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STUDY OF THE POOLE-FRENKEL EFFECT IN TlS CRYSTALS EXPOSED TO RADIATION INFLUENCE

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Abstract: Electric conductivity of tetragonal modification of γ-irradiated TlS crystals has been studied in strong electric fields (up to 10^3 V/cm). It has been established that, increase in electric conductivity (σ) in electric field is explained by Frenkel's thermoelectron ionization and it allows calculating the concentration of traps (N_t), length of free path of charge carriers (λ), Frenkel coefficient (β) and distance from trap centers to the maximum of potential hole (x_m).

Keywords**:** electric conductivity, thermoelectronic ionization, semiconductors

1. Introduction

Double chalcogenide $A^{III}B^{VI}$ group compounds are considered interesting semiconductors for studying the photoelectric, electric and luminescence events. Currently, the TlS crystal with a chain structure from this group is of great interest for its structural features. So, the chemical bonds between chains are different in these semiconductors; it leads to the anisotropy of physical properties.

Experimental and theoretical studies show that the local levels in photoconductivity and luminescence of semiconductors play an important role. The aim of this work is to study the electric conductivity of the irradiated TlS semiconductor compound of $A^{III}B^{VI}$ group in a strong electric field (10^3 V/cm) at the temperature range of 100-300K, determine the current conductivity mechanism and important parameters of local levels.

The ionization levels occurred under the influence of temperature and strong electric field in semiconductors, dielectrics and compounds based on them have been studied theoretically by Frenkel. Therefore, an increase in electric conductivity of the above-shown materials under the influence of electric field is explained with Frenkel's thermoelectronic ionization. Poole has shown that the electric conductivity in strong electric field increases with exponential law in the form $\sigma = \sigma_0 e^{\alpha E}$ (here, σ_0 – electric conductivity in the area subjected to Ohm's law, α - inclination in lnσ-E dependence).

Frenkel's thermoelectronic ionization theory shows that the electric conductivity of semiconductor and dielectrics in strong electric field is exponentially dependent on tha radicand ($\sqrt{E}$) of electric field ($\sigma = \sigma_0 e^{\beta\sqrt{E}}$) [1,2]. Here

$$\beta = \frac{e^2}{\sqrt{\pi\varepsilon\varepsilon_0 kT}} \quad (1)$$

According to Poole theory, α - is not associated with the nature of the material, but in accordance with Frenkel theory, as it is seen from (1) β - is dependent on dielectric permittivity (ε), in other words, the nature of the material.

First of all, it should be noted that Frenkel's thermoelectronic ionization is not realized in an electrode, but in the whole volume of semiconductor and dielectric. The Poole-Frenkel effect has been reviewed theoretically in lots of studies [3-5] and experimentally found out in semiconductors, dielectrics and compounds based on them [6-8]. The main point of the Poole-Frenkel effect is the fact that, a decrease in activation energy level in electric field leads to an increase in concentration of dielectrics and semiconductors depending on current.

As it is known that in Volt-Ampere Characteristics (VAC) within deviations from linear dependence of strength of current on voltage, that is in the areas above ohmic area there observed a number of properties in VAC. At this time, in many cases the electrical properties in strong electric field can not be provided with one conductivity mechanism and are explained through various mechanisms in different values of electric field intensity.

In connection with breaking down of bonds or their restructuring in semiconductor materials, a number of capturing traps, i.e. valence-alternative defects, as well as donor and acceptor type defects with the same concentrations are formed; as a result, donor centers lead to a shift of electric conductivity to Poole-Frenkel conductivity.

According to Frenkel theory [2], an increase in E-electric field value leads to a decrease in activation energy of traps.

$$E_{(t)}(E) = E_{(0)} - \sqrt{\frac{e^2 E}{\pi \varepsilon \varepsilon_0}} \tag{2}$$

In the expression (2) $E_{(0)}$ – is the activation energy of traps in the area of Ohm's law. $E_{(t)}$ is determined from temperature dependence of electric conductivity in strong electric field. When the minimum distance between traps is the same with the distance from trap to the maximum of potential barrier, the Pooel-Frenkel effect is of great importance.

$$r_m = \sqrt{\frac{e}{2\pi \varepsilon \varepsilon_0 F_{cr}}} \tag{3}$$

This condition determines the concentration of traps.

$$N_t \approx \frac{1}{(2r_m)^2} = \left(\pi \varepsilon \varepsilon_0 F_{cr} e^{-1}\right)^{\frac{3}{2}} \tag{4}$$

Here, F_{er} – is the minimum price of electric field when the Poole-Frenkel effect was observed. In order to calculate the value of N_t from the expression (4), we need to know the value of ε-dielectric permittivity. While determining Frenkel coefficient at different temperatures, the expression of N_t is as follows.

$$N_t = \frac{3}{4}\left(\frac{2e}{kT\beta} F_{cr}^{\frac{1}{2}}\right)^3 \tag{5}$$

2. Experimental method

Semiconductor compound TlS with double chalcogenide tetragonal structure has been synthesized and grown by Bridcman method.

