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SWITCHING EFFECTS IN THE DIELECTRIC PHASE OF THE $Pb_{1-x}Sn_xTe(In)$ COMPOUNDS

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The current-voltage characteristics (CVC) and switching effects have been investigated in the monocrystalline $Pb_{1-x}Sn_xTe$ alloys doped with In at liquid helium temperatures. Experimental results are interpreted in terms of joule heat model.

В настоящей работе были изучены вольтамперные характеристики (ВАХ) и эффекты переключения в монокристаллических сплавах $Pb_{1-x}Sn_xTe$ легированных In при гелиевых температурах. Экспериментальные результаты интерпретируются в рамках модели джоулева разогрева.

1. The Introduction.

The characteristic feature of the investigated compounds is the high sensitivity to infrared (IR) illumination[1,2] at liquid helium temperatures ($T < 20°K$). The ratio $\Delta\sigma/\sigma_T$ is found to be higher than 10^5, $\Delta\sigma$ being the photoconductivity under IR illumination and σ_T - dark conductivity value ($\sigma_T \lesssim 10^{-5} Ohm^{-1} \cdot sm^{-1}$). This fact is due to the existence of the energy barrier W between the impurity states and the conduction band.[3] Since the electron lifetime achieves the value 10^4-10^5 sec. at $T = 4.2°K$ [1], the conductivity under IR illumination rises sharply up to the value $n \simeq 10^{16}$ sm^{-3}. Electron lifetime $\tau_n(T)$ is expected to be exponentially dependent upon the temperature according to the activation character of the photocarriers recombination process:

$$\tau_n \sim \Delta\sigma \sim \exp\left(\frac{W}{T} - \frac{W}{T_o}\right) \quad (1)$$

(T is the temperature of the sample, T_o - the temperature of surrounding space). For the $Pb_{1-x}Sn_xTe(In)$ alloy which is in dielectric phase (DP) [4] the activation energy $\mathcal{E}_A$ corresponding to the deep level $\mathcal{E}_o$ is approximately 20 meV. The concentration of thermally excited electrons in the conduction band is less than $n \simeq 10^{10} sm^{-3}$ at T=4.2°K. So the dark conductivity $\sigma_T(T)$ rises when the temperature increases:

$$\sigma_T \sim \exp\left(\frac{\mathcal{E}_A}{T_o} - \frac{\mathcal{E}_A}{T}\right) \quad (2)$$

Fomulas (1) and (2) are correct, at least, in some temperature interval. The facts mentioned above can provide a joule warming-up of the sample, which in turn may cause changes in the CVC.

The measurements were performed in special brass chamber cooled by liquid helium. The heat flow between the sample and the chamber walls was transferred by gaseous helium or penthan. Such construction protects the sample from background IR illumination.

2. The Model

For the discussion of the view of CVC curves the condition mentioned above should be taken into consideration. The expression for CVC can be deduced from the stationary heat equation averaged over the whole length of the specimen [5]:

$$\sigma(T)E^2 = \frac{c\rho}{\tau}(T - T_o), \quad (3)$$

where $\sigma = \Delta\sigma + \sigma_T$, E - electric field, ρ, c are the average density and specific heat respectively, τ - the thermal relaxation time of a sample. The left part of the equation (3) corresponds to the specific joule power and the right one is the specific dissipation of the energy into the surrounding space which has the temperature T_o. Using the eq. (3) and Ohm law the differential conductivity σ_d can be deduced:

$$\sigma_d = \frac{dj}{dE} = \frac{\left[\frac{c\rho}{\tau} + \frac{d\sigma}{dT}\cdot E^2\right]\cdot\sigma}{\frac{c\rho}{\tau} - E^2\frac{d\sigma}{dT}} = \frac{\left[\frac{T-T_o}{\sigma}\cdot\frac{d\sigma}{dT} + 1\right]\cdot\sigma}{1 - \frac{T-T_o}{\sigma}\cdot\frac{d\sigma}{dT}} \quad (4)$$

The magnitude $\frac{d\sigma}{dT}$, according to equations (1) and (2), equals to:

$$\frac{d\sigma}{dT} = \frac{1}{T^2}\cdot\left[\mathcal{E}_A\cdot\sigma_T(T) - W\cdot\Delta\sigma(T)\right] \quad (5)$$

This magnitude depending on the specimen temperature T and power of IR illumination can be negative as well as positive. Thus the denominator or numerator in (5) may become zero. When the values of j and E are rather small and $\Delta\sigma(T_o) \gg \sigma_T(T_o)$ it is possible to neglect the dark

conductivity: $\sigma \simeq \Delta\sigma$, $j \simeq \Delta\sigma E$ (branch A, Fig. 1), so

$$\frac{d\sigma}{dT} \simeq -\frac{W \cdot \Delta\sigma}{T^2} < 0 \qquad (6)$$

From the (4) and (6) we have $\sigma_d = 0$ (point A_c, Fig. 1) if $T = T_c^1 \simeq T_o(1 + T_o/W)$ (7) ($T_o \ll W$). The further increase of E is accompanied by some decrease of $\Delta\sigma$ and j values (branch B, Fig 1). In the

