

Optical properties of thin copper sulphide films obtained by thermal evaporation

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Thin copper sulphide films were grown on glass substrates by "explosive" thermal evaporation method. X-ray diffraction measurements show amorphous structure of the films. The thicknesses of grown films ($13 \div 84$ nm), energy of optical direct (2.25 eV \div 2.74 eV) and indirect (0.55 eV \div 1.60 eV) transitions were obtained using Tauc plot from the measurements of optical transmission and reflection spectra. The dependences of optical band gap E_g on the film thickness, copper content and ambient temperature during deposition have been studied. The observed nonmonotonic dependences of E_g are analyzed from the point of view of influence of the Burstein-Moss effect and the structural rearrangement of growing films. The influences of the ambient temperature, copper to sulfur ratio on the structural and optical properties are analyzed.

Keywords: thin films of copper sulphide, transmission spectra, energy of direct and indirect transitions.

Методом термического испарения получены аморфные пленки сульфида меди. На основе измерения спектров оптического пропускания и отражения рассчитаны толщины выращенных пленок ($13 - 84$ нм), энергии E_{onm} для прямых (2.26 эВ – 2.74 эВ) и непрямых (0.53 эВ – 0.8 эВ) переходов и изучены зависимости E_{onm} от толщины пленок, содержания меди и влияния температуры окружающей среды во время напыления. Наблюдаемые немонотонные зависимости проанализированы с точки зрения влияния эффекта Бурштейна-Мосса и структурной перестройки растущих пленок. Проанализировано влияние температуры окружающей среды, соотношения меди и серы на структурные и оптические свойства.

Оптичні властивості тонких плівок сульфіді міді, отриманих методом термічного випаровування. *Т.В.Семікіна, С.В.Мамікін, Л.М.Шмирьова.*

Методом термічного випаровування отримано аморфні плівки сульфіді міді. На основі вимірювання спектрів оптичного пропускання та відбиття розраховано товщини вирощених плівок ($13 - 84$ нм), енергії E_{onm} для прямих (2.26 еВ – 2.74 еВ) і непрямих (0.53 еВ – 0.8 еВ) переходів і вивчено залежності E_{onm} від товщини плівок, імстуді міді і впливу температури навколишнього середовища під час напылення. Немонотонні залежності, що спостерігалися, проаналізовано з точки зору впливу ефекту Бурштейна-Мосса і структурної перебудови зростаючих плівок. Проаналізовано вплив температури навколишнього середовища, співвідношення міді та сірки на структурні та оптичні властивості плівок.

1. Introduction

Copper sulphide (Cu_2S) has optical and electrical properties that allow applying in photoelectric energy converters [1]. Cu_2S films were used in $\text{CdS}/\text{Cu}_2\text{S}$ solar cells (SC), developed back in 1954 [2]. This type of SC was not further developed due to the electrochemical decomposition of Cu_2S at a voltage above 0.33 V and subsequent diffusion of copper through a heterojunction [2]. One of the main problems in the creation of $\text{CdS}/\text{Cu}_2\text{S}$ SC was also the lack of technology that allows to obtain Cu_2S films with a reproducible composition [1]. As well known, copper sulfide is a material that can exist in several modifications, the properties of which are different [1]. The highest content of copper is inherent in the modification of chalcocite (Cu_2S), while the modification of covellite (CuS) has the highest concentration of sulfur. Identification of other modifications of Cu_xS takes place either by the type of crystal structure, either by the composition or by both characteristics simultaneously. Among the technological methods for producing Cu_xS films, chemical methods (liquid solutions) [1, 3] and thermal evaporation are most often considered [4–6]. By applying different technological methods, films with different compositions are obtained. Evaporation by thermal method is one of the simplest ones [4–6]. However, films obtained from different authors also differ in their properties. Therefore, in spite of the variety of technological methods that make it possible to obtain copper sulfide films, the development of a method for obtaining Cu_xS possessing certain properties for specific applications continues to be an urgent task. The instability of the Cu_2S phase with its subsequent decomposition into other phases, which are non-stoichiometric and whose proportion varies depending on the deposition technique, is also the reason of the observed variations in the properties of Cu_xS films. In this connection, it is necessary to determine the relationship between the phase composition of the films and their properties, including optical ones, since the literature presents contradictory information on the optical properties of Cu_xS compounds [7, 8].

