SWITCHING EFFECT IN COMPOUNDS $InGaSe_2$ AND $InGaTe_2$

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ABSTRACT

The presented work presents the results of studying the current-voltage characteristics of ternary compounds of the type, crystallizing in the tetragonal syngony, at various temperatures in a static mode. It was found that the compounds $InGaSe_2$, $InGaTe_2$ have switching properties with memory. With increasing temperature, the threshold voltage decreases and the most pronounced S-shaped characteristics are observed at low temperatures. It is shown that an obligatory condition for the appearance of negative resistance in the investigated phases is the existence of an additional mechanism of increase in the conductivity of the base region that accompanies injection. During injection, physical processes occur that lead either to an increase in the penetration depth of injected carriers, or to an additional increase in their concentration at each point, or to an increase in the proportion of injected carriers in the total p-n junction current. It was found that at low voltages across the diode, the base resistance is high and almost all of the applied voltage drops across it. As the voltage increases, the concentration of injected carriers in the base increases and its resistance decreases. Therefore, as the current increases, the total voltage increases. The current is a monotonic function of the applied voltage. This leads to a decrease in the share of the voltage drop at the base, which leads to amplification and a new redistribution of voltage between the base and the p-n junction. This is the positive feedback necessary for the appearance of negative resistance. Thus, in ternary semiconductors of the type, the obligatory conditions for the appearance of negative resistance are the existence of an additional mechanism of an increase in the conductivity of the base region that accompanies injection.

Keywords: memory switching effect, negative resistance, injected carriers, $InGaSe_2$, $InGaTe_2$ compounds.

INTRODUCTION

It is known that semiconductor switches have certain advantages: the symmetry of current-voltage (I-V) characteristics allows switching regardless of the signal polarity, and the device can be in any of the two possible states indefinitely when disconnected from the power sources. The presence of switching with memory is determined by the composition of the active material and the electrical mode of transfer from one state to another. Insensitivity to radiation levels at which bipolar devices fail, the simplicity of design and the ability to combine the fabrication technology of these switches with the technology of hybrid and monolithic integrated circuits, are of great interest to these devices. The limited number of “switching’s” is a common problem of such devices and an obstacle to their mass application in technology. Therefore, the search for new materials with switching properties and memory is an urgent problem [1-6].

The effect of switching and memory has been observed in chalcogenide glassy semiconductors, which have a chain crystal structure. It occurs at a certain duration and amplitude of the acting pulse, and its mechanism is associated with a reversible “glass-crystal” phase transition in the current channel [7-11].

In this work, the current-voltage characteristics of $InGaSe_2$ and $InGaTe_2$ ternary compounds are studied in order to reveal the possibility of their practical application in the formation of stable and controllable memory elements.

RESULTS AND THEIR DISCUSSION

The volt-ampere characteristics of the $InGaSe_2$ and $InGaTe_2$ compounds in the static mode are shown in Fig. 1. I-V measurements were carried out in the temperature range of 80-350 K.

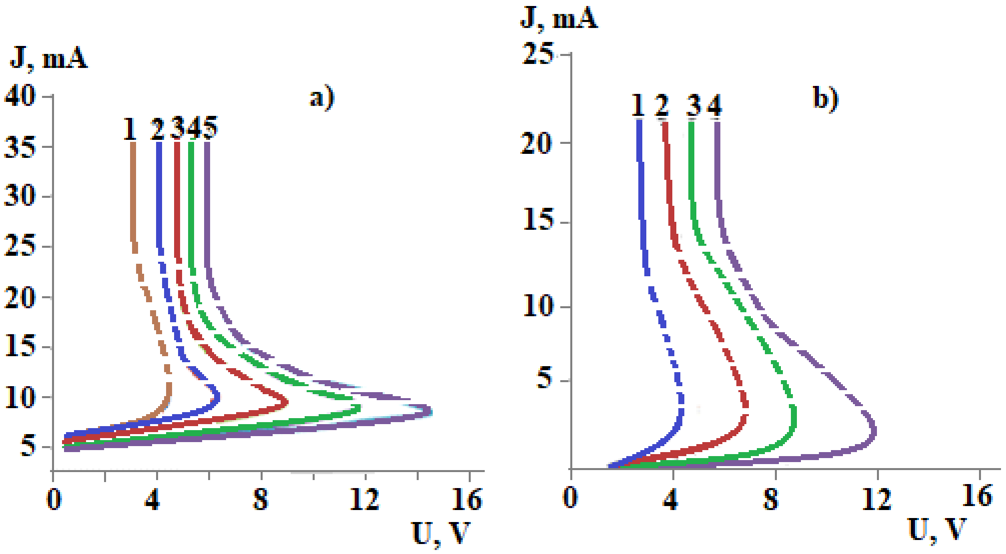

Fig 1. Volt-ampere characteristics of the $InGaSe_2$ (a) and $InGaTe_2$ (b) at different temperatures (1 – T=350 K, 2 – T=300 K, 3 – T=250 K, 4 – T=200 K, 5 – T=80 K)

As follows from the figures, for both studied compounds, up to a certain threshold voltage value, the current changes linearly, and then the samples abruptly pass from a high-resistance state to a low-resistance state, i.e. I-V curve has an S-shape with a region of negative differential resistance. In addition, as the operating temperature decreases, the threshold voltage increases.

Let us try, using the currently available models, to explain the essence of the switching effect in compounds of this type.

