Chapter

Fiber-Optic Temperature Sensors with Chalcogenide Glass and Crystalline Sensing Element

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Abstract

Fiber-optic temperature sensors (FOTSs) are competitive in cases where it is necessary to provide stable operation in harsh operating conditions—strong electromagnetic fields, elevated background radiation, and explosive environment—and at large distances between sensing element and receiving device. In addition to high reliability and stability when measurements are performed in extreme conditions, such sensors have good metrological characteristics. For FOTSs the main functional node is a temperature-sensitive element (TSE), which defines the main operational and metrological characteristics of these devices. Therefore, the search for new promising materials for innovative TSEs is relevant. From this point of view, chalcogenide amorphous materials of the As_xSe_{100-x} system deserve special attention. They are characterized by a unique combination of high inertia under the influence of intensive external factors and the possibility of significant changes of their optical parameters with changing of their chemical composition within the range of glass formation. In this scientific work, a comparative analysis of opportunities for traditional GaAs crystals and As_xSe_{100-x} chalcogenide glasses for TSEs of modern FOTSs is carried out.

Keywords: fiber-optic temperature sensor, temperature-sensitive element, transfer characteristics, chalcogenide glass semiconductor materials, optical transmission

1. Introduction

Nowadays, it is impossible to imagine modern industry without automated control systems. Complex structures and mechanisms require constant control of various parameters and processes that happen in them. Monitoring of complex engineering structures and industrial systems is an integral part of their day-to-day operation. To perform such control, sensors and control systems of various physical quantities such as temperature, mechanical deformation, pressure, etc. are required.

At present, the market of measuring systems and sensors was dominated by electronic measuring technologies, which involve the transformation of the measuring parameter into an electrical signal and its subsequent processing [1]. An alternative to such an approach is the use of fiber-optic measurement systems, where the measured parameter is converted into an optical signal transmitted over an optic fiber. The market of fiber-optic sensors has been growing from the moment they appeared, 2.5 billion dollars in 2004 with an annual increase of 11% in all industries, according to Frost and Sullivan's marketing agency. Fiber-optic sensors have some advantages over more traditional electronic technologies: (a) explosion safety; (b) zero sensitivity to electromagnetic interference (noise immunity); and (c) high separation ability. Despite all mentioned above, the relative share of fiber-optic sensors in the overall market of measuring systems remains small. In essence, fiber-optic sensors occupy only a very small position where traditional measuring instruments cannot be used or their use is very expensive.

However, it is worth noting two trends that are observed in our time. Firstly, the rapid development of related technologies, fiber-optic transmission of information, reception and processing of images using digital photo and video equipment, microprocessor technology, contributes to the development of fiber-optic measuring technology and in cheapening their production. Secondly, industry and regulators put increasingly stringent requirements on the operating conditions of such devices, namely, noise immunity requirements, measurement safety, accuracy, etc. These are the criteria that can satisfy modern fiber-optic sensors. It can be seen that these two trends can lead to a situation where the fiber-optic measuring systems will become more competitive in than traditional systems [2]. This is due, not only, to the performance characteristics but also to the cost of individual measuring channel.

2. Types of fiber-optic sensors

Fiber-optic sensors can be classified by many parameters, one of which is the classification based on the coding of measured information:

- Phase sensors using a highly coherent source of radiation and measuring the phase of a light wave that changes under the influence of the external parameters [3].
- Spectral coding sensors, which, in contrast to the purely phase, use radiation sources with a wide spectrum and the possibility of analyzing the entire spectrum [4].
- Amplitude sensors, in which the measured parameters modulate the intensity of light waves that passed through the sensor or are reflected from it [5].
- Polarizing sensors, using information about the polarization of the light wave [6].

Another classification of fiber-optic sensors is by the work principle:

- Interference [7].
- Distributed [8].
- Luminescent [9].
- Using the gratings inside optic fibers [10].
- Combined [11].

You can also classify sensors by localization of the measured parameter:

- Pointing.
- Distributed.
- Imaginary distributed.