In the work presented, a vacuum thermal method was used to deposit Cu_xS films of nanometer thickness. The choice of low thickness is due to the following reasons. Thin films have an amorphous structure in which the diffusion length of copper should

be less than that of crystalline films, resulting in the stability increase of the SC characteristics of copper sulphide films. The next reason for choosing a low thickness is that increasing the thickness of the Cu_xS film will lead to an increase in light absorption in the Cu_xS layer that will reduce the efficiency of the absorbent layer of the solar cell lying below the Cu_xS layer. Therefore, in this paper we studied the optical properties of Cu_xS films, which will be subsequently used in the structure of solar cells based on materials of the A_2B_6 group. To solve the task, Cu_xS films were deposited on optical glasses and polyceramic substrates. The optical properties of Cu_xS films were studied along the change in technological parameters, namely the mass of the initial sulfur powders and copper sulphide and the ambient temperature.

2. Experimental

2.1. Technology of Cu_xS films deposition and studying of their structure

Cu_xS films were deposited in a vacuum chamber (a vacuum of 10^{-5} mm·Hg) by an "explosive method" on the substrates of optical glass and polyceramic. Powders of sulfur and copper sulphide were placed in the boat (crucible), the ratio of which varied both in the direction of increasing the mass of copper sulfide and in the decrease of it. As a result of the boat heating, the powders evaporated and settled on a substrate located on 14 cm from the crucible. The substrates were not specially heated or cooled. Evaporation of powders occurred within a few seconds, which gave the name of the method "explosive". In the course of the experiment, two batches of samples were made: at an ambient temperature of 14°C (samples 8–13) and 26°C (samples 1–7). In each batch, the ratio of the weight of copper and sulfur powders varied, the values of which are given in Table 1.

The crystal structure of the films was investigated by X-ray diffraction on an X'Pert MPD diffractometer in the 20° – 100° angular range with $\text{Cu-K}\alpha$ radiation (wavelength $\lambda = 0.1542$). The results of measuring X-ray diffraction spectra for Cu_xS films deposited on glasses showed that the structure of the films is amorphous.

2.2. Optical properties of Cu_xS

The optical properties of Cu_xS films are determined mainly by their composition [1]. The value of the width of the band gap,

Table 1. Parameters of obtained Cu_xS films.

Sample #	Cu_2S powder weight, mg	S powder weight, mg	Film thickness, nm	Light transmittance at $\lambda = 650$ nm	Energy of direct transitions E_{opt} , eV	Energy of indirect transitions E_{opt} , eV	Ambient temperature during deposition T , °C
1	5	5	50	0.66	2.50	1.60	26
2	5	5	46	0.75	2.49	1.57	26
3	2.5	5	22	0.76	2.49	1.34	26
4	10	5	52	0.62	2.64	1.49	26
5	5	5	49	ceramic glass substrate	2.56	1.58	26
6	10	10	84	0.54	2.26	0.96	26
7	5	2.5	59	0.73	2.54	1.24	26
8	2.5	5	13	0.80	2.74	1.42	14
9	5	5	26	0.73	2.73	1.56	14
10	2.5	7.5	37	0.65	2.45	0.62	14
11	2.5	10	51	0.61	2.25	0.55	14
12	5	2.5	23	0.87	2.40	1.57	14
13	7.5	5	36	0.75	2.38	1.55	14

depending on the value of x , varies over a wide range [7, 8]. The change in optical absorption in Cu_xS films in the region of interband transitions is usually associated with a lattice rearrangement with a change in the value of x [7, 8]. So, in the chalcocite, indirect optical transitions occur, with an energy of 1.2 eV and direct ones with a transition energy of 1.8 eV [1], and in [7, 8] the values of 1.2 eV and 2.2 eV are indicated, respectively. While the composition deviates from the stoichiometric ratio, the width of the forbidden band and the corresponding transition energy value increase.

