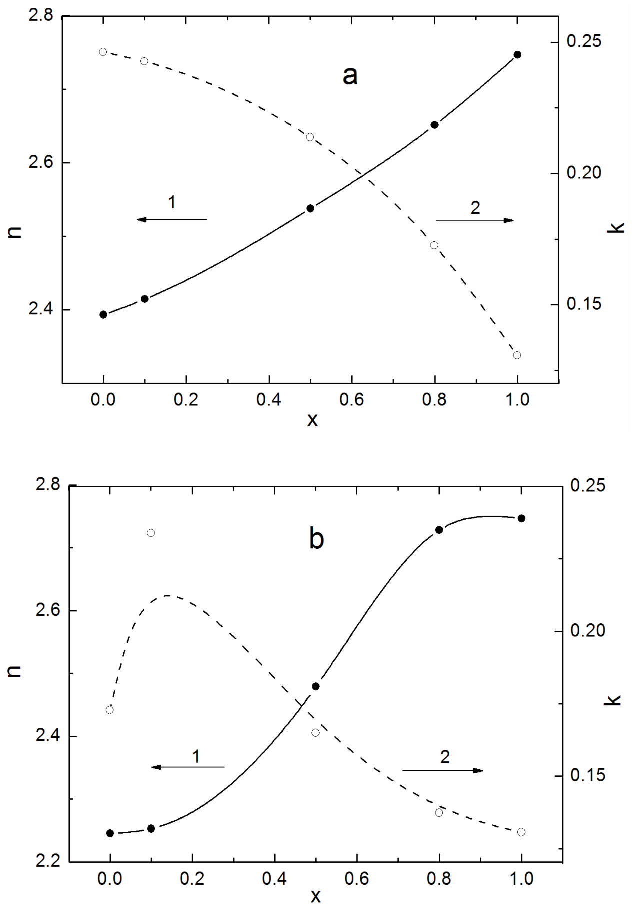

Fig. 3. Compositional dependences of the refractive index *n* (*1*) and extinction coefficient *k* (*2*) for $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ (*a*) and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ (*b*) mixed crystals.

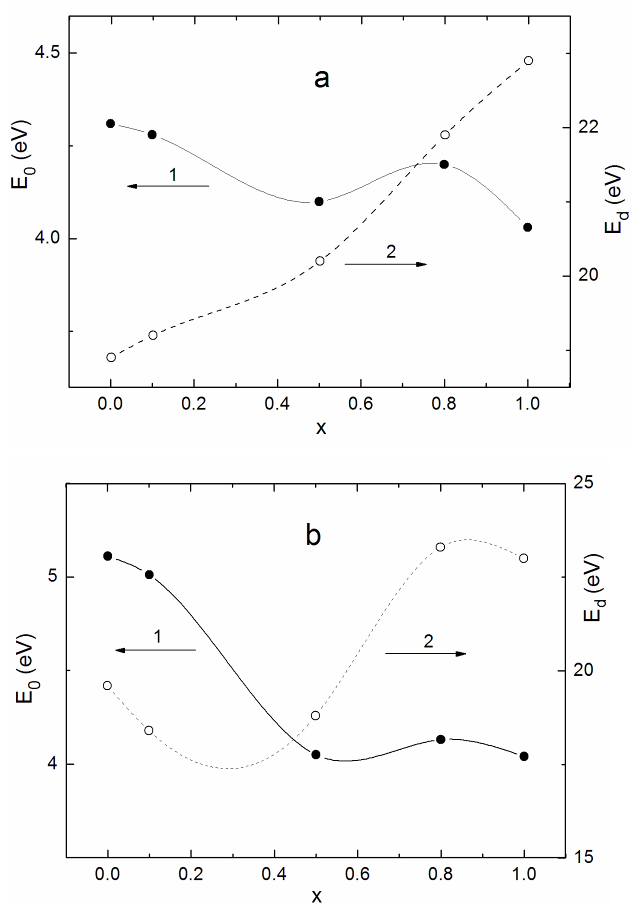

Fig. 4. Compositional dependences of Wemple and DiDomenico parameters E_0 (*1*) and E_d (*2*) for $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ (*a*) and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ (*b*) mixed crystals.

