Physical bases of fiber-optic temperature sensors development with chalcogenide vitreous semiconductors sensors

Ig. Iv. Chychura[1], S. V. Kutchak[1], Iv. Iv. Chychura[2]

[1]National Universiry of Uzhhorod, Uzhhorod, Ukraine,
[2]Institute of Electron Physics, Ukranian National Academy of Sciences, Uzhhorod, Ukraine,
*Corresponding author. E-mail: igor.chechura@uzhnu.edu.ua

Paper received 04.09.21; Accepted for publication 29.09.21.

https://doi.org/10.31174/SEND-NT2021-262IX33-04

Abstract. A method of manufacturing sensitive elements for fiber-optic temperature sensors from chalcogenide semiconductor has been developed. Temperature dependences of the Urbach edge of such elements were measured in the temperature range from 246 to 443 K. Based on the analysis of experimental results, a clear functional dependence of the absorption coefficient of the Urbach region as function of two arguments (photon energy and temperature) for sensitive elements made from $As_{45}Se_{55}$ glass were proposed.
Keywords: *fiber-optic temperature sensors, Optical transmission, Chalcogenide vitreous semiconductors.*

Introduction. The widespread implementation of fiber-optic communication lines as a modern and highly efficient way of transmitting information creates favorable conditions for the development of alternative ways of using fiber-optic technologies, among which a variety of sensors based on fiber-optic technology. In such devices, the optical fiber can serve as an element of information transmission or perform the function of a sensitive element. Among modern fiber-optic sensors, amplitude type fiber-optic temperature sensors have reached a certain level of distribution [1-4]. Sensors of this type can be used to monitor the temperature at distances up to several kilometers in explosive environment, because the information parameter in them is optical radiation as opposed to the traditional ones, which use electric signals. At present time, semiconductor crystals (GaAs, GaP, etc.) are a sensitive element which used in the vast majority of such sensors [5]. These crystals are also widely used in modern optoelectronics: in the basic elements of infrared optics, television technology and fiber optic communications. An alternative to the use of crystalline materials as temperature sensitive elements of fiber-optic temperature are chalcogenide vitreous semiconductors (CVS). Despite the narrower operating temperature range due to low crystallization temperatures of (CVS), such sensors can be successfully used for a long time in the zone of strong electromagnetic fields and intense radiation background without significant decrease of their metrological characteristics.

In this paper, we studied the methods of manufacturing high-quality temperature sensitive elements from (CVS) and investigated their spectra of the optical absorption edge in a wide temperature range to create a mathematical model for modeling of parameters in fiber-optic temperature sensors.

Methods. Our experimental studies show that the optimal thickness of temperature sensitive elements for FOTS should be in the range from 0.3 mm to 0.5 mm. Production of such samples from (ChS) by traditional methods of grinding and polishing is an extremely difficult task, due to the peculiarities of the behavior of these materials during machining. There is a high probability of microcracks and even complete destruction of the samples during the manufacturing process.

It is well known that as the temperature of (CVS) increases above the glass transition temperature, their viscosity decreases sharply. This allows us to make thin plates for sensitive elements in a completely different way, which we studied.

The basis of this technology is the grains from the source material with calibrated mass and dimensions. Such a grain can be placed between two quartz plates and compressed while heating to a temperature close to the softening temperature Tg of the corresponding glass. To ensure the required thickness of the sensing element, the grain was placed in the middle of a steel washer with calibrated diameter and thickness, in accordance with the required shape and size of the sensing element.

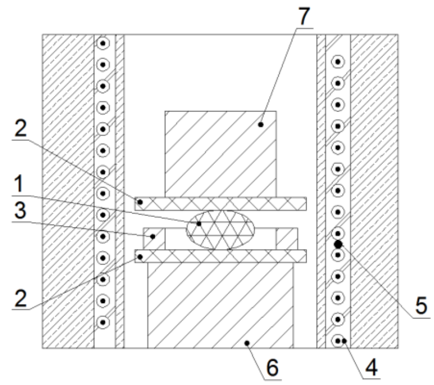

Fig. 1. The design scheme of the thermal press for the manufacturing of sensitive elements for FOTS from (CVS): 1 - calibrated grain of glass; 2 - a plate from quartz glass; 3 - steel ring; 4 - electric furnace; 5 - thermocouple; 6 - base, 7 - load.

The technological process of making samples was carried out in a specially designed sealed chamber, the design of which is shown in Fig.1. The main technological parameters in this process are:

- the amount of mechanical load (≈ 103 N);
- heating rate (about 0.5 ± 0.1 K per minute);
- the temperature of formation of the sensitive element is close to (Tg ± 10 K).