The optical transmission and reflection spectra of the investigated films were measured with an setup consisting of an IKS-12 monochromator, a CDSH-100 lamp, and a silicon Hamamatsu S1227BQ photodetector. The characteristics were measured at angles of incidence of polarized light of 15° , 45° , 60° , and 75° within the spectral range $0.40 \pm 1.1 \mu\text{m}$. Wavelength dependences of the optical constants (reflection coefficient and absorption coefficient) were taken into account. The calculations were performed under the assumption of a single-layer model. The experimental dependences of the obtained transmission/reflection spectra at different angles of incidence were simulated using the Fresnel formulas [9]. Based on the obtained model calculations, the thicknesses of Cu_xS films were determined. Also, from the transmission and reflection spectra, the optical band gap E_{opt} was determined under the assumption that the main ones are di-

rect or indirect optical transitions. The results of the calculations are given in Table 1. It is known [6] that the absorption coefficient α is related to the width of the forbidden band E_{opt} in the case of indirect transitions by the following expression:

$$\alpha h\nu = B(h\nu - E_{opt})^2,$$

where h is the Planck constant, ν is the frequency of the incident radiation, and B is the constant. Extrapolating the straight portion of the curve $(\alpha h\nu)^{1/2}$ to the intersection with the axis $h\nu$, we obtain the value E_{opt} . Similarly, the value of E_{opt} for direct transitions is determined with the difference that the relationship has the following form:

$$\alpha h\nu = B(h\nu - E_{op})^{1/2}$$

3. Results and discussion

On the basis of the obtained spectra, the dependence of the absorption coefficient α on the energy of the incident light was plotted (Fig. 1). It is known that the process of light absorption by free charge carriers is accompanied by the excitation of carriers from the filled levels below the Fermi level with their transfer to free levels above the Fermi level. Thus, the process is accompanied by the absorption or emission of a polar optical phonon, an acoustic phonon, or energy dissipation due to the ionization of impurities. The effect of free charge carriers on optical properties is described in the

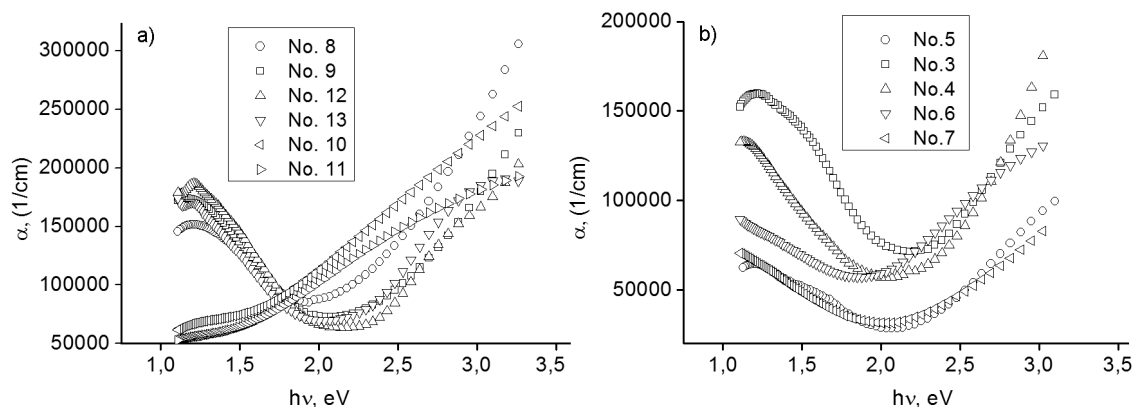


Fig. 1. Optical absorption spectra for Cu_xS films obtained at 14°C (a) and 26°C (b).

framework of the classical Drude theory [10]. From Fig. 1 we conclude that all samples, except for samples 10 and 11, have a high absorption in the energy range $1.0 \div 1.5$ eV. Thus, we observe a significant contribution of the Drude component to the optical properties of films already in the visible region, which is explained by the presence of quasi-free charge carriers in the films [11, 12].

