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Dynistor effect in n -CdSb crystals

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Abstract. The I - V characteristics of cadmium antimony crystals doped with tellurium (n -CdSb:Te) were studied. Specific changes in the I - V characteristics of n -CdSb with different amount of doping impurity and different of illumination intensity at temperatures from liquid nitrogen and slightly higher were found. The nature of the I - V change had an S-shaped form (dynistor effect). For all groups of samples, the dependences of the current flowing through the crystal on the applied voltage showed a switching of the material from a low-conductive to a high-conductive state. In the process of switching to a high-conductive state, a slight increase in the current was accompanied by a rapid decrease in the voltage on the sample.

1. Introduction

Along with the currently existing materials, such as Si, Ge GaAs, for the production of devices in semiconductor electronics, an intensive search for new materials is ongoing, in particular based on A^2B^5 compounds [1-4]. The characteristic of current-voltage and resistance-voltage prove that the SET and RESET operations can be achieved by electric induction, implying the excellent candidate of Y-doped $Zn_{15}Sb_{85}$ material for high thermal and high reliability application [1]. The results [3] provide insights into potential strategies for improving ZT value by tailoring the charge carrier concentration in the bulk arsenides by doping. Doping CdSb crystals with some compensating impurities or radiation irradiation leads to a strong increase in photosensitivity in the low-temperature range. In particular, photoresistors with n -CdSb doped with tellurium cooled to 80 K are not inferior in sensitivity to known IR radiation receivers based on PbS and Ge. This opens up the possibility of using photodiodes based on CdSb:Te as IR radiation detectors.

Of great interest are the studies of nonlinear current-voltage (I - V) characteristics not only in devices, but also in materials. They have both applied significance and provide an opportunity to explain from a physical point of view the causes of the manifestation of nonlinearity. The nonlinearity of the I - V characteristic is strongly influenced by various external actions: temperature change [5, 6], mechanical deformation [7, 8], magnetic field [9], lighting [7, 10, 11], etc. The nonlinearity of the I - V curve is a characteristic feature not only of many semiconductor devices that have p - n junctions [6-8, 10-14], but also of many semiconductors [5, 9, 15].

The behaviour of both NDR's can be explained by the change of the conductivity due to the Joule heat generated in specimens. I - V characteristics of symmetric $In/p-TlInSe_2/In$ structures exhibit two distinct regions: an ohmic region at low current densities and a non-linear region (S-shaped) having NDR at moderate and higher current densities [5]. An electrothermal model is used for the explanation of this non-linear behaviour. A theory is given to explain the magnetic-



field effects on the hysteresis properties in semiconductors with an S-shaped negative differential conductivity [9].

The paper [8] presents the design of pressure sensor with a frequency output signal that is based on the physical processes in a resonant tunnel diode under the action of pressure. The use of devices with negative differential resistance can significantly simplify the design of pressure sensors in the entire radio frequency range. In paper [13], ISE-TCAD, a device simulation software, is used to carry out simulation experiments on silicon-based trench MOS Schottky (TMBS) diodes with different trench dimensions under the condition of forward biases and obtain a series of experiment data associated with the negative resistance. In study [14] perform a simulation of Resonant Tunneling Diode design for oscillator circuit at a target frequency of 500 – 600 GHz.

A necessary condition for the occurrence of thermal-electrical instability in *n*-CdSb crystals is the presence of deep energy levels in their band gap [16, 17]. Ionization of these levels by various methods (lighting, electric field, temperature changes or a combined method) makes it possible to obtain an S-shaped *I-V* characteristic of *n*-CdSb:Te [17].

2. Materials and Method

The *I-V* characteristic were studied in *n*-CdSb crystals with different doping concentrations of tellurium: 0.005 %, 0.05 %, 0.5 % and different of illumination intensity levels at temperatures from liquid nitrogen and higher.

Before measurements, the crystals were polished with a micron diamond paste and etched in a mixture of concentrated H₂O₂, HF(70 %), HCl and glycerin (10:3:1:6). This was done to remove the surface layer, which in many cases could affect the results of volumetric studies. Current contacts on the sample were applied with tin with an admixture of antimony. The contacts were checked for ohmicity. The electric field was applied along the crystallographic direction [010].

A low-power light source with a spectral maximum of 1200 nm was used to illuminate the samples. This allowed to eliminate heating of the sample by the illuminator and interband phototransitions of charge carriers.

3. Result and discussion

The study of static current-voltage (*I-V*) characteristics in cadmium antimony crystals with deep energy levels allows to further clarify the role of these levels in the formation of thermal-electrical instability (TEI), and can also provide information about the interaction of the electronic and phonon subsystems in a crystal in the presence of a moderate electric field. Figure 1a shows the static *I-V* characteristics of *n*-CdSb:Te crystals, typical for all the studied samples. These characteristics are reproducible and symmetrical with respect to the polarity of the applied voltage.

