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Research Article

VOLT-AMPERE CHARACTERISTICS OF THE CRYSTALS $TlIn_{1-x}Gd_xSe_2$

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Annotation

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ABSTRACT

The presented work describes the research of volt-ampere characteristics of the crystals $TlIn_{1-x}Gd_xSe_2$. Research was conducted in a non-static mode in temperature range of 80 ÷ 400° K. Results of study showed that the crystals $TlIn_{1-x}Gd_xSe_2$ possess the switching properties with the memory. By increasing the temperature the threshold voltage increases, while the threshold current decreases. It is possible to control the threshold parameter of the crystals $TlIn_{1-x}Gd_xSe_2$ with the change in the composition of the crystals and ambient temperature.

INTRODUCTION

Discovery of the switching effect in chalcogenide semiconductors [1, 2] and development of the switching devices on their basis led to goal-directed study of volt-ampere characteristics (VAC) of semiconductors with complex composition in the scope of strong electric fields, including breakdown field [3, 4].

Usage of semiconductor devices (with the switching effect or devices with negative resistance (NR)), that operational principle is associated with the switching effect or devices with negative resistance (NR), makes it possible to considerably simplify the circuitries, since the feedback is not realized by external circuits, but by the device itself, due to the presence of internal positive feedback. Therefore, the usage of devices with NR makes it possible to considerably improve dependability with a significant reduction in size, mass of electronic equipment and power consumption at the same time. The most complete advantages of devices with NR become apparent when used in microelectronics. In fact semiconductor devices with NR are essentially elementary solid functional circuits; because of the presence of NR they can perform the functions of amplifiers, generators, converters, and so on. Due to this effect it is usually enough to connect the load and power source to them. Having created several devices with NR in a single plate of semiconductor and having carried out a volume connection between them it is possible to obtain more complex functional schemes [5-8].

The main advantages of semiconductor switches are: symmetric property of VAC, which allows switching regardless of the polarity of the signal; memory effect, i.e. to be in either of two possible states unlimitedly long when disconnected from power sources. The presence of a switch with memory is determined by the composition of the active material and the electric mode of transferring the device from one state to another. Insensitivity to level of radiation, in which bipolar devices fail, simplicity of construction and ability to combine the technology for creating switches with the technology of hybrid and monolithic integrated circuits attract the great interest to such devices and a limited number of switching is a common problem of the devices and temporary obstacle for their mass usage in engineering technology [9-11].

The switching effect with memory arouses particular interest. Such switching is stable in open and close states when the voltage is removed from them. Manufactured device is in a high-resistance state. The effect of forming, in contrast to switches without memory, is missing. It comes at certain time

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values and amplitude of current passing through the element in the open state. Therefore, in order to ensure high reliable performance of memory elements it is recommended to provide a mode of operation, when a simpler glass-crystal transition is realized. Memory cells allow raising the operating temperature and providing photolithography. The study of the volt-ampere characteristics makes it possible to understand the causes of the sharp change in the electrical conductivity of the test specimen during their transition from the high resistance state to a high conductivity state, as well as the reasons, leading to the known instability of threshold switches. The study also allows developing devices with the stability of the threshold voltage not worse than 1-2%. These actual problems have not been satisfactory resolved up to date [12-15].

In recent years, researches of volt-ampere characteristics of triple and fourfold $A^{III}B^{VI}$ type compounds and solid solution on their basis have revealed that these phases have switching properties with memory [16-18]. In the next work [19-21] similar researches were also carried out in $TlIn_{1-x}Ln_xC_2^{VI}$ type crystals. It is shown that:

- electrical memory in samples of various compositions is controlled by current in a conducting state;
- VAC of a high-resistance state in a wide range of electric fields covers ohmic and nonlinear sections and steep growth of current, followed by a switching effect.
- the threshold switching voltage, depending on the composition varies over a wide range of voltages and weakly depends on the number of switching and on the thickness of the active region (area).

The present work presents research results in VAC of alloys in static mode, at different temperature values.

Experimental static VAC of alloys of the systems $TlInSe_2 - TlGdSe_2$ were recorded at constant current according to the procedure described in [12].