It is known that Cu_xS films are a *p*-type semiconductor. Hole type conductivity is formed due to the vacancy of copper, which act as acceptors [6]. A distinctive feature of samples 10 and 11 is the lack of copper in the initial ratio of powders. Accordingly, the number of quasi-free holes in these samples is smaller in comparison with other samples. However, an increase in the proportion of copper sulphide in evaporated powders does not automatically lead to an increase in the absorption of Cu_xS . Thus, samples 8 and 3 showed the greatest absorption, while the ratio $\text{Cu}_2\text{S}/\text{S}$ was 0.5. The change in the proportions of copper and sulfur atoms leads to the formation of different phases of copper sulphide, and it is the presence of different phases that affects the number of charge carriers and, as a consequence, the amount of absorption. However, due to the fact that the films we studied were very thin and amorphous, it was not possible to correlate accurately between the crystal structure and the absorption.

It can be seen from Fig. 1 that a change in the ambient temperature by 12°C leads to a change in absorption. Thus, at lower temperatures (14°C), films grow with a larger absorption amount. Thus, there are more free carriers in them, and, consequently, the number of copper vacancies is also greater. At lower temperatures, the mobility of both ions reaching the surface of the substrate and growing clusters is less,

which, most likely, leads to the formation of a film with a large number of defects. A phase diagram is shown in [1] that describes the relationship between the temperature stability regions of Cu_xS films, their modifications and the value of x . So, in the temperature range $10 \div 70^\circ\text{C}$, the phases anilite + durlite are stable, and the value of x lies in the range from 1.76 to 1.93. At temperatures above 70°C and values of $x = 1.76 \div 1.82$, a digenite is obtained, and in the temperature range of $70 \div 90^\circ\text{C}$ at $x = 1.82 \div 1.93$, we obtain a digenite + durlite. Based on the temperature values used in our experiment, we can assume that we obtain films with a mixed phase of anilite and durlite in short order.

It is known [1, 4, 6] that in Cu_xS films a dependence of E_{opt} on the thickness is observed: for example, at a thickness $d = 0.17 \mu\text{m}$, $E_{opt} = 2.1$ eV; at $d = 0.45 \mu\text{m}$, $E_{opt} = 1.8$ eV.

The obtained dependences of the optical width of the forbidden band on the film thickness are nonmonotonic. If for optical transitions at a temperature of 14°C it is observed a tendency to decrease E_{opt} with increasing thickness (Fig. 2a), then in the case of optical transitions at a temperature of 26°C there are observed extreme values in the region of 50 nm (Fig. 2b). The thickness of the samples varied due to the change in the weight of the initial powders. But a change in the character of the dependences, even with a slight increase in temperature, indicates a change in the dynamics of the processes occurring on the substrate. A higher temperature promotes a faster growth of the film due to an increase in the energy of the particles on the substrate. Apparently, for films with thickness up to the extreme point, the amorphous phase is mainly characterized, which then