To complete the process, the heated glass grain was kept in a softened state for 10 ÷ 15 minutes. Under the action of the applied load heated to the softening temperature (CVS) slowly changes shape into a plate of the sensitive element (Fig. 2).

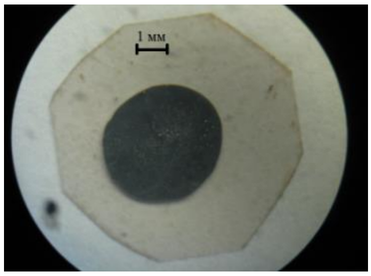

Fig. 2. View of the formed sensitive element from $As_{45}Se_{55}$ after completion of the manufacturing process.

Results and discussion. The absorption spectra for $As_{45}Se_{55}$ plates, which were made according to the methods described above, are shown in Fig. 3. The resulting spectra provide workspace of transmission changes for sensitive elements of temperature sensors at variations in the photon energy radiation and measured by temperature sensors.

It was found that for As-Se glasses temperature dependence of the optical absorption spectrum α (hν,T), in the edge region, is well described by the Urbah expression [6]:

$$\alpha(h\nu,T) = A(T)\exp\left(\frac{h\nu - E_g(T)}{E_0(T)}\right), \quad (1)$$

where E_0 (T) is the characteristic energy of the Urbach edge, E_g (T) is the extrapolated optical band-gap energy, and $A(T)$ is the optical absorption coefficient. It is clearly that all these parameters are temperature dependent. This mathematical function was used to analyze the absorption of doped GaAs crystals in our previous work [7]. It is also assumed that the band gap in (1) is equal to the extrapolated optical gap. Although this may not give precisely the same values as other definitions of the band gap.

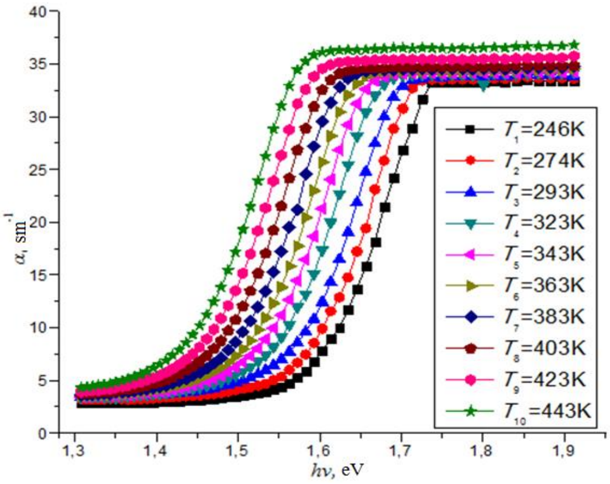

Fig. 3. Spectral dependences of the optical absorption coefficient of $As_{45}Se_{55}$ sample at different temperatures.

Ratio (1) is more convenient to use in converted form:

$$\ln[\alpha(h\nu,T)] = \ln[A(T)] + \left(\frac{h\nu - E_g(T)}{E_0(T)}\right) = \ln[A(T)] + B(T)\cdot h\nu - \frac{E_g(T)}{E_0(T)} = A''(T) + B(T)\cdot h\nu \quad (2)$$

In this case, we obtain for each temperature a linear dependence of the natural logarithm of the absorption coefficient from photon energy. Parameters of this linear dependence:

$$A''(T) = \ln[A(T)] - E_g(T)/E_0(T) \text{ and } B(T) = 1/E_0(T) \quad (3)$$

are functions of temperature.

The maximum deviation of the interpolation process of edge at all temperatures does not exceed the value 0.1276 for $A''(T)$ and 0.0511 for $B(T)$. Values of the obtained parameters of interpolation of the absorption edge at different temperatures are shown in table 1.

The temperature dependences of the parameters E_0, E_g and A (Urbach region) edge are shown in Fig. 4-6. The characteristic energy E_0 shows some growth with temperature increasing.

A similar temperature behavior was observed by us and other authors [7,8] for both undoped and doped with various impurities GaAs crystals. The value of the parameter E_0 for our glasses is several times larger compared to these crystals. The temperature dependence of $E_0(T)$ obtained by us in the temperature range from 250 to 450 K is well described by the linear function $E_0(T) = e_0 + e_a \cdot T$, which is typical for most (CVS)'s. As a result of mathematical processing of experimental data, the coefficients e_0 and e_a were obtained, quantitative values of which are given in table 2.

Table 1. Parameters of interpolation of the absorption edge of $As_{45}Se_{55}$ plates by linear function (3) and defined from them parameters of Urbach region (2).