All of the mentioned fiber-optic sensors have certain advantages and disadvantages associated with their design, operation principle, etc. All of this affects on their price and application possibilities.

For example, phase sensors using laser radiation sources are quite common but mostly in lab installations and not in industry. This is due to the needs of accurate adjustment of devices and presence of additional phase-adjustment schemes, which greatly complicate their design. In addition, such sensors do not allow measurements of absolute values. To eliminate these disadvantages, several frequencies of optic radiation are used, which makes this method an intermediate type of measurements between phase and spectral [12], which are presented below.

Sensors with spectral coding are mostly promising in terms of their implementation into the industry due to their resistance to various parasitic parameters: drift of radiation power source, uncontrolled power loss in fibers, losses due to fiber coupling using connectors, etc. In addition, this type of sensors allows measurements of absolute values and does not require recalibration after switching off the instrument. For now, this measurement method was considered very difficult and expensive. It needed the presence of a spectrometer and optic image processing equipment. But the situation is changing, and due to the cheapening of the methods of optic spectrum processing, development of microprocessor technology and the technology of receiving an optic image, and cheapening of optoelectronic components, the price of the fiber-optic measurement channel comes close to electronic analogues [13].

Amplitude sensors have their area of application due to their low cost and can be used where there is no need for high measurement accuracy (e.g., as counters of rotation, microphones, temperature distribution sensors, etc.). However, in high-precision measuring systems, they are not widely used due to their relatively low accuracy and probability of parameter drift.

Tunnel sensors are highly sensitive devices, but they also have parameter drift, so they can only find limited use, for example, in high-precision positioning devices, microphones, hydrophones, etc.

Polarizing sensors, in essence, are analogues to interference sensors. Their commercialization is mainly hampered by the need to use expensive fiber while maintaining polarization.

3. Fiber-optic temperature sensors with amplitude modulation of light

From the types of fiber-optic sensors being represented in the previous paragraph, sensors with amplitude modulation of light are most suitable for further processing of the output signal from optical fiber. Most of the schemes with amplitude modulation of signals do not require the use of coherent light and therefore do not include specific requirements for emission source (LED) and emission detector (photodiode).

The amplitude modulation of optic signal can be done in several ways: (1) attenuation of light when α absorption coefficient changes; (2) changes in the cross section on the way of light passing; (3) changes in the coefficient of reflection of the medium when refractive index n is changing; (4) receiving additional radiation when the temperature of the sensitive element of sensor is changing; and others.

The operation principle of the first-type fiber-optic sensors is that light passing through a semiconductor material is absorbed in the case when the photon energy $h\nu$ is greater than the width of the bandgap Eg [14].

With increasing temperature, the width of the bandgap decreases monotonously. In works [5, 15–17], as a temperature sensor, a *GaAs* crystal was selected. The principle of operation of the sensor is to shift the edge of optic absorption induced by temperature change (**Figure 1**). From the graph, it is seen that, for example, passing the sample at wavelength λr will be different when temperature changes. Knowing the optic characteristics of a material, one can estimate the transmission characteristic of such a sensor.

Indeed, according to the Beer–Lambert law of absorption

$$I(l,T) = I_0(1-R)\exp\left[\alpha(T)\cdot l\right] \tag{1}$$

where:

I_0 is the intensity of the falling light.

I is the intensity of the light passing through the sample.

R is coefficient of reflection.

$\alpha(T)$ is the material absorption coefficient at a given temperature and wavelength.

As shown in [16], for *GaAs*.

$$\alpha(T) = A\cdot\left[h\nu - E_g(T)\right]^{1/2}, \tag{2}$$

where:

A is the constant of the material.

$E_g(T)$ is the width of the bandgap at temperature T.

h is Planck's constant.

ν is the light frequency.

In the temperature range of 20–297 K, $E_g(T)$ can be described by the formula:

$$E_g(T) = \frac{E_g(0)-\gamma T^2}{(\beta+T)}, \tag{3}$$

where $E_g(0)$ is the width of the forbidden zone at 0 K and γ and β are empirical constants.