3. Results and discussion

Refractive indices *n* and extinction coefficients *k* for $Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals were obtained from the spectral ellipsometry measurements which were carried out within the spectral range 370 to 1000 nm (Figs. 1 and 2). In the region of transparency, the refractive index dispersion is observed, besides, the refractive index increases when approaching to the absorption edge. The one anomaly (in the form of broader and smeared maximum) of refractive index is revealed in the region of the extinction coefficient increase (Figs. 1 and 2). The observed anomaly corresponds to the band-to-band optical transition, and the spectral position of this anomaly relates to the energy gap value. It should be noted that in the region of extinction coefficient *k* increase, the knee was observed in the spectral dependences of *k*, the spectral position of which is related with the value of band gap energy.

Fig. 3 presents the compositional dependences of the refractive index and extinction coefficient at $\lambda = 1$ μm obtained from spectral ellipsometry measurements for $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals. With increasing the Cu_7PS_6 content the nonlinear increase of refractive index as well as the nonlinear decrease of extinction coefficient are also observed, moreover, the above mentioned compositional dependences in $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ mixed crystals, contrary to those in $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals, is monotonous without any peculiarities.

A number of models which described the refractive index dispersion are based on the relationship between the refractive index and the energy gap [12–14]. Among them one should, first of all, mention the well-known Wemple–DiDomenico (WDD) model [13]. Wemple and DiDomenico have proposed the model where the refractive index dispersion is studied in the transparency region below the gap, using the single-oscillator approximation [13].

In this paper, the dispersion dependences of refractive indices were analyzed in the framework of the WDD model [13]. In this case, the energy dependence of refractive index can be described using the relationship [13]

$$n^2(E) - 1 = \frac{E_d E_0}{E_0^2 - E^2}, \quad (1)$$

where E_0 is the single-oscillator energy, and E_d is the

Table 1. Wemple and DiDomenico parameters, optical band gap, static refractive index and ionicity for $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ mixed crystals.

Crystal	E_0 (eV)	E_d (eV)	E_g^{opt} (eV)	n_0	f_i
Cu_6PS_5I	4.31	18.9	2.16	2.321	0.48
$(Cu_6PS_5I)_{0.9}(Cu_7PS_6)_{0.1}$	4.28	19.2	2.14	2.340	0.47
$(Cu_6PS_5I)_{0.5}(Cu_7PS_6)_{0.5}$	4.10	20.2	2.05	2.433	0.45
$(Cu_6PS_5I)_{0.2}(Cu_7PS_6)_{0.8}$	4.20	21.9	2.10	2.490	0.44
Cu_7PS_6	4.03	22.9	2.02	2.587	0.42

Table 2. Wemple and DiDomenico parameters, optical band gap, static refractive index and ionicity for $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals.

Crystal	E_0 (eV)	E_d (eV)	E_g^{opt} (eV)	n_0	f_i
Cu_6PS_5Br	5.11	19.6	2.56	2.199	0.52
$(Cu_6PS_5Br)_{0.9}(Cu_7PS_6)_{0.1}$	5.01	18.4	2.51	2.160	0.52
$(Cu_6PS_5Br)_{0.5}(Cu_7PS_6)_{0.5}$	4.05	18.8	2.03	2.375	0.46
$(Cu_6PS_5Br)_{0.2}(Cu_7PS_6)_{0.8}$	4.13	23.3	2.06	2.579	0.42
Cu_7PS_6	4.04	23.0	2.02	2.587	0.42

dispersion energy. The dispersion energy E_d characherizes the average strength of interband optical transitions and relates with the changes in the structural ordering of the material (ionicity, anion valency and coordination number of the material). From the dependences $(n^2-1)^{-1}$ on E^2 by using Eq. (1) the E_0 and E_d values were determined. The above mentioned parameters of the WDD model for $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals are listed in Tables 1 and 2. It is shown that with the increase of Cu_7PS_6 content the single-oscillator energy E_0 nonlinearly decreases as well as the dispersion energy E_d nonlinearly increases for both $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals (Fig. 4). The nonlinear and nonmonotonous compositional behaviour of the parameters of the WDD model (Fig. 4) and optical constants (Fig. 3b) is explained by the structural transformation during the transition from $Cu_6PS_5I(Br)$ compound to Cu_7PS_6 compound [10, 11] as well as the compositional disordering of crystal lattice typical for argyrodite-type mixed crystals [8, 9].