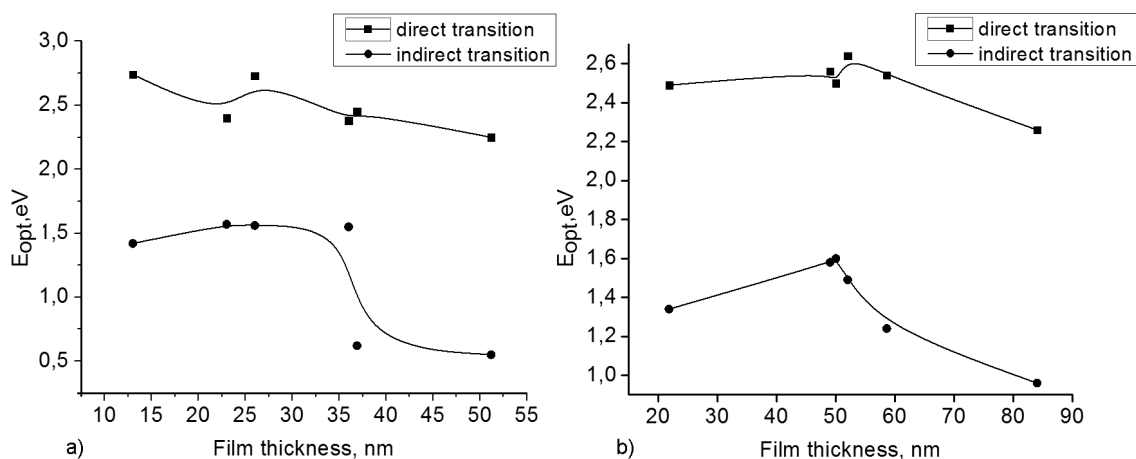


Fig. 2. Dependences of the optical band gap for direct and indirect transitions on the film thickness for the temperature of 14°C (a) and 26°C (b).

after the extreme point (reaching the critical thickness) begins to undergo structural changes with the formation of crystalline inclusions and the properties of the films change, which we observe on the graphs.

The obtained result differs from the results of [6], where an increase in the film thickness (from 300 nm to 700 nm) was accompanied by a monotonic decrease of E_{opt} (from 2.2 eV to 1.8 eV) and the observed change was explained by a change in the height of the potential barriers between growing crystallites. The difference with our experiment was that the film thicknesses in [6] were an order of magnitude larger (300 ÷ 700 nm against our 20 ÷ 80 nm) and the films in [6] had a crystalline structure. Amorphous films with thicknesses similar to ours were investigated in [13]. The results obtained for the case of direct transitions $E_{opt} = 2.55$ eV at a thickness of 26 nm and $E_{opt} = 2.74$ eV for $d = 65$ nm are close to our results. The values of E_{opt} (2.25 eV ÷ 2.74 eV) obtained in our work are higher in comparison with the typical value of 1.8 eV for the crystalline copper sulfide film [1].

The increase in the energy of the optical transition is often explained by a violation of the stoichiometry of the film [6, 13]. However, an increase in the value of E_{opt} can also be due to the Burshtein-Moss effect [14], which consists in the fact that the shift of the edge of the region of intrinsic light absorption into the higher energy region occurs when the conduction electron density is increased, and the conduction band is filled with them. According to the Pauli principle, optical quantum transitions are possible only under the condition that

the state into which the electron passes is not occupied by another electron. In the case of a high carrier concentration (about 10^{20} cm⁻³), many states near the bottom of the conduction band are already filled, and therefore they cannot receive electrons optically excited from the valence band. The free levels in degenerate semiconductors are above the edge of the conduction band (for the *n*-type) or below the edge of the valence band (for the *p*-type). The Fermi level in degenerate semiconductors is located in the region of allowed energy values. In this case, the population of electrons in the conduction band in an *n*-type semiconductor or holes in the valence band in a *p*-type semiconductor leads to a short-wavelength shift of the interband absorption edge of light.

Since for thin films the influence of the surface, and the associated increase in conductivity, the greater the thinner the film, the Burshtein-Moss effect will be more pronounced for thinner films. An additional contribution to the conductivity will be given by grain boundaries, surface states associated with amorphous films. Thus, for the films under consideration, the influence of the Burshtein-Moss effect can be significant.

Table 2 gives comparative data on the width of the forbidden band for direct and indirect transitions, obtained in our work and literature. It is believed that the difference in the values of the optical band gap for different samples is mainly due to the fact that films with different values of x are obtained for different technological regimes. From Table 2 it can be seen that the values of E_{opt} vary considerably. In some works [3, 13, 15] only direct transitions are considered. The values of E_{opt} for direct