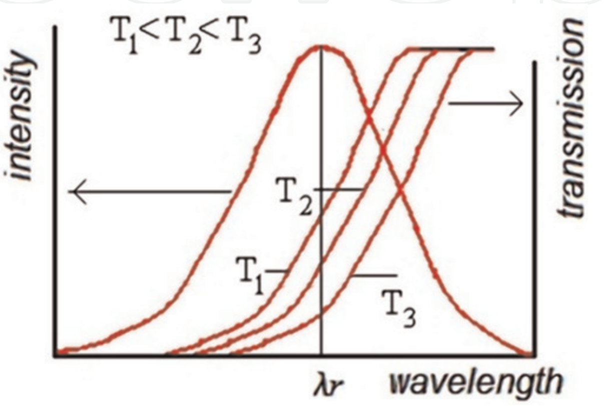

Figure 1.
The principle of operation of the fiber-optic temperature sensor: (1) spectrum of light source radiation; (2, 3, 4) the dependence of the optic transmittance of the material on the wavelength λ at different temperatures T2 < T3 < T4.

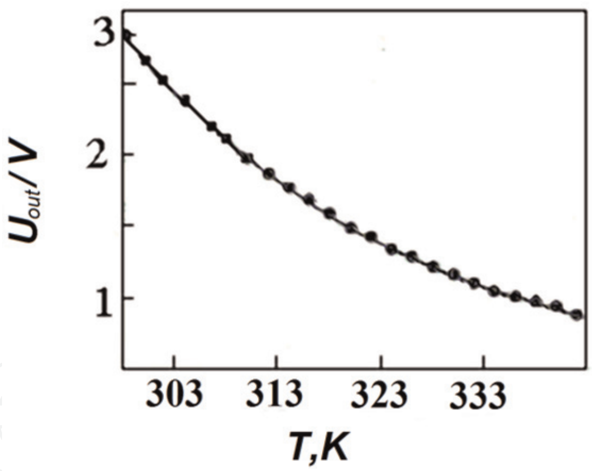

Figure 2.
Dependence of the photodiode output voltage from temperature sensor temperature [2].

For *GaAs*, $E_g(0)$ = 1.522 *eV*, γ = 5.8 · 10-4E/K, β = 300 K, A = 2.446 · 10-4 (cm · eV)$^{-1}$. Proceeding from Eq. (3), we can find the wavelength λ_g of light on which a given semiconductor will absorb:

$$\lambda_g(T) = \frac{n_c}{E_g(T)} = \frac{n_c}{\frac{E_g(0) - \gamma T^2}{(\beta + T)}} \tag{4}$$

Taking into account the Eqs. (2) and (3), the connection between the intensity of light I passing through the sensitive element and its temperature can be written as

$$I(l, T) = I_0(1 - R) \exp\left\{A\left[h\nu - E_g(0) + \frac{\gamma T^2}{T + \beta}\right]^{1/2} \cdot l\right\} \tag{5}$$

Thus, if the light passes through the sample in the region of its absorption, the intensity of light will diminish, with increasing of sample temperature. If the emission detector (photodiode) is chosen in the working range, then change in intensity of light will lead to a decrease in the photodiode voltage (**Figure 2**).

4. Fiber-optic temperature sensor with chalcogenidic glass sensitive element

The operation principle of such fiber-optic sensors is similar to the one discussed above. Change in the light transmission in chalcogenide vitreous semiconductor (ChVS) with temperature change. The use of as sensitive elements of ChVS gives the possibility for better optic coordination of emission source (LED), temperature-sensitive element, and emission detector (photodiode), since the physical and chemical, optic properties of glass can be changed in wide range by changing their composition within the region of glass formation. Developed FOTS are using a film of single crystals *GaAs* and *Ge*, with given optic constants, as a sensitive element. Our previous studies [18] have shown that, as an active element of FOTS, from a large number of ChVS can be used *As-Se* glass system.