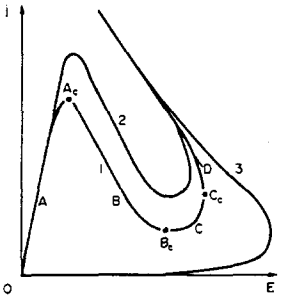

Fig. 1. Schematic view of current-voltage characteristics under infrared illumination (curves 1 and 2) and in the darkness (curve 3). Curve 2 corresponds to the higher intensity of IR illumination.

falling branch of N-type CVC with $\sigma_d < 0$ the curriers lifetime is diminished exponentially due to the temperature T increase under joule heating. So the rise of E and T_2 causes the decrease of $\Delta\sigma$, and at $T = T_c$ (see eq.(4)) σ_d equals zero again:

$$T_c^2 = \frac{\mathcal{E}}{2} - \frac{\mathcal{E}}{2}\sqrt{1 - \frac{4T_o}{\mathcal{E}}}, \quad \mathcal{E} = \frac{W \cdot \Delta\sigma - \mathcal{E}_A \cdot \sigma_T}{\sigma}$$

(point B_c, Fig. 1). (8)

The rise of E, T, σ_T and decrease of $\Delta\sigma$ (branch C, Fig. 1) finally leads to the change of the deviation $\frac{d\sigma}{dT}$ sign (see eq. (5)). The region of the negative differential conductivity (NDC) in CVC curve appears at the temperatures $T > T_c^3$, where T_c^3 is determined from the condition $\sigma_d \to \infty$:

$$T_c^3 = \frac{\mathcal{E}^*}{2} - \frac{\mathcal{E}^*}{2}\cdot\sqrt{1 - \frac{4T_o}{\mathcal{E}^*}}; \quad \mathcal{E}^* = \frac{\mathcal{E}_A \cdot \sigma_T - \Delta\sigma \cdot W}{\sigma} \qquad (9)$$

(branch D, Fig. 1). Temperature T_c^3 corresponds to point C_c in Fig. 1.

Thus in samples with "frozen" conductivity under IR illumination the N-S-type CVC can be detected. When temperature T rises, the appearance of N-type branch in the CVC curve is due to the lifetime decrease and S-type one is caused by the increase of dark conductivity. The existence of N or S-type CVC is a well known phenomenon in semiconductors, but simultaneous observation of N and S-type CVC is specific for the $Pb_{1-x}Sn_xTe$(In) compounds.

The exponential dependence $\sigma(T)$ leads to the very small differences between T_c^1, T_c^2, T_c^3 ($T_c^1 < T_c^2 < T_c^3$) and T_o. One can notice that according to eq. (7)-(9) the increase of IR illumination intensity results in the shift of the N-S-type CVC region along the current axis (branch 2, Fig. 1). For rather large values of j and E (when $\Delta\sigma \ll \sigma_T$) corresponding to various $\Delta\sigma(T_o)$ CVC curves asimptotically converge with the S-type dark characteristic (see equation (5) and branch 3, Fig. 1). The critical temperature T_c for dark CVC (see equation (9)) is equal to:

$$T_c = T_c^3 \simeq T_o\,(1 + T_o/\mathcal{E}_A) \qquad (10)$$

To obtain formulas (7)-(9) we have used only the minimal root of the equation for determining T_c.

3. The Experimental Results.

The typical experimental results for one of the samples of $Pb_{0.75}Sn_{0.25}Te$ alloys doped with ~0.5 at% In are shown in Fig. 2. The dimentions of the sample are (0.5 x 0.6 x 2.9) mm^3.

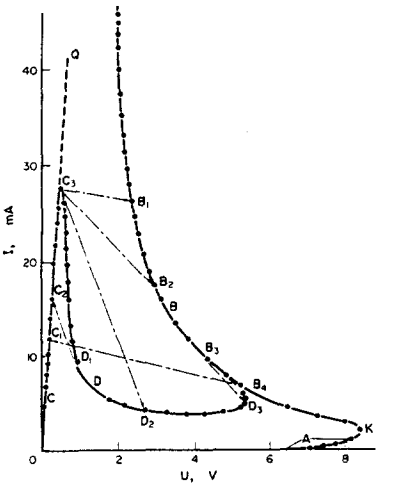

Fig. 2. The typical N-S-type static CVC under IR illumination (branches C, D, B) and dark static one (branches A, B). The dimensions of the sample $Pb_{0.75}Sn_{0.25}Te$ with ~0.5 at% In are 0.5 x 0.6 x 2.9 mm^3. T_o = 4.2°K.