Table 2. Optical transition values of Cu_xS films

Sample	E_{opt}^{direct} , eV	$E_{opt}^{indirect}$, eV	References
No. 6, $d = 84$ nm	2.26	0.96	Present publication
No. 8, $d = 13$ nm	2.56	1.58	Present publication
No. 9, $d = 26$ nm	2.73	1.56	Present publication
Thin film	2.0–2.5	~ 1.2	[5]
Thin film, $d = 113$ nm	2.26	1.03	[5]
Thin layer	1.83	1.21	[5]
Thin layer	1.7	1.05	[5]
Thin film	2.1	1.4	[5]
Thin film, $d = 26$ nm	2.55	–	[13]
Thin film, $d = 65$ nm	2.74	–	[13]
Thin film, $d = 300$ nm	2.2	–	[6]
Thin film, $d = 700$ nm	1.8	–	[6]
Thin film, $d = 266$ nm	2.67	–	[15]
Thin film, $d = 217$ nm	3.1	–	[15]
Thin film, $d = 400$ nm	–	–	[3]
Thin film, $d = 130$ nm	2.36	–	[3]
Thin film, $d = 200$ nm	2.35	–	[21]

transitions in [3, 13, 15] coincide with the values of E_{opt} for indirect transitions in [5]. Thus, the researchers do not have an unambiguous opinion as to which optical transitions are realized in films of copper sulphide. This is due to the fact that the objects studied were different. There is no general explanation for the observed different E_{opt} values.

It can be seen from Table 2 that films obtained in the same technology have different E_{opt} values for different thicknesses [3, 6, 13, 15]. The observed dependences of E_{opt} on the thickness of the films differ in various papers. Thus, in [3], the increase in E_{opt} as the film thickness is decreased is explained on the basis of the effect of the quantum-size effect due to small crystallites that grow in a thinner film. In [6], the increase in the value of E_{opt} with decreasing thickness is explained by the fact that in a thicker film, where there is already no amorphous phase, the crystal structure is transformed. And in work [13], the increase in E_{opt} occurs vice versa with increasing thickness. But the thickness of the films in this work is an order of magnitude smaller (see Table 2) than in the previous papers and the structure of these films is amorphous. We believe that an increase in the thickness of the film leads to ordering of the structure, as can be seen from the decrease in the value of E_{opt} , both in most of the literature data and in our characteristics presented in Fig. 2.

The next factor affecting the value of E_{opt} is the increased content of copper or sulfur in the composition of the film. So in [15] the data $E_{opt} = 2.67 \div 3.1$ eV are given for the case of $\text{Cu}_{1.8}\text{S}$ film (copper enrichment) and $E_{opt} = 2.46 \div 2.49$ eV for CuS (copper depletion). The values obtained in our work are in the range $2.25 \div 2.74$ eV. To analyze the effect of the depletion or copper enrichment factor on the E_{opt} value, we consider Fig. 3.

As can be seen from Fig. 3, an increase in the proportion of copper for samples obtained at a temperature of 26°C leads to an insignificant increase in E_{opt} due to an increase in the conductivity and the influence of the Burstein-Moss effect and correlates with the results presented in [15]. But in our work, the value of E_{opt} is on the average in the range $2.5 \div 2.55$ eV and smaller in comparison with the data of [15] ($2.67 \div 3.1$ eV), which were obtained for samples enriched in copper. For samples obtained at a temperature of 14°C , a nonmonotonic change in E_{opt} from the ratio of powders is observed. At a powder ratio of $\text{Cu}_2\text{S}/\text{S} = 0.5 \div 1.0$, the maximum value $E_{opt} = 2.74$ eV is observed, after which E_{opt} decreases to 2.4 eV. Thus, the increase in copper in the initial mixture of powders in the beginning led to an increase in E_{opt} , but then a further increase in copper leads to a drop in the value of E_{opt} . It was expected that an increase in the proportion of copper will lead to an increase in conductivity and an increase in E_{opt} . To explain the decrease

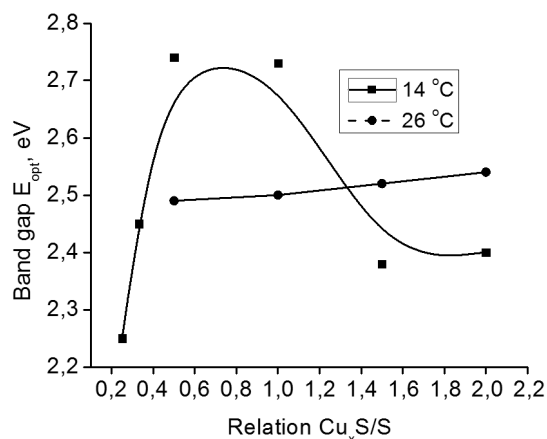


Fig. 3. The dependences of the energy of direct transitions on the ratio of Cu₂S/S powders.