According to the relation $E_0 \approx 2E_g^{opt}$ [15], the optical band gap values E_g^{opt} were estimated and presented in Tables 1 and 2. It should be noted that E_g^{opt} values and the energy pseudogap E_g ones obtained from the analysis of diffuse reflection spectra for $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals do not differ more than 10% [11]. The transition from halogen-containing $Cu_6PS_5I(Br)$ to halogen-free Cu_7PS_6 argyrodites leads to the optical band gap E_g^{opt} decrease in $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals.

The static refractive index n_0 for the mixed crystals under investigations was calculated using the equation

$$n_0 = \left[1 + \frac{E_d}{E_0}\right]^{1/2}. \quad (2)$$

The variation of the static refractive index n_0 on the composition of $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals is presented in Tables 1 and 2. It is revealed that with the increase of Cu_7PS_6 content, the static refractive indices n_0 increase for $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals.

By using the parameters of the WDD model, one can calculate this important parameter for superionic conductors as the ionicity [16]

$$f_i = \left[\frac{E_0}{E_d}\right]^{1/2}. \quad (3)$$

The values of ionicity for $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals are presented in Tables 1 and 2. It is shown that, with increase of the Cu_7PS_6 content, the ionicity of mixed crystals under investigation is decreased. This fact is in a good agreement with the recent studies of electrical conductivity in $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$-based composites [17]. It is shown in Ref. [17] that the ratio of ionic to electronic components of electrical conductivity decreases at the transition from halogen-containing Cu_6PS_5I compound to halogen-free Cu_7PS_6 compound.

4. Conclusions

$(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals were obtained using a direct crystallization technique from the melt. The ellipsometric studies were performed in the spectral range 370 to 1000 nm. Optical constants (refractive indices and extinction coefficients) for mixed crystals were obtained from the spectral ellipsometry measurements. In the region of transparency, the refractive indices dispersion is observed, the refractive indices increase when approaching to the absorption edge, and the one anomaly of refractive indices is revealed in the range of the extinction coefficients increase. The refractive indices anomaly corresponds to the band-to-band optical transition, and the spectral position of this anomaly relates to the energy gap value.

The dispersion of refractive indices is described in the framework of the Wemple–DiDomenico model. The nonlinear increase of the refractive indices and the nonlinear decrease of the optical band gap E_g^{opt}, the nonlinear decrease of the single-oscillator energy E_0 and the nonlinear increase of the dispersion energy E_d as well as the ionicity decrease are revealed with increase of Cu_7PS_6 content in $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ and $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals.