Devices with negative resistance are classified according to the form of current-voltage characteristics, which can be of two types: N-type characteristics, controlled by voltage - voltage uniquely determines the current, but at a given current, the voltage is determined ambiguously; b) S-type characteristics controlled by current - in a given range of currents, the current uniquely determines the voltage, but at a given voltage, the current is determined ambiguously. One of the big advantages of S-type I-V devices is that they have an inductive reactance. Therefore, to create a resonant system, it is enough to connect an external capacitance to them, which can be easily implemented by microelectronic technologies.

An area with negative resistance on the I-V characteristic of a diode can only form if there is internal positive feedback. For a diode with an S-type I-V characteristic, this is positive current feedback, i.e., any change in current must cause a further change in current in the same direction.

Let us analyze the condition for the occurrence of negative resistance on the example of a diode created on the basis of $InGaSe_2$ ($InGaTe_2$) compounds. Such a diode is a series-connected electron-hole (p-n) junction and a high-resistance base region.

In this case, the voltage U applied to the diode consists of the voltage drop across the p-n junction U_0 and across the thickness of the base U_T:

$$U = U_0 + U_T, \tag{1}$$

with

$$U_T = JR_T = \frac{J}{\sigma_T}; U_0 = \left(\frac{\beta kT}{q}\right) ln\left(\frac{J}{J_0}+1\right),$$

where J_0 is a pre-exponential factor equal at not very high currents to approximately the saturation current, β is a coefficient that takes values between 1 and 2 depending on the parameters of the p-n junction and the flowing current; R_T and σ_T resistance and conductivity of the thickness of the base of the diode: $\sigma_T=\sigma_0+\sigma^*$ (σ_0 is the base conductivity in the absence of injection, σ^* is the additional conductivity due to injection, which increases with increasing current through the p-n junction).

If the semiconductor is homogeneous and does not contain capture centers, then the concentration of injected current carriers grows linearly with increasing current through the p-n junction. In the presence of traps or inhomogeneities, the conductivity of the base region will change according to a linear, but more complex law, which can be expressed as

$$\sigma_T = \sigma_0\left[1+\left(\frac{I}{I_1}\right)^{\gamma}\right],$$

where I_1 is a constant value expressed in terms of the electrophysical parameters of the base material, γ is the charge carrier injection coefficient.

In this case, expression (1) will take the form:

$$U = \frac{Id}{\sigma_0\left[1+\left(\frac{I}{I_1}\right)^{\gamma}\right]} + \frac{\beta kT}{q} ln\left(\frac{I}{I_0}+1\right), \tag{2}$$

where d is the thickness of the base region.

The differential resistance of the forward branch of the current-voltage characteristic has the form:

$$\frac{dU}{dI} = \frac{1+\left(\frac{I}{I_1}\right)^{\gamma}(1-\gamma)}{\sigma_0\left[1+\left(\frac{I}{I_1}\right)^{\gamma}\right]^2} d + \frac{\beta kT}{q(I+I_0)}.$$

In the transition from positive to negative differential resistance $\frac{dU}{dI}=0$. Therefore, the condition for the existence of negative resistance can be written as:

$$1+\left(\frac{I}{I_1}\right)^{\gamma}(1-\gamma)+\frac{\beta kT}{qd}\frac{\sigma_0[(1+I/I_0)^{\gamma}]}{I+I_0}=0.$$

This condition can be fulfilled only when $\gamma>1$. With a linear and weaker dependence of the base conductivity on the current through the p-n junction, i.e. at $\gamma\leq1$, there is no negative resistance part on the I-V curve. Thus, it can be seen from the above example that a change in the base conductivity only due to injection does not lead to the appearance of an negative resistance. There must be another reason for the change in conductivity. At low voltages across the diode, the base resistance is high and almost all of the applied voltage drops across it. As the voltage increases, the concentration of carriers injected into the base increases and its resistance decreases. However, at $\gamma\leq1$ R_T decreases no faster than the resistance of the p-n junction. Therefore, as the current increases, the total voltage increases. The current is a monotonic function of the applied voltage. If $\gamma>1$, then the conductivity of the base increases faster than the conductivity of the p-n junction. So, the voltage drops at the base decreases, which leads to a new redistribution of voltage between the base and the p-n junction. This is the positive feedback necessary for the appearance of negative resistance. Thus, an obligatory condition for the appearance of negative resistance is the existence of an additional mechanism of an increasing in the conductivity of the base region that accompanies injection.

With base thickness $d>>L$ and $\gamma=1$, the current-voltage characteristic can be approximately represented by the following expression:

$$I=\frac{kTch(d/L)}{2q\rho_0 L(b+1)}\left(e^{qU/ckT}-1\right),$$

where L is the diffusion path at high injection levels, ρ_0 is the resistivity of the semiconductor, b is the ratio of the electron and hole mobilities:

$$c=2(b+chd/L)/(b+1)$$

The constant c increases exponentially as the ratio d/L increases. Therefore, the total current depends very much on this ratio.

CONCLUSION

It was found that chalcogenide glassy semiconductors $InGaSe_2$ and $InGaTe_2$ have switching properties with memory, which makes them promising materials for creating controlled memory elements. It is shown that in diodes made on the basis of the materials under study, along with a high injection of charge carriers, the appearance of a region of negative resistance in the I–V characteristic is promoted by an additional mechanism of increasing the conductivity of the base region.

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