in the value of E_{opt} observed after the extreme point by increasing the thickness of the films and, accordingly, improving the stoichiometry is impossible, because the data on the plot were plotted for films of similar thickness (26 ÷ 36 nm). It is known that the E_{opt} changes in the case of a degenerate p -type semiconductor are due not only to the Burstein-Moss effect, but also to intraband transitions between the subbands of light and heavy holes. Along with the Burstein-Moss effect and intraband transitions, the absorption coefficient of a highly degenerate semiconductor can vary due to a decrease in the band gap E_g , which is caused by the so-called renormalization of the forbidden band due to screening of the periodic potential of the crystal lattice by charge carrier plasma [12]. In our experiment we investigated amorphous films in which the crystal lattice did not form. Therefore, the reasoning will be built on the basis of technological factors influence. During the growth of films at lower temperatures (14°C), the change in the number of atoms and ions of copper sulfide and sulfur to the composition of the growing film is most likely to occur because at 14°C the mobility of clusters on the substrate is lower. From the results (Fig. 3), it can be seen that there is some critical range in the ratio of copper sulfide and sulfur, at which the structure of the film changes. In our experiment, such a critical range was the ratio of Cu₂S:S = 0.6 ÷ 0.9. Thus, during the growth of films, several processes operate and a simple change in the thickness of the films or the ratio of the initial powders does not allow one to uniquely regulate the optical properties, and in particular, E_{opt} .

In order to obtain films with a certain E_{opt} value, it is necessary to take vapor pressures into account, and even insignificant temperature changes.

The transmission and reflection of the film is important for further practical applications [16–20]. It is known that thin Cu_xS films transmit in the ultraviolet region, slightly reflect in the visible (less than 10 % reflection) and relatively strongly reflect in the infrared spectrum (more than 15 % reflection) [21]. There are several works where the transmission and reflection of films of copper sulfide are studied. So, in [21] the films with a thickness of 200 nm, obtained by the chemical method, had a maximum transmission of 53.4 % at a wavelength of $\lambda = 630$ nm. The reflection in the range $\lambda = 610 \div 670$ nm was ~ 0.34. In [6, 22] films of thickness 100 ÷ 700 nm, obtained by the vacuum evaporation method, showed a low reflection coefficient for films of small thickness. The transmission for these films was significant. The refractive index was proportional to the thickness of the film, which indicates the potential of using these films as an antireflection coating.

The results of measuring the transmission of the investigated films at a wavelength $\lambda = 650$ nm are presented in Table 1. The values obtained lie in the range 0.535 ÷ 0.87. A general decrease in the transmission was observed with increasing film thickness, thus with increasing thickness, the absorption of the film increased. On the basis of the obtained results, it is possible to select the optimum thickness of the Cu_xS film, which is the upper current collector contact in the structures of the CdS/CdTe SC that are under investigation [17, 19–20].

4. Conclusions

Optical and structural studies have shown that obtained Cu_xS films are nanosized (13 ÷ 84 nm) and amorphous. Direct and indirect optical transitions are observed in the films. For indirect transitions, the calculated values of E_{opt} were 0.55 eV ÷ 1.6 eV, and for direct transitions, respectively, 2.25 eV ÷ 2.74 eV. The change in E_{opt} observed for films that have different thicknesses, ratios of copper and sulfur in the powders evaporated mixture and obtained at different ambient temperatures is explained on the basis of structural changes and the influence of the Burstein-Moss effect. It has been found that at different

temperatures of environment the films with different properties grow, which is reflected in the different character of the E_{opt} dependence on the thickness and the copper-sulfur ratio of the initial powders. It is determined that in the film obtained at 26°C with a thickness approaching 50 nm, an abrupt change in the properties begins. It is shown that there is a certain critical region in the ratio of copper and sulfur, at which the properties of the film also change. Such a critical region was the ratio of $Cu_2S:S \sim 0.6 \div 0.9$ for films obtained at 14°C.