In few scientific and technical publications, several analogues of FOS with semiconductor crystals as a temperature-sensitive element were published [5, 15–17]. Often, these are two-wave single-channel fiber-optic circuits, which use two LEDs

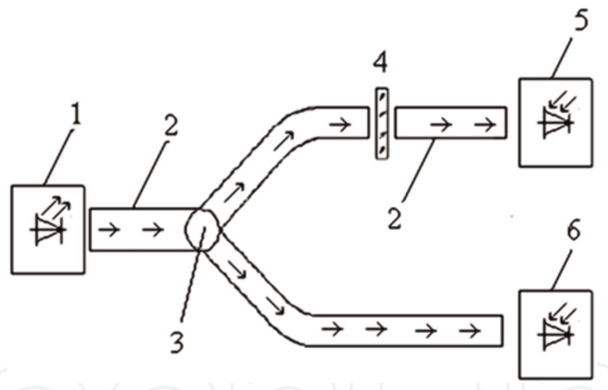

Figure 3.
Optic scheme of the primary converter: 1, radiation source (LED); 2, fiber-optic coupler; 3, place of optic signal division; 4, temperature-sensitive element; 5, the first photodiode (FD1); and 6, the second photodiode (FD2).

with different wavelengths (operating and reference). If the ambient temperature changes, the change in characteristics will not be the same, and the compensation scheme will not be able to eliminate the measurement error in this case. In our view, a more stable scheme of temperature measurement with a fiber-optic sensor is a single-LED dual-channel circuit, which is shown in **Figure 3**.

The operation principle of this type of FOS is that light signal after passing through the Y-cutter on two channels (working and reference) is received by two identical photodiodes. The registration system measures the ratio of signals from photodiodes 5 and 6 (**Figure 3**). Therefore, changes that can occur in the fiber-optic line for a given temperature will not affect the ratio of signals on photodiodes.

In scientific work (article) [18], we developed a method for performing calculations of the transmission characteristics of the fiber-optic temperature sensor. In this chapter, a method of selecting the elements of the primary measuring transformer and the optic parameters of LED, photodiode, and sensitive element of such fiber-optic temperature sensor was simulated. The results of the transfer characteristic in the form of a plot of the dependence of the change in the voltage of the emission detector (photodiode) on the temperature of the medium in which the temperature-sensitive element is shown demonstrate the performance of this technique.

In this chapter, a plate of ChVS *As-Se* was used as a temperature-sensitive element. The change in the composition of the components of the temperature-sensitive element allowed us to ensure the optimum harmonization of the spectral characteristics of the receiver source and the temperature-sensitive element, which are very convenient for the construction of fiber-optic thermometers. However, not only ChVS can be used as a temperature-sensitive element in a fiber-optic temperature sensor; some crystalline materials can also be effectively implemented in these devices.

5. Fiber-optic temperature sensor with crystalline sensitive element

Preliminary analysis of the probable variants of crystalline materials which can be used as temperature-sensitive elements indicated the possibility of using base materials of the A_3B_5 (*GaAs*, *GaP*), which today are the basic semiconductor crystals for modern microelectronics [19, 20].

From the practical point of view, the interest in these materials is due to their wide application in the elements of infrared optics, television equipment, and fiber-optic communication. These materials are resistant to radiation, which makes their practical application under conditions of radioactive exposure possible, and the possibility of anatomy of radioactive defects opens the possibility of their multiple use in extreme radiation conditions. In addition, the optical properties of these crystals are immune to high-frequency electromagnetic fields.

All of this indicates a possibility of effective application of *A3B5* crystals as sensitive elements for amplitude-type FOS for temperature, pressure, and other physical quantities.

For modeling parameters of primary measuring converter, *GaP* crystals doped with *Zn* (*GaP:Zn*) were used. These crystals are used to construct different types LEDs [21].

For experimental studies of optical transmittance, special samples were made. The methods of making are as follows: crystal plates were cut out of solid material and polished on abrasive powders, then polished on diamond paste of different consistency, and electropolished to a high class of roughness. As a result, we got plates with a thickness of 300 microns and high-quality surface.

Figure 4 shows a picture of one of the crystal *GaP:Zn*. This plate was used in our optical studies.

Results of these studies, in the form of direct records, were made on a specialized optical installation.