For researches of VAC of $TlIn_{1-x}Gd_xSe_2$ alloys, single crystals grown by the Bridgman-Stockbarger method were used as a sample. They were rectangular in shape. Ohmic contacts were In and Ag. Volt-ampere characteristics were studied in the temperature range $80 \div 400$K. In the study of crystals of the above type it turned out that at low voltages $I(U)$ the characteristics are linear and, accordingly, contact is ohmic (Fig.1). At high voltages, the characteristics were non-linear and had S-shape. For studied crystals the S-shaped curve in the field of high currents with a better expressed area of negative differential resistance (NDR) subsequently became a critical (threshold) current. Part of the NDR on the curve is more expressed at low ambient temperatures (Fig. 1). It turned out that crystals $TlIn_{1-x}Gd_xSe_2$ as well as $TlInSe_2$ have an S-shaped VAC. At low current values, the characteristics are linear and starting from a certain value of the voltage, the samples pass from the high-resistance state to the low-resistance state.
The analysis of the obtained results showed that decrease of the voltage of direct transition at each subsequent switching and essential nonlinearity of (the) VAC in the subthreshold electric fields is a characteristic for all studied crystals. Super linear section of VAC is well described by a three-term polynomial in the form

$$I = aU + bU^2 + cU^3,$$

where the numerical values of the coefficients are easily determined and different for various compositions.

Note that the form of the representation of the section of VAC - V characteristic in subthreshold electrical fields in the form of a three-term polynomial is very visible when physical components are interpreted and convenient in calculations, since it affects the nomogram of the coefficients and thus excludes additional experiments to record the VAC. The nonlinear change of conductivity in the subthreshold fields can be explained by the process of filling and emptying the traps. The presence of an experimental dependence indicates a quasi-continuous energy distribution of local levels in the forbidden band of a chalcogenide semiconductor of this composition.

It was found, that with an increase of the active region of samples, the change of the value of the threshold voltage of the alloys has an exponential character.

$$U_n(d) = U_0 e^{-\alpha d},$$

where $\alpha -$ the coefficient, depending on the composition of the samples, and $d -$ the thickness of their active area. For the samples studied by us, depending on the composition α varies within $0.052 \le \alpha \le 0.066$, and U_n within $36 \le U_n \le 22$.

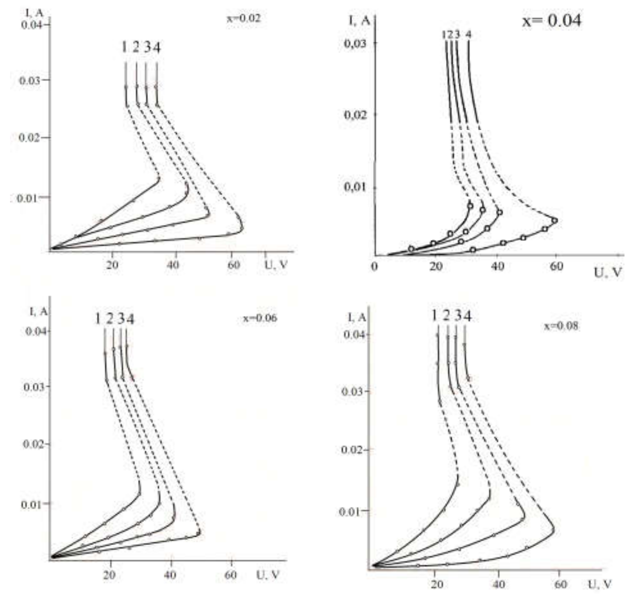


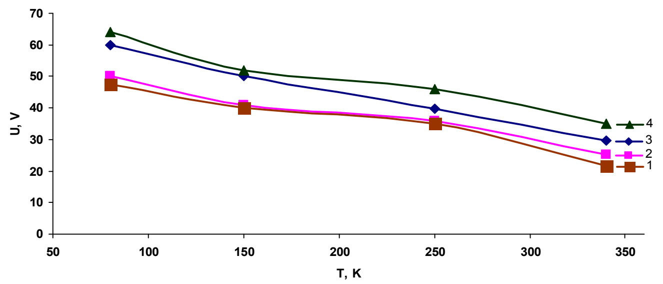
Fig 1 VAC of single crystals $TlIn_{1-x}Gd_xSe_2$ where a) x=0.02, b) x=0.04, c) x=0.06, d) x=0.08 at different temperatures: 1-350K, 2-250K, 3-150K, 4-80K.