The nature of the changes in the current-voltage characteristic had an S-shaped form. Depending on the values of the applied voltage *V* and the current *I* flowing through the *n*-CdSb crystal, several sections of the S-shaped *I-V* characteristic can be distinguished. (a) The *I-V* curve in the section limited by the applied voltage interval $0 \div V_{th}$ corresponds to the high resistance (low-conduction state) of the material. Increasing the voltage has little effect on the current until the threshold (switching) voltage V_{th} is reached, at the value of the current I_l that flows through the sample (latching or switching current). (b) The *I-V* curve in the section (dashed line), from the values of V_{th} and I_l to the values of V_h and I_h (holding voltage and current), corresponds to the

switching of the material from a low-conductivity to a high-conductivity state (unstable region). During the switching to a high-conductivity state, a slight increase in current is accompanied by a rapid decrease in voltage across the sample. Since the curve has an S-shape, the resistance of the sample is negative. (c) The I - V curve from the values of V_h and I_h and above corresponds to the highly conductive state.

Up to the threshold voltage V_{th} , the I - V characteristic exhibits curves typical of semiconductors. At electric field strengths above 138 V/cm, the I - V characteristic deviates from a linear dependence (section ab). An electric field strength of 148 V/cm corresponds to the threshold voltage at which the sample switches from a high-resistance state to a low-resistance state, accompanied by a change in the voltage drop across the element from 245 V to 25 V. The voltage across the sample in the low-resistance state changes insignificantly over a wide current range. Currently, there are several theories explaining the switching mechanism of elements based on CdSb semiconductors [16, 17]. However, none of them provides a comprehensive explanation of this phenomenon.

To elucidate the operating mechanism of switches based on n -CdSb:Te crystals, I - V characteristics were studied at various temperatures. The measurement results are shown in Fig. 1a. Curve 1 corresponds to a temperature of 78 K, curve 2 to 87 K and curve 3 to 90 K. As can be seen from the figure, the threshold voltage for the same sample increases sharply with decreasing temperature. The overall pattern of threshold voltage change with temperature across the element is close to linear (see Fig. 1b, curve 2).

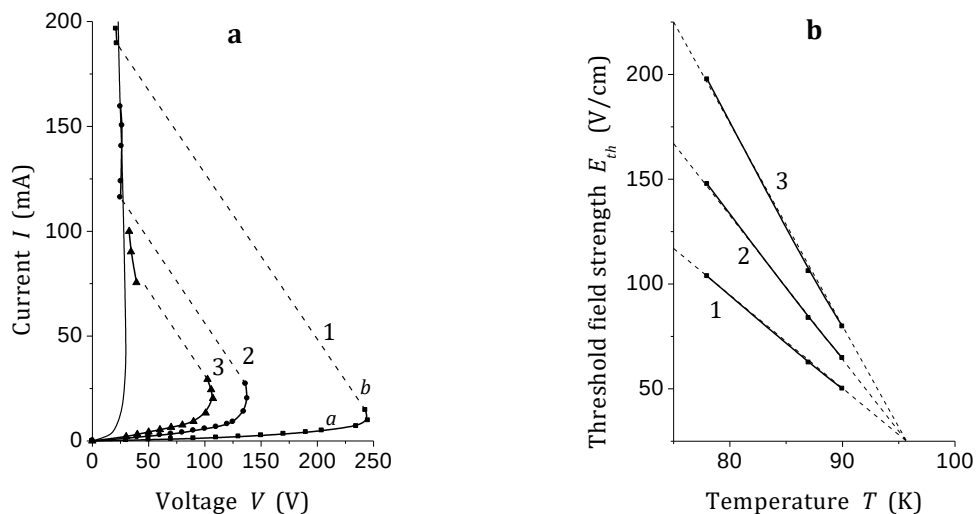


Figure 1. (a) I - V characteristics of CdSb + 0.05 % Te at different temperatures T : curve 1 – 78 K; curve 2 – 87 K; curve 3 – 90 K. (b) Threshold electric field strength as a function of temperature for CdSb with different amount of Te i dopant: curve 1 – 0.005 % Te; curve 2 – 0.05 % Te; curve 3 – 0.5 % Te.

The switching of the element to the open state in the S-shaped I - V characteristic is preceded by a section ab (see Fig. 1a). The presence of this section can be attributed to heating of the sample. The strong temperature dependence of the threshold voltage suggests that the switching effect the element to the low-resistance state is caused by thermal breakdown. This point of view is also supported by studies of switching phenomena in semiconductors with deep energy levels in the low-temperature region [16-18].