According to the transmission spectrum, which is shown in **Figure 5**, the optical absorption spectra at different temperatures, shown in **Figure 6**, were calculated.

Optical absorption in *GaP:Zn* crystals according to the literature data [22] is indirect banded, which determines the angle of absorption dependence from wavelength. For the convenience of determining the width of the bandgap at different temperatures, the dependence $\alpha_2 = f\ (h\nu)$ was constructed (**Figure 7**).

Subsequent processing on the computer obtained experimental results in the form of transmission spectra of *GaP:Zn* crystal at various temperatures which is shown in **Figure 8**. It can be seen from **Figure 8** that with increasing of temperature, the transmittance dependence shifts to greater wavelengths and overall bandwidth drops. This allowed us to determine the wavelength position which will determine the controlled level of transmission at given temperature. It was most convenient to use a λ = 600 nm, which was determined by the level of transmission at a fixed temperature. The results of the analysis of the temperature shift of the transmission level, determined by the spectra in **Figure 8**, are presented in **Figure 9**.

Dependence of the absorption coefficient α in non-triangular semiconductors to which *GaP* belongs is described by the dependence:

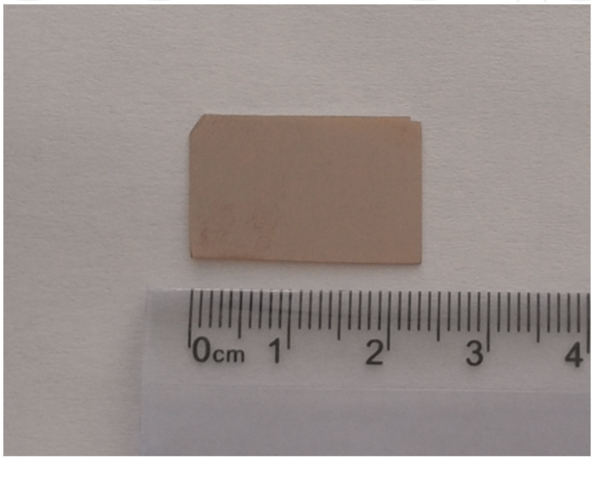

Figure 4.
Photograph of GaP:Zn *crystal used in optical studies.*

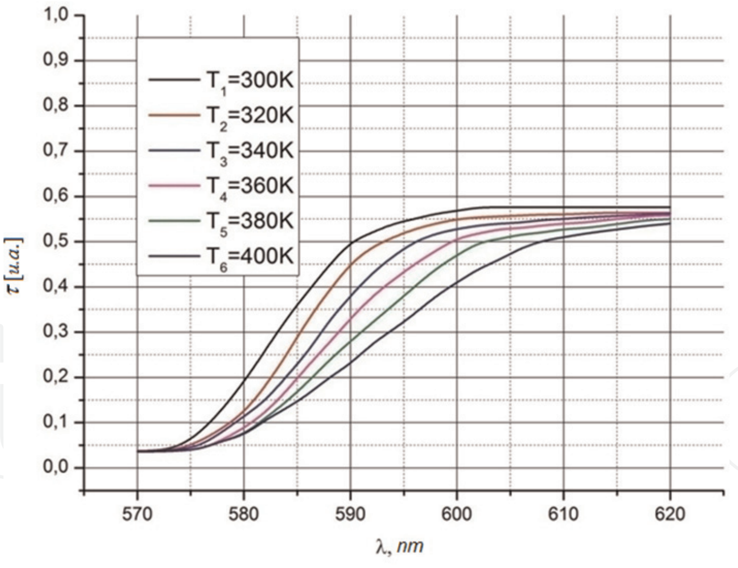

Figure 5.
GaP:Zn crystal spectrum at different temperatures T (K).