The sample in the form of parallelepiped with the thickness of 1.5 mm, width of 4 mm and length of 4.3 mm has been prepared in order to study the electrical properties of TlS crystal irradiated by γ-rays. Silver paste of the samples has been drawn perpendicular to crystallographic "c" axis as current contacts. Ohmic rate of current contacts has been checked.

Four-probe measurement method has been used within the research. In order to study temperature dependence of VAC, the sample has been placed in cryostat and the measurement has been carried out after adding liquid nitrogen in it. Copper-constantan thermocouple has been used for measuring the temperature of sample. VAC of sample has been measured after obtaining the stable temperature.

VAC of the samples has been studied at the temperature range of 90-300 K to get the information about the mechanism of current flow in TlS crystal irradiated by γ -rays and energetic parameters of levels in band gap.

TlS crystal has been placed in special closed evacuated ampoules after measuring the initial parameters in order to irradiate it by γ-quanta. Then the ampoules have been placed in the special chamber of ^{60}Co device. It has been used ferrosulphide method for obtaining different values of irradiation dose in the chamber. The following formula has been used to define irradiation dose rate.

$$p = \frac{2{,}8 \cdot 10^4 \Delta D_n}{t},$$

Here, ΔD_n is optical density of medium; t – duration of irradiation.

The value of absorbed dose in the solution is defined by this method. The following formula is used to move from absorbed dose to exposure dose:

$$D_{medium} = D_{air} \frac{87\gamma_{medium}}{100\gamma_{air}}$$

Here γ_h and γ_m - are absorption coefficients of quantum rays in the air and solution. So, if we consider the energy of gamma quanta being ($E_\gamma = 1{,}25 MeV$) for ^{60}Co, we get the absorption dose correlation of D_{medium} (rad) = 0,968D_{air} (roentgen) between the air and medium.
Cartogram of exposure rate is obtained in working chamber based on obtained data.

3. Results and discussion

VAC of TlS crystal, exposed to irradiation, has been studied at various temperatures and shown in figure 1. As it is seen from the curves, there are linear and non-linear ($J \sim U^n$) parts in VAC at different temperatures and different values of electric field. It is observed the decrease in Ohmic area by increasing the temperature and in this case, transition voltage shifts to lower values. Such increase is associated with the increase of concentration of charge carriers.

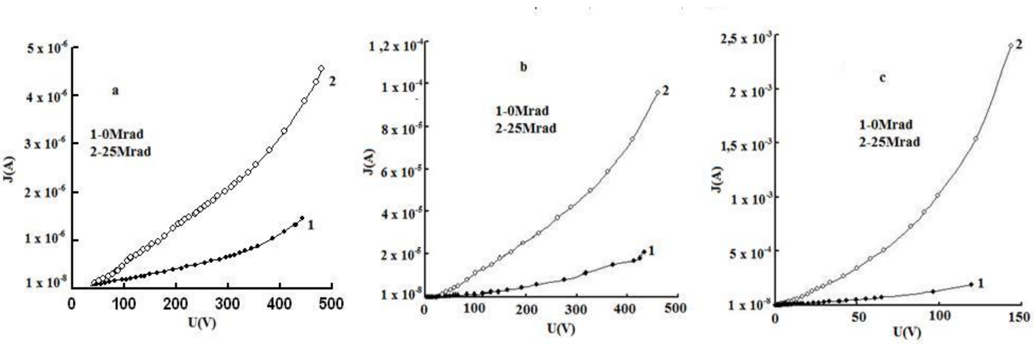

Fig. 1. VAC of TlS crystal at different temperatures: a-215 K, b-238 K, c-300 K

The analysis of experimental data shows that, the dependence of σ on E has been well described by Frenkel formula in the TlS compound before and after irradiation in strong electric field (3 ·10^3 V/cm). On the basis of experimental data, dependence curves of $\lg\sigma - E$ and

$\lg\sigma - \sqrt{E}$ for TlS crystal have been shown in the figures 2 and 3.