The static dark CVC appears to be a continuous S-type curve (compare with [6]). The initial branch A (Fig. 2) is well described by quadratic dependence $I \sim U^2$, which transforms to $I \sim U^n$ ($n > 2$) at $E > 10^3$ V/sm. The critical temperature value measured with the thermocouple equals to $T = T_c^3 = 5$°K, that corresponds to point K in Fig. 2 ($\sigma_d \to \infty$). The T_c^3 value calculated from the equation

$$\frac{c\rho}{\mathcal{C}} = E^2 \cdot \frac{d\sigma_T}{dT} \qquad (11)$$

(see equation (4)) using experimental dependence $\sigma_T(T)$ coincides with the experimental value within the precisi-

on limits. The experimental dependence $\sigma_T(T)$ deviates from the exponential law $\sigma_T \sim \exp\left(\frac{\varepsilon_A}{KT}\right)$ at temperatures $T < 8°K$, so T_c^3 founed from equation (11) is greater than T_c value obtained from equation (10):

$$T_c = T_o\ (1 + \frac{T_a}{\varepsilon_A}) \simeq 4{,}3°K.$$

Investigations of nonstationary (pulsed) CVC's confirm the suggestion about the joule heat nature of the negative differential conductivity (NDC) branch in the dark characteristic. The temperature setting characteristic time τ after a voltage pulse is applied equals to $\simeq 10^{-2}$ sec. Thus nonstationary CVC's closely coincide the static one if the duration of the pulse Δt is longer than 0.1 sec. (see [6]). The NDC branch in CVC shifts to the higher voltages and currents if the pulse duration Δt is decreased. At $\Delta t < 10^{-3}$ sec. we have never succeeded in observing a NDC-region in CVC. Improving heat exchange between the sample and surrounding space (decreasing τ) by means of decreasing the sample's crosection S, or filling the sample-chamber with penthan, we have observed the rise of I_c and U_c values (I_c and U_c are critical current and voltage that correspond to point K, Fig. 2). This effect occurs because of the critical temperature T_c^3 does not depend on the thermal relaxation time τ.

Heated up to $T^* = 25K$ carbon resistor was used as a IR illumination sourse (this procedure is described in [1]). It is found that under IR illumination the static CVC's are N-S-type curves (see branches C, D, B at Fig. 2). Under more powerful illumination (for higher T^*) branches C, D, B shift along the current axis in the positive direction. Under various power of IR illumination S-type branches in CVC coincide with the dark characteristic in a higher currents region. Hall effect measurements have confirmed the electron concentration decrease in the falling N-type branch. Naturally, one can observe the working point jumps between various branches in the CVC corresponding to some values of a load resistance R_L (the magnitude of R_L is indicated further in parenthesis): $C_3 - B_1$ (1kOhm), $C_3 - B_2$ (70 Ohm), $B_3 - D_3$ (70 Ohm), $C_3 - D_2$ (25 Ohm), $D_1 - C_2$ (25 Ohm), $B_4 - C_1$ (1 kOhm).

When IR illumination is switched off the resistance R relaxes slowly (for several hours) down to the resistance in the darkness[1,2]. Residual photoconductivity (RPC) can be extinguished by joule heat using rather high load resistor R_L. As a result the transitions from branch C to branch B occur (see transitions $C_3 - B_1$, $C_3 - B_2$). When the current decreases the working point shifts along branches B & A and RPC are, obviously, extinguished in the whole volume of the sample. In our experiments electrothermal extinguishing of RPC time equals to $10^{-3} - 10^{-2}$ sec. The same time is required for the transition from the branch A to branch B in avalanche delay breakdown.[6] In the pulse regime point C_3 shifts along the C - Q curve into the region of higher currents. For example, the current value necessary for RPC being extinguished in 10^{-3} sec. equals to 100 mA. In this case the value of applied to the sample voltage changes from 1 to 8 volts. In order to reveal possibilities of more rapid RPC extinguishing the investigation of the pulsed CVC under higher currents have been made. Probing 6 μsec. pulse amplitude was varied up to 2 A. It was found that if voltage is applied (I = 1,5 A, U ≃3V) the pulse current decrease with the characteristic time 10^{-7} sec takes place in 10^{-6} sec. However the resistance value R, measured at the small currents increases only by 30 times after passing of the nonrecurrent pulse with the indicated parameters.

The total resistance of the sample in the state of such partially extinguished RPC is restored under the repeated IR illumination pulse. RPC extinguishing in the pulse regime may be caused both by decreasing recombination time τ_r when the specimen's temperature rises and by the electron gas warming-up. Unfortunately, we have not any possibility to estimate the latest effect because there are no experimental data about the relaxation time of the warmed-up electrons in the investigated compounds.

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