The presence of Drude-tails in the absorption spectra suggests that the films exhibit significant absorption and conductivity. The results of measuring the transmission spectra of Cu_xS films showed that only the thinnest films (~ 20 nm) had a transmission of about 87 % at a wavelength of $\lambda = 650$ nm. An increase in the film thickness to 84 nm resulted in a significant decrease in transmission to 50 %.

The results presented in the paper determine the relationship between the technological conditions for the production of copper sulfide films and their optical properties, which is necessary for the subsequent use of films in photoconverters and solar cells.

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References

1. Kasturi Lal Chopra, Suhit Radgan Das, Thin Film Solar Cells, Plenum Press, New York (1983).
2. M.A.Green, K.Emery, Y.Hishikawa et al., *Prog. Photovolt. Res.Appl.*, **25**, 3 (2017).
3. M.S.Shinde, P.B.Ahirrao, I.J.Patil et al., *Indian J. Pure & Appl. Phys.*, **50**, 657 (2012).
4. M.Ramaya, S.Ganesan, *Iranian J. Mater. Sci. & Engin.*, **8**, 34 (2011).
5. M.Saadeldin, H.S.Soliman, H.A.M.Ali et al., *Chin. Phys. B*, **23**, 046803 (2014).
6. M.Ramaya, S.Ganesan, *IJST*, **37A3**, 293 (2013).
7. M.B.Muradov, G.M.Eyvazova, N.G.Darvishov et al., *Trans., Ser. Phys. Math. Sci.*, **24**, 145 (2004).
8. M.B.Muradov, G.M.Eyvazova, Ya.M.Elchiev, *Prikladnaya Fizika*, **5**, 94 (2010).
9. H.Fujiwara, Spectroscopic Ellipsometry: Principles and Applications, John Wiley & Sons Ltd., England (2007).
10. Sadao Adachi, Properties of Group-IV, III-V and II-VI Semiconductors, Wiley Series in Materials for Electronic and Optoelectronic Applications, John Wiley & Sons Ltd., England (2005).
11. J.I.Pankove. Optical Processes in Semiconductors, Prentice-Hall, Inc., Englewood Cliffs, New Jersey (1971).
12. R.A.Smith, Semiconductors, Cambridge University Press, Cambridge London-New York-Melburne (1978).
13. Fuwei Zhuge, Xiaomin Li, Xiangdong Gao, Xiaoyan Gan et al., *Mater. Lett.*, **63**, 652 (2009).
14. T.Moss, Optical Properties of Semiconductors, Butterworth's Scientific Publication, LTD, London (1959).
15. Luminita Isac, Ionut Popovici, Alexandru Enesca et al., *Energy Procedia*, **2**, 71 (2010).
16. Yu.N.Bobrenko, S.Yu.Pavelets, T.V.Semikina et al., *Semicond. Phys., Quant. Electron. Optoelectron.*, **18**, 101 (2015).
17. T.V.Semikina, S.V.Mamykin, M.Godlewski et al., *Semicond. Phys., Quant. Electron. Optoelectron.*, **16**, 111 (2013).
18. Yu.N.Bobrenko, S.Yu.Pavelets, A.M.Pavelets et al., *Semiconductors*, **49**, 519 (2015).
19. T.V.Semikina, S.V.Mamykin, G.I.Sheremet et al., *Ukr. J. Phys.*, **61**, 732 (2016).
20. T.V.Semikina, *Ukr. J. Phys.*, **63**, 156 (2018).
21. H.M.Pathan, J.D.Desai, C.D.Lokhande, *Appl. Surf. Sci.*, **202**, 47 (2002).
22. M.Ramaya, S.Ganesan, *Iranian J. Sci. Techn.*, **37A3**, 293 (2013).