The exponential nature of the dependence $U_n(d)$ indicates that semiconductors of the specified thickness exhibit both the electronic and thermal nature of the switching mechanism. This model makes it possible to explain the presence of a negative-resistance region, the presence of a delay time before switching and the formation of threadlike channels. It seems almost obvious that switching in bulky samples on the basis of crystals $TlIn_{1-x}Gd_xSe_2$ is conditioned with the thermal effects, although the purely thermal model cannot fully explain the observed switching characteristics by influence of Joule heat, especially they cannot be neglected in the conductive state. With the electron-thermal mechanism of the switching effect, the combined effect of the electric field and temperatures on the semiconductor is taken into account, which passes from a high-resistance state to a low-resistance state. The thermal mechanism of the effect is determined generally by the heat capacity, thermal conductivity and the dependence of resistance of the active region of the sample on temperature.

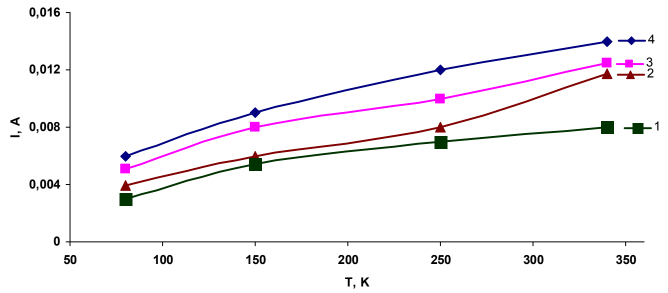
With decreasing of the temperature the characteristic acquires clearly expressed S –shaped form. At high temperatures, the samples behave as rectifiers (Fig.1)

When passing from $TlInSe_2$ to solid solutions on its basis, the threshold voltage values decrease (Fig. 1).

In solid solutions $TlIn_{1-x}Gd_xSe_2$ with partial substitution of indium atoms by gadolinium atoms in the lattice $TlInSe_2$, a gradual decrease of the threshold switching occurs. This is apparently due to the fact, that atoms of indium are partially replaced by those gadolinium atoms, which as opposed to indium atoms, have a less likely desire to form sp^3- hybrid connection and contribute to the increase of the metal fraction of the chemical bond.



a



b

Figure 2 Temperature dependencies of the threshold voltage a) x = 1- 0.04, 2-0.06, 3- 0.08, 4- 0.02 and threshold current; b) x = 1-0.04, 2-0.02, 3- 0.06, 4-0.08 crystals:

This is due to the fact, that with partial replacement of indium atoms by gadolinium atoms, the displacement of the electron density maximum to the compositions of selenium atoms decreases, i.e. the possibility of completion of the outer electron shells of an atom to a stable configuration s^2p^6 are reduced. In this connection, the degree of ionicity of the chemical bond decreases, i.e. the statistical weights of s^2p^6- configuration decrease and the values of the threshold voltage in the crystals $TlIn_{1-x}Gd_xSe_2$ also decrease.

The resulting VAC of these crystals are identical. This is due to the fact, that the crystal structure and the type of chemical bond between the atoms of the studied crystals, as well as the initial $TlInSe_2$, are practically the same. In this connection, we confine ourselves to a discussion of the results of the study $TlInSe_2$. For mentioned phase in each ohmic region of VAC the electrical conductivity is determined and the temperature of the samples is measured.

Our results show that the area controlled by current is corrected by increasing the temperature of the sample. Analysis of the results shows that as the ambient temperature decreases, migration U_{nop} to high values occurs. When the ambient temperature rises there is a weak appearance of a region of NDR on the VAC.
These results prove that indeed the electro-thermal processes are responsible in the appearance of the region of ODS in crystals.