In the absence of a sufficiently deep energy level in the forbidden band of a semiconductor, the static I - V characteristic corresponds to Ohm's law without any deviations up to the region of influence of high-intensity electric fields. In semiconductors with deep energy levels in the low temperature region, the TEI effect can be observed. The effect consists in a sudden increase in the current strength, which occurs at certain critical voltage values. In this case, the samples enter a state of high non-equilibrium conductivity with the formation of a region with increased current density in the volume of the semiconductor [18] (the emergence of a high-temperature "current channel-cord"). Therefore, the static I - V characteristic has an S-shaped form. It is stimulated mainly by the interaction of current carriers with acoustic phonons in the presence of an external electric field, therefore, the influence of overheating mechanisms on the TEI effect is often discussed.

However, the TEI effect in neutron-irradiated [16] and Te doped [17] CdSb crystals with deep levels ($E_c - 0.16$ eV and $E_c - 0.12$ eV) at nitrogen temperatures has significant differences. It was observed that in irradiated crystals, with an increase in the number of switchings, the resistance of the sample decreases sharply, and accordingly, the magnitude of the current jump and the critical voltage at which the switching effect occurs decrease. With a sufficient number of switchings, the current jump completely disappears. Repeated measurements of the I - V characteristics, which were carried out after several months, showed that the samples partially restore their properties. The authors [16] suggest that an important role in the formation of the I - V characteristics is played by the disordered regions, which are apparently surrounded by volume charges and protected from recombination with the main carriers of the matrix by potential barriers.

Of interest is the study of the characteristics of switching elements based on CdSb crystal materials with different concentration of Te dopant. Current-voltage characteristics were measured on samples with varying degrees of doping. The measurement results are shown in Figure 2a. Curve 1 was recorded at 78 K on samples with of Te impurity concentration 0.005 % Te; curve 2 – 0.05 % Te; curve 3 – 0.5 % Te. As can be seen from Fig. 2a, the shape of the I - V

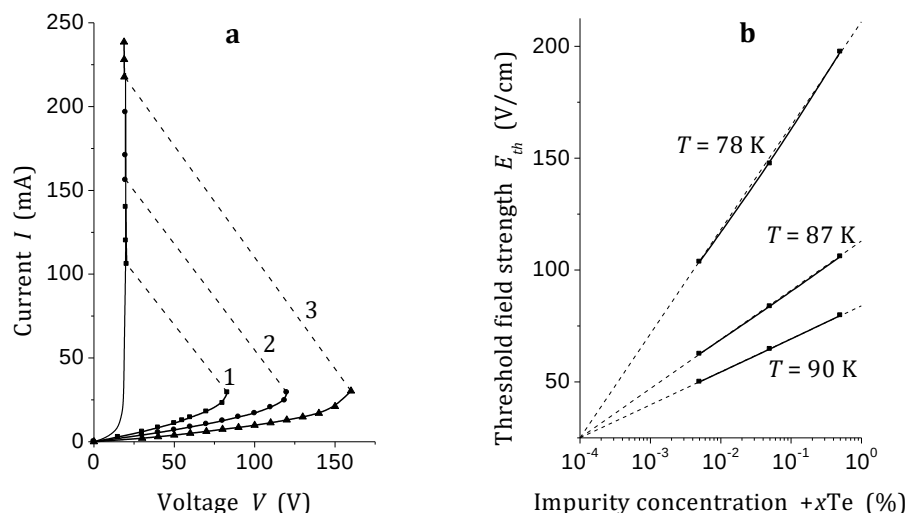


Figure 2. (a) I - V characteristics at 78 K of Te-doped CdSb: curve 1 – 0.005 % Te; curve 2 – 0.05 % Te; curve 3 – 0.5 % Te. (b) Threshold electric field strength vs. impurity concentration (semilog plot) at different temperatures for CdSb.

characteristics for the studied samples is significantly different. An increase in the concentration of the dopant from 0.005 % Te to 0.5 % Te leads to an increase in the threshold voltage from 85 V to 162 V.

An electric field strength of 104 V/cm corresponds to the threshold voltage at which the sample with 0.005 % Te switches from a high-resistance state to a low-resistance state, accompanied by a change in the voltage drop across the element from 85 V to 20 V. While for the sample with 0.5 % Te at the same temperature, the electric field strength of 198 V/cm corresponds to the threshold voltage. The overall pattern of threshold voltage (field strength) change vs. different amount of Te dopant the element (semilog plot) is close to linear (see Fig. 2b, curve at 78 K). Apparently, impurity regions play a dominant role in the switching mechanism of the CdSb:Te-based samples.