T, K	$A''(T)$, a.u.	$B(T)$, eV^{-1}	$E_0(T)$, eV	$E_g(T)$, eV	$E_g(T)/E_0$, a.u.	$A(T)$, cm^{-1}
246,00	-18,75	12,98	0,077	1,630	21,17	11,2
274,00	-18,16	12,79	0,0785	1,610	20,51	11,5
293,00	-17,54	12,54	0,0795	1,595	20,06	11,6
323,00	-16,89	12,33	0,081	1,575	19,44	11,8
343,00	-16,61	12,21	0,082	1,560	19,02	12,1
363,00	-16,21	12,04	0,083	1,545	18,61	12,3
383,00	-15,63	11,85	0,084	1,530	18,21	12,6
403,00	-15,32	11,69	0,085	1,510	17,75	12,7
423,00	-14,83	11,55	0,086	1,490	17,33	13,2
443,00	-14,31	11,45	0,087	1,470	16,90	13,3

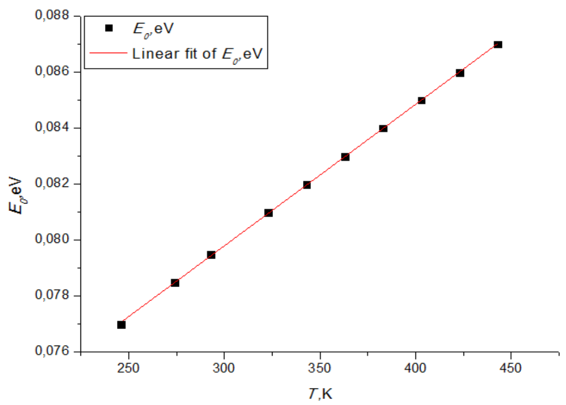

Fig. 4. Temperature dependence of E_0 for $As_{45}Se_{55}$ sample.

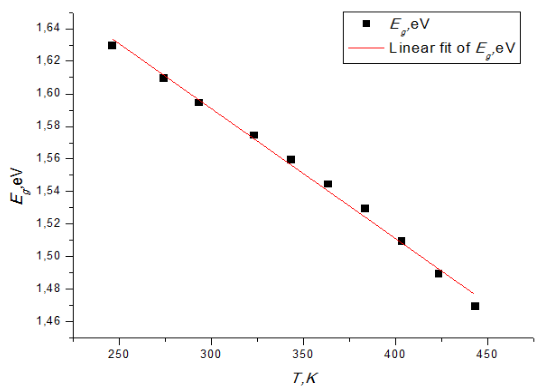

Fig. 5. Temperature dependence of E_g for $As_{45}Se_{55}$ sample

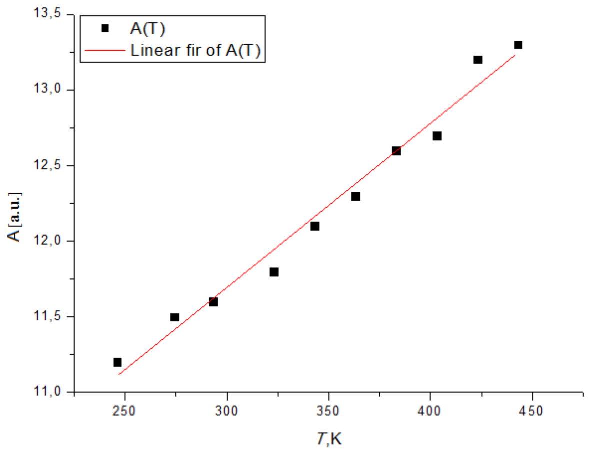

Fig. 6. Temperature dependence of A parameter for linearization of the absorption edge of $As_{45}Se_{55}$ sample..

The magnitude of the optical width of the band gap of the glasses we studied at room temperature is close to 1,6 eB. With temperature increasing, the value of *Eg* naturally decreases Fig.5. The average coefficient of temperature changes is approximately - $5\cdot10^{-4}$ eB/K. Comparing this value with the corresponding parameters obtained by us for GaAs crystals, it can be concluded that the temperature coefficient of $As_{45}Se_{55}$ glasses is almost twice higher. According to the Fig. 5 the temperature dependence of *Eg* can be well described by a linear function. In our previous studies [7] and in work [8], we used a second-degree polynomial to represent the band gap of GaAs crystals doped with various impurities. In this case, the use of the linear function led to much larger absolute errors. In case of using $As_{45}Se_{55}$ glasses, we presented Eg (T) as a linear function, the explicit form of which is written in table 2.

Table 2. Representation of the parameters of the Urbach region of the absorption edge of $As_{45}Se_{55}$ glasses by the corresponding polynomials and errors of this representation.