References

1. Nilges T., Pfitzner A. A structural differentiation of quaternary copper argyrodites: Structure – property relations of high temperature ion conductors. *Z. Kristallogr*. 2005. **220**. P. 281–294.
2. Andrae H., Blachnik R. Metal sulphide-tetraphosphorusdecasulphide phase diagrams. *J. Alloys and Compounds*. 1992. **189**. P. 209–215. https://doi.org/10.1016/0925-8388(92)90709-I.
3. Gagor A., Pietraszko A., Kaynts D. Diffusion paths formation for Cu^+ ions in superionic Cu_6PS_5I single crystals studied in terms of structural phase transition. *J. Solid State Chem*. 2005. **178**, Issue 11. P. 3366–3375. https://doi.org/10.1016/j.jssc.2005.08.015.
4. Haznar A., Pietraszko A., Studenyak I.P. X-ray study of the superionic phase transition in Cu_6PS_5Br. *Solid State Ionics*. 1999. **119**. P. 31–36. https://doi.org/10.1016/S0167-2738(98)00479-2.
5. Studenyak I.P., Kranjčec M., Kovacs Gy.Sh., Panko V.V., Azhnyuk Yu.M., Desnica I.D., Borets O.M., Voroshilov Yu.V. Fundamental optical absorption edge and exciton-phonon interaction in of Cu_6PS_5Br superionic ferroelastic. *Mat. Sci. Eng. B*. 1998. **52**, Issue 2-3. P. 202–207. https://doi.org/10.1016/S0921-5107(97)00278-X.
6. Fiechter S., Gmelin E. Thermochemical data and phase transition of argyrodite-type ionic conductors Me_6PS_5Hal and Me_7PS_6 (Me = Cu, Ag; Hal = Cl, Br, I). *Thermochimica Acta*. 1985. **87**. P. 319–334. https://doi.org/10.1016/0040-6031(85)85351-X.
7. Šalkus T., Kežionis A., Banys J., Izai V.Yu., Pogodin A.I., Kokhan O.P., Sidey V.I., Sabov M.Yu., Studenyak I.P. Structural and electrical properties of argyrodite-type Cu_7PS_6 crystal. *Lithuanian Journal of Physics*. 2017. **57**. P. 243–251.
8. Kranjčec M., Studenyak I.P., Bilanchuk V.V., Dyordyaj V.S., Panko V.V. Compositional behaviour of Urbach absorption edge and exciton-phonon interaction parameters in $Cu_6PS_5I_{1-x}Br_x$ superionic mixed crystals. *J. Phys. Chem. Solids*. 2004. **65**, Issue 5. P. 1015–1020. https://doi.org/10.1016/j.jpcs.2003.10.061.
9. Studenyak I.P., Kranjčec M., Kurik M.V. Urbach rule and disordering processes in $Cu_6P(S_{1-x}Se_x)_5Br_{1-y}I_y$ superionic conductors. *J. Phys. Chem. Solids*. 2006. **67**. P. 807–817. https://doi.org/10.1016/j.jpcs.2005.10.184.
10. Studenyak I.P., Luchynets M.M., Izai V.Yu., Pogodin A.I. *et al*. Structure and Raman spectra of $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ mixed crystals. *SPQEO*. 2017. **20**. P. 369–374. https://doi.org/10.15407/spqeo20.03.369.
11. Studenyak I.P., Luchynets M.M., Izai V.Yu., Pogodin A.I., Kokhan O.P., Azhniuk Yu.M., Zahn D.R.T. Structural and optical properties of $(Cu_6PS_5Br)_{1-x}(Cu_7PS_6)_x$ mixed crystals. *J. Alloys and Compounds*. 2018. **782**. P. 586–591. https://doi.org/10.1016/j.jallcom.2018.12.214.
12. Moss T.S. Relations between the refractive index and energy gap of semiconductors. *phys. status solidi* (*b*). 1985. **131**, Issue 2. P. 415–427. https://doi.org/10.1002/pssb.2221310202.
13. Wemple S.H., DiDomenico M., Jr. Behaviour of the dielectric constant in covalent and ionic materials. *Phys. Rev. B*. 1971. **3**. P. 1338–1352. http://dx.doi.org/10.1103/PhysRevB.3.1338.
14. Gupta V.P., Ravindra N.M. Comments on the Moss formula. *phys. status solidi* (*b*). 1980. **100**, No 2. P. 715–719. https://doi.org/10.1002/pssb.2221000240.
15. Tanaka K. Optical properties and photoinduced changes in amorphous As-S films. *Thin Solid Films*. 1980. **66**, Issue 3. P. 271–279. https://doi.org/10.1016/0040-6090(80)90381-8.
16. Tubbs M.S. A spectroscopic interpretation of crystalline ionicity. *phys. status solidi* (*b*). 1970. **41**, Issue 1. P. K61–K64. https://doi.org/10.1002/pssb.19700410164.
17. Izai V.Yu., Luchynets M.M., Studenyak I.P. *et al*. Preparation and electrical properties of composites based on $(Cu_6PS_5I)_{1-x}(Cu_7PS_6)_x$ mixed crystals. *Semiconductor Physics, Quantum Electronics & Optoelectronics.* 2019. **22**. P. 182–187. https://doi.org/10.15407/spqeo22.02.182.

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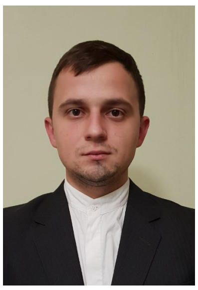

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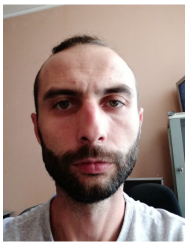

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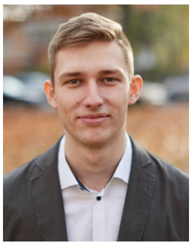

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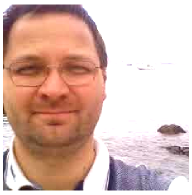

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