This linearity of the change in V_{th} or E_{th} values vs. the Te impurity concentration is preserved when the temperature increases to 90 K, but the slope of the line $E_{th} = E_{th}(xTe)$ changes (see Fig. 2b). Linear extrapolations of $E_{th} = E_{th}(xTe)$ in a wider interval of doping values (see Fig. 2b) and $E_{th} = E_{th}(T)$ at any temperatures (see Fig. 1b) allowed us to estimate the limit of the existence of the TEI effect. These limiting values for the existence of the TEI effect for CdSb:Te crystals are equal to the maximum temperature of 95 K, and the minimum of doping impurities is 10^{-4} % Te.

Also, the higher the illumination intensity, the lower the V_{th} voltage at which the sample switches to a low-resistance state (Fig. 3a). For unilluminated samples (dark conductivity) (Fig. 3a, curve 1), the applied voltages increase to values at which the Joule heat released on the samples becomes sufficient to ionize the tellurium donor level $E_C - 0.12$ eV [19]. In this case, an avalanche-like transition of electrons to the conduction band occurs, which leads to a current jump. Fig. 3b shows the dynamics of the change in conductivity as a function of the level of illumination intensity. If in the absence of illumination when switching the sample, the conductivity increases by almost two orders of magnitude, then with increasing illumination level the threshold conductivity and holding conductivity curves quickly approach each other. The switching effect practically disappears at the value of $I/I_0 \approx 5$ (see Fig. 3).

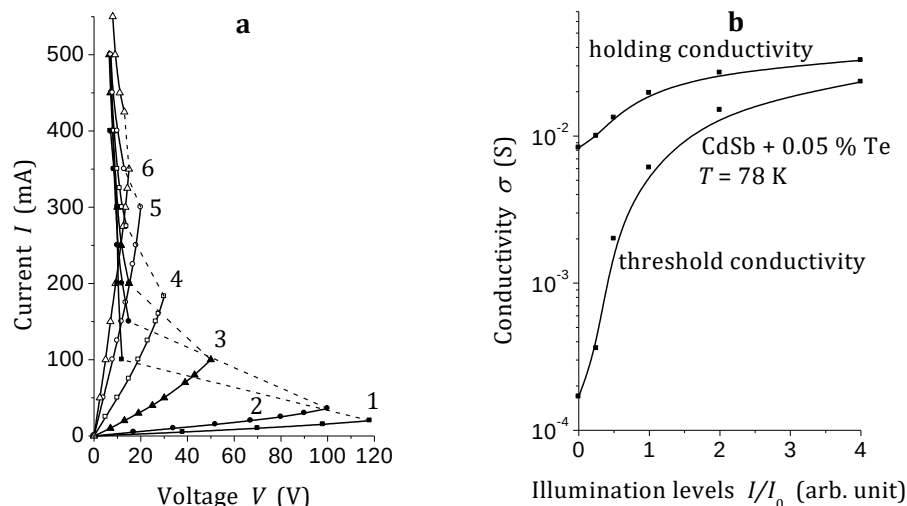


Figure 3. For CdSb + 0.05 % Te at 78 K (a) I - V characteristics at different illumination levels (in arb. units): curve 1 – 0; curve 2 – 0.25; curve 3 – 0.5; curve 4 – 1; curve 5 – 2; curve 6 – 4 and (b) threshold conductivity and holding conductivity as a function of the illumination level.

An increase in the concentration of the dopant (see Fig. 2a, curves 1-3) leads to an increase in the limit values of the applied electric field voltage, which is associated with different levels of ionization [17] and inhomogeneities [20] of the tellurium impurity. An increase in the temperature (see Fig. 1a, curves 1-3) or the level of illumination intensity (Fig. 3a, curves 2-6), and therefore an increase in the level of thermal- or photoionization of the tellurium impurity, leads to a decrease in the threshold applied voltage. An increase in the impurity concentration or a decrease in the level of illumination allows you to achieve the current value required to heat the sample at higher electric fields.

4. Conclusions

With increasing dopant concentration, an increase in the limiting values of the applied electric field voltage was found, which is associated with different ionization of the tellurium impurity level. On the contrary, an increase in temperature above 78 K and an increase in the level of crystal illumination intensity reduces the threshold voltage.

From the analysis of S-shaped I - V characteristics, the values of the parameters of the quantities that are important in the development of controlled sensor devices of semiconductor electronics with predetermined characteristics have been established. By changing the dopant content, temperature and illumination intensity in n -CdSb:Te, it is possible to control the values of the V_{th} turn-on voltage.

A wide variation of the threshold voltage of elements based on CdSb:Te crystals by changing the linear dimensions of the samples and the amount of doping impurity, low power consumption, ease of manufacture – all this allows us to hope for the possible practical use of this material for creating memory elements or switches from a highly conductive to a low-conductive state and vice versa.

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