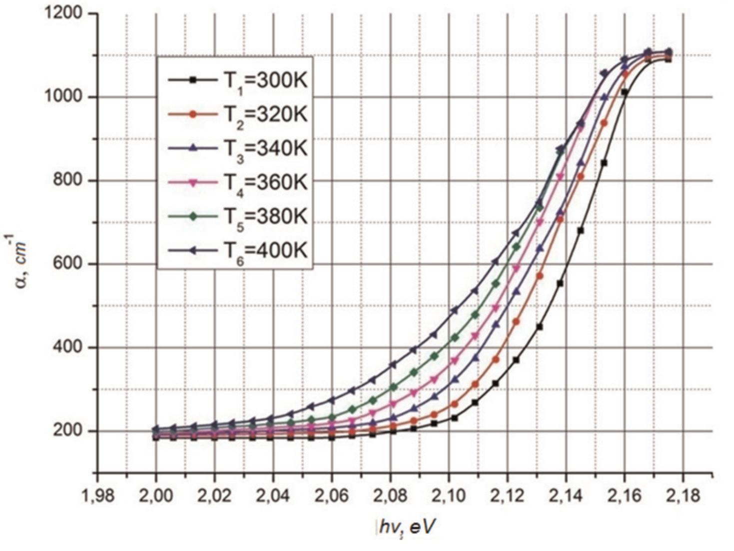

Figure 6.
Dependence of absorption of GaP:Zn *crystals at different temperatures T (K).*

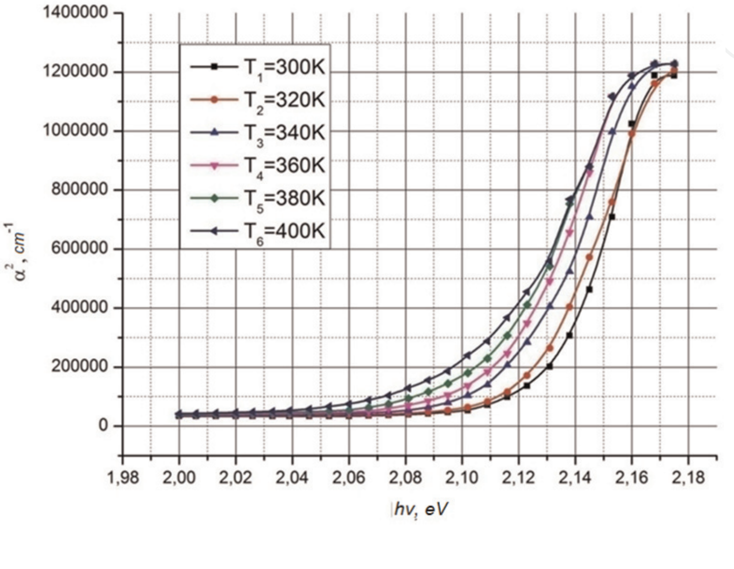

Figure 7.
Dependence of absorption of GaP:Zn *crystal at different temperatures T (K).*