Parameter	Relative processing errors
$E_0(T) = 5{,}05\cdot10^{-5}\cdot T + 0{,}065$	2 %
$E_g(T) = -9{,}89\cdot10^{-7}\cdot T^2 - 1{,}15\cdot10^{-4}\cdot T + 1{,}72$	7 %
$A(T) = 0{,}01\cdot T + 8{,}44$	9 %

According to relation (3), the parameter A (T) determines the value of the optical absorption coefficient at temperature *T* for the photons energy of $h\nu = E_g(T)$. Its behavior with increasing temperature is illustrated by the graph of Fig.6. According to Fig.6, despite a fairly significant scatter of experimental points, there is a linear dependence of the parameter *A* on temperature. The explicit form of linear function obtained by us is given in Table 2.

Using all the obtained results of the theoretical analysis of experimental data, we can write an explicit form of the mathematical relation for the coefficient of optical absorption of $As_{45}Se_{55}$ glasses, which serve as materials for temperature sensitive elements for FOTS's:

$$\alpha(h\nu, T) = (0{,}01\cdot T + 8{,}44)\exp\left(\frac{h\nu + 9{,}89\cdot10^{-7}\cdot T^2 + 1{,}15\cdot10^{-4}\cdot T - 1{,}72}{5{,}05\cdot10^{-5}\cdot T + 0{,}065}\right) \quad (4)$$

In the obtained expression, the energy of photons should be given in eV, the temperature in Kelvin degrees, and the coefficient of optical absorption is obtained in cm^{-1}. This ratio allows for reliable theoretical analysis, modeling and optimization of operational parameters of FOTS's based on $As_{45}Se_{55}$ glasses. Using our approach, we can prepare a theoretical basis for the development of FOT on the basis of temperature sensitive elements from a variety of both crystalline and (CVS) optical materials.

Conclusions. The behavior of the optical absorption edge of $As_{45}Se_{55}$ChS at temperature changes from 240 to 450 K was investigated. Near-parallel shift of the absorption edge into the region of lower photon energies of optical radiation with increasing temperature was obtained. It is shown that in the absorption region up to 35 cm^{-1}, the spectrum has the character of the Urbach edge. The temperature shift of the edge may be explained by the increase in the dynamic structural disorder of the lattice of doped crystals with temperature increasing. The temperature dependences of the Urbach edge parameters are determined. It is shown that these dependencies are well described by linear functions. Determined temperature patterns are much simpler in comparison with doped GaAs crystals, for which the temperature dependences of optical parameters are described by polynomials of the second degree. It was offered a correct view of the absorption coefficient in Urbach edge of $As_{45}Se_{55}$ ChS as a function of two arguments (photon energy and temperature) which simplifies parameters modeling and optimization of this material.

REFERENCES

1. D. A. Krohn, Fiber Optic Sensors: Fundamentals and Applications, Instrument Society of America (Pub.), Research Triangle Park, NC, USA, 2nd ed., ISBN 0-55617-010-6, 1992
2. J. M. López-Higuera, Handbook of Optical Fibre Sensing Technology, John Wiley & Sons (Pub.), Chichester, West Sussex, England, ISBN 0-471-82053-9, 2002
3. W. J. Bock, I. Gannot and S. Tanev, Optical Waveguide Sensing and Imaging, Springer (Pub.), Dordrecht, The Netherlands, ISBN 978-1-4020-6951-2, 2006
4. S. Yin, P. B. Ruffin and F. T. S. Yu, Fiber Optic Sensors, CRC Press (Pub.), Taylor & Francis Group, Boca Raton, FL, USA, 2nd ed., ISBN 978-1-4200-5365-4, 2008
5. Igor Chychura, Fiber-Optic Temperature Sensors with Chalcogenide Glass and Crystalline Sensing Element (2019) (DOI: 10.5772/intechopen.89207).
6. Taylor P.C., Theye M.L., Orenstein J., Elliott S.R., Golding B., Fox D.L. (1984) Optical Properties of the Chalcogenide Glasses. In: Fleury P.A., Golding B. (eds) Coherence and Energy Transfer in Glasses. Springer, Boston, MA. https://doi.org/10.1007/978-1-4684-4733-0_12
7. ChychuraI. I., TurianytsiaI. I., & ChychuraI. I. (2020). Temperature dependence of the optical absorption edge of doped gallium arsenide. *Physics and Chemistry of Solid State*, *21*(2), 288-293. https://doi.org/10.15330/pcss.21.2.288-293
8. Uesugi, Katsuhiro. Appl. Phys. Lett. 76, 1285 ~ 2000. https://doi.org/10.1063/1.126010