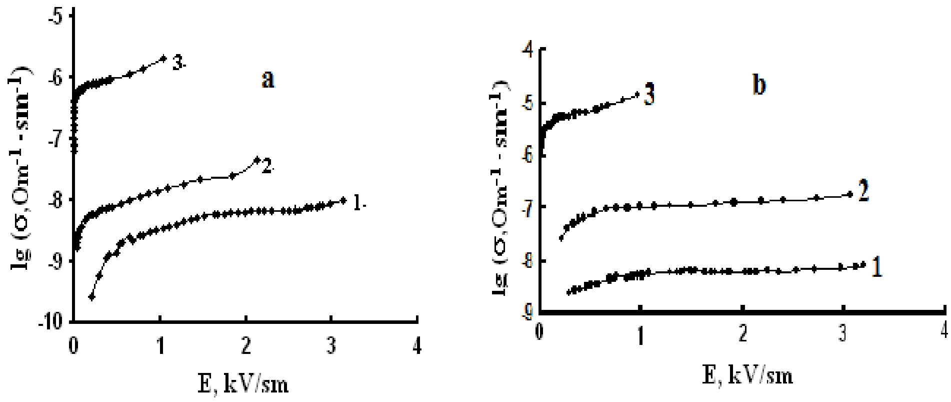

Fig 2. The dependence of $\lg\sigma$ on E at different temperatures of TlS crystal: 1-215K, 2-238K, 3-300K. (a- before irradiation, b- after 25 Mrad irradiation)

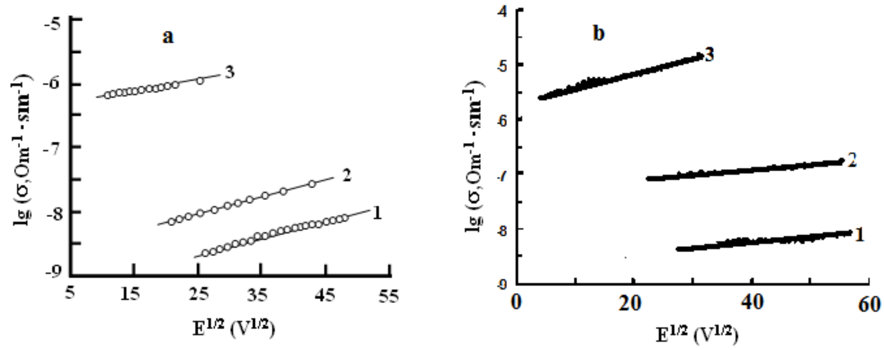

Fig. 3.The dependence of $\lg\sigma$ on $\sqrt{E}$ at different temperatures of TlS crystal: 1-215K, 2-238K, 3-300K. (a- before irradiation, b – after 25 Mrad irradiation)

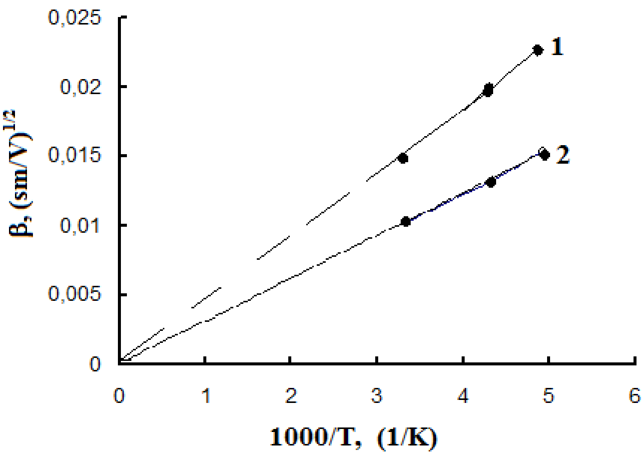

Fig. 4. Temperature dependence of β - Frenkel coefficient of TlS crystal: (1 - before irradiation, 2 – after 25Mrad irradiation)

As it is seen from dependencies, $\lg\sigma - \sqrt{E}$ coordinates (figure 3) are more consistent with linear dependence than $\lg\sigma - E$ coordinates (figure 2). And it is much more consistent with theoretical expression of β-Frenkel coefficient. While analyzing the dependence of β on inverse value of temperature it is seen that, the dependence between these quantities is a straight line (figure 4). At the same time it has been determined that, the dependence of β - Frenkel coefficient defined from lnσ ($E^{1/2}$) dependence, corresponds to $\beta = \frac{\sqrt{e^3}}{kT\sqrt{\pi\varepsilon\varepsilon_0}}$ and extrapolation of $\beta \sim 10^3/T$ line passes from the beginning of coordinate.

The analysis of obtained data shows that, satisfaction of Frenkel law of TlS crystal, which has tetragonal structure allows determining: the activation energy of the levels, dielectric permittivity, length of free run of carriers of a current, concentration of traps.

We can calculate the length of free run of carriers of a current ($\lambda = \frac{kT\beta}{2e\sqrt{E_{кр}}}$), Frenkel coefficient (β), as well as the concentration of ionized centers (N_t) by considering the results obtained from electric conductivity of TlS crystal in strong electric field at the temperature range of 100÷300K. The values obtained from calculation after and before irradiation, have been comparatively given in table 1. As it is seen from the table, the concentration of ionization centers formed due to radiation defects after gamma irradiation, increases.