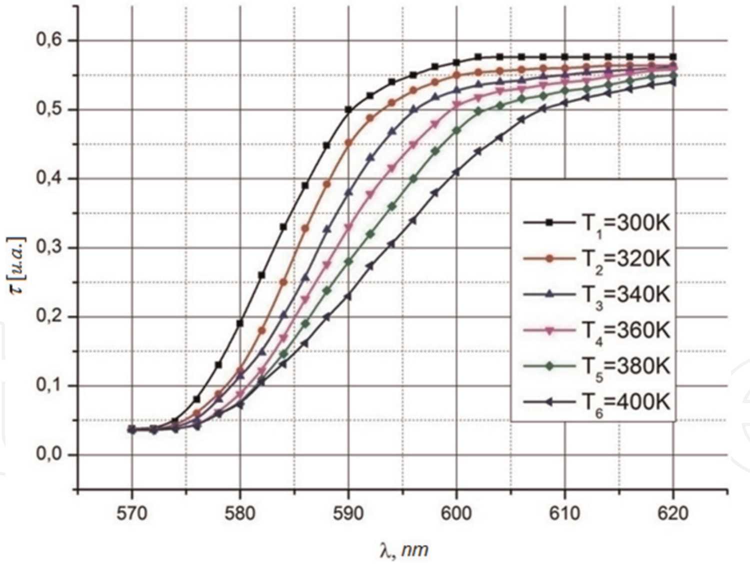

Figure 8.
Spectrum of GaP:Zn *crystal at different temperatures T (K).*

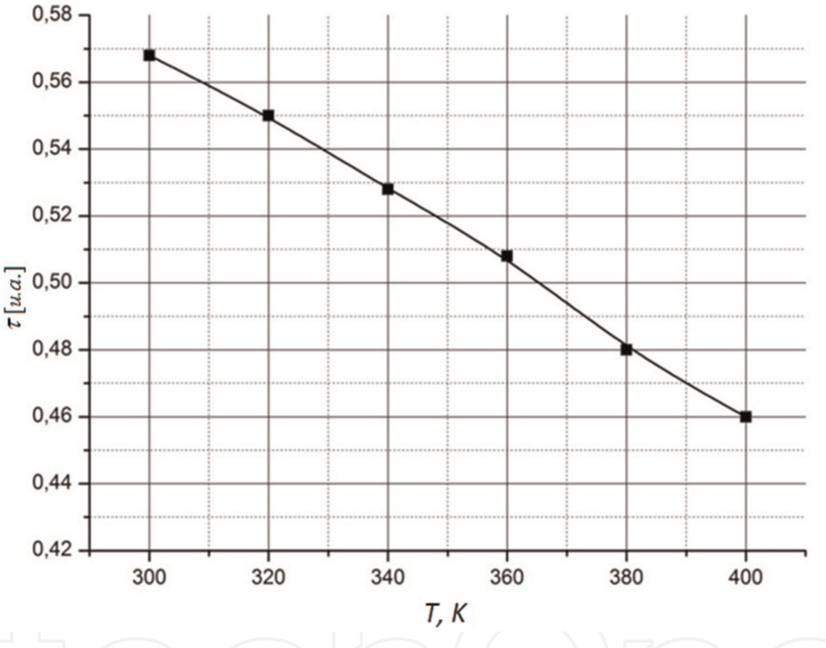

Figure 9.
Temperature dependence of transmission τ_λ on $\lambda\tau$ = 600 nm for the GaP:Zn crystal.

$$\alpha = \alpha_0 \left[\mathrm{hv} - \mathrm{E_g} \right]^{\frac{1}{2}} \tag{6}$$

This means that when α_2 dependence is built, it is possible to obtain the expression:

$$\alpha^2 = {\alpha_0}^2 \left[\mathrm{hv} - \mathrm{E_g} \right] \tag{7}$$

From which it is easy to obtain the value of the width of the indirect bandgap *Eg* by extrapolating to the zero of the linear part of the dependence $\alpha^2 = f\ (hv)$.

Analyzing **Figure 8**, we can select the required operating wavelength to demonstrate the practical use of GaP:Zn crystals as a temperature-sensitive element of a fiber-optic temperature sensor. As a result we obtained temperature dependence of transmission of GaP:Zn crystal (**Figure 9**).

It can be seen from **Figure 9** that the passage of the *GaP:Zn* plate at a controlled wavelength λ = 600 nm linearly decreases in the temperature range from 300 to 400 K. This, not directly, indicate that the expected and calculated full-cycle photocurrent will also change with temperature change. That suggests the possibility of using GaP:Zn crystals as temperature-sensitive element of a fiber-optic temperature sensor.

6. Conclusions

Currently, fiber-optic sensors do not occupy a leading position in the measurement system market. However, the continuous development of technologies, including fiber-optics, makes such devices more competitive and provides consumers with the advantages that traditional measurement systems cannot give. This, in turn, expands their scope. In this paper, our focus was on fiber-optic temperature sensors, namely, sensors with amplitude modulation of light. These sensors are just one of a wide variety of modern fiber-optic devices. In our previous work, which was briefly presented in Section 4, we used ChVS materials as a temperature-sensitive element for a fiber-optic temperature sensor. Further studies have shown the possibility of using A3B5 crystals as a temperature-sensitive element also. Section 5 presents the possibility of using such semiconductor materials on the example of GaP:Zn crystals. The temperature dependence shown in **Figure 9** confirms that A3B5-type semiconductor materials can be used as a temperature-sensitive element of a fiber-optic sensor.

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