In electro-thermal processes, small local deviations from the homogeneous distribution of imperfections that lead to high current densities in these regions are allowed. Such an increase in the current density is usually accompanied by the formation of a high-current density of the filament in the samples. In these "channels" the increased current density is the result of an increase in the scattering energy leading to Joule's heat. In connection with the increase in temperature, the electrical conductivity also increases and makes it possible for a high current to flow. The steady state of this behavior will be achieved when thermal dissipation is equal to the thermal losses. The steady state of the I-V characteristic and the features of their region of SLM can be interpreted by the electro-thermal approximation. At low current values, this corresponds to the norms.

The temperature dependence of the volt-ampere characteristics is an important factor in determining the interconnect material for technological applications. The choice of material for storing information depends on changing the switching properties with temperature change. Therefore, the I-V characteristics of single crystals were studied at different temperatures (Fig. 2). It can be seen from the figure that the threshold voltage increases with decreasing temperature, and the threshold current decreases. Apparently the threshold voltage is increased because of what was indicated in the works for other compounds [22]. A portion of the I-V characteristic showing a negative slope is a region of negative differential resistance. Its main characteristics are its width, slope, threshold voltage and threshold current, as well as the holding voltage and holding current. Therefore, in the retention branch, the electro-thermal balance between the heat of Joule produced in the volume and heat flux in the electrodes seems to play an important role in maintaining a high current density, with a decrease in the ambient temperature, the critical voltage Vn, at which the slope dI / dV first become negative displacements to values of a higher voltage, and the corresponding current (threshold current) is shifted to lower values of the current. The switching and threshold voltages can be explained using an electro-thermal model [23, 24]. The temperature of the semiconductor is increased due to Joule heating. Since the conduction process in the material is thermally activated, the conductivity of the sample will increase when it is heated, this will allow a larger current to flow through the heated regions and provide more Joule heating, leading to a further increase in the current density. Eventually, an increase in temperature will be sufficient to initiate thermal breakdown due to a strong temperature dependence of the conductivity. As follows from the experimental results, and also from the electro-thermal model, the temperature strongly affects both the shape of the current-voltage curves and the threshold voltage Vn. According to this assumption, the threshold current decreases with increasing threshold voltage. As can be seen, the I-V characteristics depend strongly on the ambient temperature of the samples under study. From these curves, a change in the threshold voltage Vn and the threshold current In with the temperature of the surrounding medium are constructed (Fig. 2). Ambient temperature increase of the samples increases the threshold current, while this reduces the threshold voltage. This indicates that an electro-thermal mechanism is involved in the switching process. The power dissipation was calculated in the investigated crystals (Pn = Vn × In). The power required to change material from the high-resistance state to the low-resistance state is called the threshold power Pn. The threshold power also depends on the ambient temperature. The calculation showed that the value of Pn decreases with increasing temperature, as shown in Fig. 3.

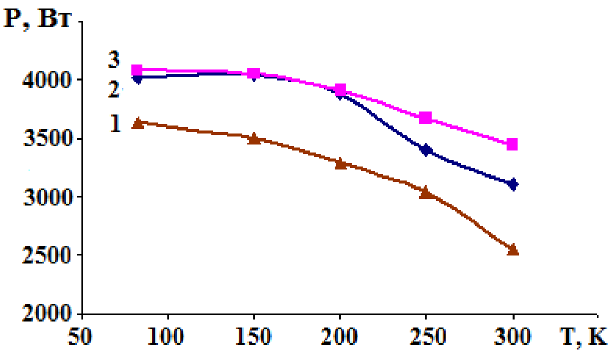


Fig 3 Temperature dependences of electric power of crystals $TlIn_{1-x}Gd_xSe_2$

This led us to the assumption that as the temperature of the number of random collisions increases, as well as the scattering between charge carriers, the rate of thermal generation of free charge carriers is less than the recombination rate and the effect of capture centers increases with increasing temperature. All these factors led to a decrease in the threshold power as the temperature rises. Thus, this result is completely logical, since the power required to initiate the switching decreases with increasing temperature.

CONCLUSIONS

Investigations of the current-voltage characteristic of crystals in the static mode, at different temperatures, revealed that these crystals have switching properties with memory. With increasing ambient temperature the value of the threshold voltage decreases and the threshold current increases. With variations in composition and ambient temperature, it is possible to control the threshold values of these crystals.

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