Table 1

The values of parameters calculated within Poole -Frenkel effect, before and after irradiation

T (K)	Irradiation dose	β $(cm/V)^{1/2}$	λ (cm)	x_m (cm)	N_t (cm^{-3})
215K	0 Mrad	0,02	$6,29 \times 10^{-6}$	$1,01 \times 10^{-6}$	$1,2 \times 10^{17}$
	25 Mrad	0,017	$1,13 \times 10^{-6}$	$6,19 \times 10^{-7}$	$5,26 \times 10^{17}$
238K	0 Mrad	0,016	$8,64 \times 10^{-6}$	$1,49 \times 10^{-6}$	$3,74 \times 10^{16}$
	25 Mrad	0,009	$2,41 \times 10^{-6}$	$7,99 \times 10^{-7}$	$2,44 \times 10^{17}$
300K	0 Mrad	0,01	$1,29 \times 10^{-5}$	$2,69 \times 10^{-6}$	$6,36 \times 10^{15}$
	25 Mrad	0,006	$1,31 \times 10^{-5}$	$2,06 \times 10^{-6}$	$1,42 \times 10^{16}$

One of the main issues for the Poole - Frenkel effect is the determination of potential well form. On the basis of experimental results it has been determined the form of potential well for TlS compound by using $x = \frac{kT\beta}{2e\sqrt{E}}$ and $\varphi(x) = -\frac{kT\beta}{2}\sqrt{E} = eEx$ and shown in the figure 5.

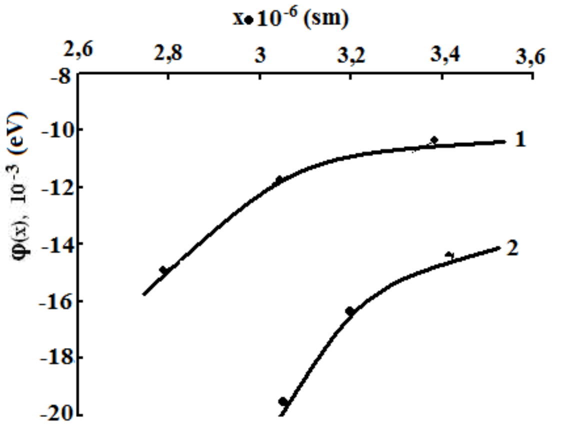

Fig. 5. The form of potential well of TlS crystal. (1 - before irradiation, 2 - after 25Mrad irradiation)

4. Conclusion

The mechanism and a number of important parameters – concentration of traps, the free running length of current conductivity of electric conductivity have been determined in strong electric field ($3 \cdot 10^3$ V/cm) of TlS crystal exposed to radiation at the temperature range 100-300K. It has been established that the current in nonlinear part of Volt-Ampere characteristics of TlS crystal is conditioned by a weak field effect and is explained in the context of Poole-Frenkel's thermal field theory.

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ИССЛЕДОВАНИЕ ЭФФЕКТА ПУЛА-ФРЕНКЕЛЯ В КРИСТАЛЛАХ TlS ПОДВЕРГНУТЫХ РАДИАЦИОННОМУ ВОЗДЕЙСТВИЮ

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Резюме: В сильных электрических полях (10^3 V/sm) исследована электропроводность тетрагональной модификации γ-облученных кристаллов TlS. Обнаруженный рост электропроводности вγ-облученных кристаллахTlSв сильных электрических полях описывается в рамках термоэлектронной ионизации Френкеля. В рамках этой теории рассчитана концентрация ловушек (N_t), длина свободного пробега носителей тока(λ), коэффициент Френкеля (β) и рассчитано расстояние от ловушечных центровдо максимума потенциальной ямы ($x_м$).

Ключевые слова: электропроводность, термоэлектронная ионизация, полупроводники

RADİASİYA TƏSİRİNƏ MƏRUZ QALMIŞ TlS BİRLƏŞMƏSİNDƏ PULL-FRENKEL EFFEKTİ

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Xülasə: Elektrik sahəsində (10^3 V/sm-ə qədər) tetraqonal quruluşa malik γ-şüalanmaya məruz qalmış TlS yarımkeçirici birləşməsinin elektrik keçiriciliyi tədqiq edilmişdir. Müəyyən olunmuşdur ki, elektrik sahəsində elektrik keçiriciliyinin (σ) qiymətinin artması Frenkelin termoelektron ionlaşması ilə izah olunur

ki, bu da tələlərin konsentrasiyasını (N_t), sərbəst qaçış yolunun uzunluğunu (λ), Frenkel əmsalını (β) və tələlərdən potensial çəpərin maksimumuna qədər olan məsafəni (x_m) təyin etməyə imkan verir.

Açar sözlər: elektrik keçiricilik, termoelektron ionlaşma, yarımkeçiricilər