Letters to the Editor

CURRENT INDUCED TRANSITION FROM A HIGH RESISTIVITY TO A LOW RESISTIVITY STATE IN SEMICONDUCTORS

ИНДУЦИРОВАННЫЕ ТОКОМ ПЕРЕХОДЫ СОСТОЯНИЯ С ВЫСОКИМ УДЕЛЬНЫМ СОПРОТИВЛЕНИЕМ В СОСТОЯНИЕ С НИЗКИМ УДЕЛЬНЫМ СОПРОТИВЛЕНИЕМ В ПОЛУПРОВОДНИКАХ

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In general, the current controlled current-voltage characteristics can be expressed by the relation

$$U=[R_1 f(I)+R_2]I. \tag{1}$$

In the case of current induced transition from a high resistivity to a low reistivity state $R_1 \gg R_2$ and the function $f(I)$ must have the following properties:

$$f(I)>0,\quad \lim_{I\to 0} f(I)=0,\quad \lim_{I\to\infty} f(I)=1,\quad \frac{df(I)}{dI}<0 \tag{2}$$

Further, if the current-voltage characteristic is of the "S" type, the equation $dU/dI=0$, i.e.

$$I\frac{df(I)}{dI}+f(I)+\frac{R_2}{R_1}=0, \tag{3}$$

should have two real and positive roots I_{th}, I_m to which the corresponding voltage U_{th}, U_m limit the region of negative differential conductivity.

The simplest function which fulfils all these conditions is

$$f(I)=\exp(-bI). \tag{4}$$

Then the current-voltage characteristic is given by the relation

$$U=[R_1\exp(-bI)+R_2]I. \tag{5}$$

In this case the condition $dU/dI=0$ gives the equation

$$(bI-1)\exp(-bI)=R_2/R_1, \tag{6}$$

which has two real and positive roots if $R_2/R_1 \leq \exp(-2)$.

We note that the formula (6) of Kimata's and Kani's paper [1] (these authors proposed a simple model for the negative resistance taking into account the impact ionization of deep level impurities) can

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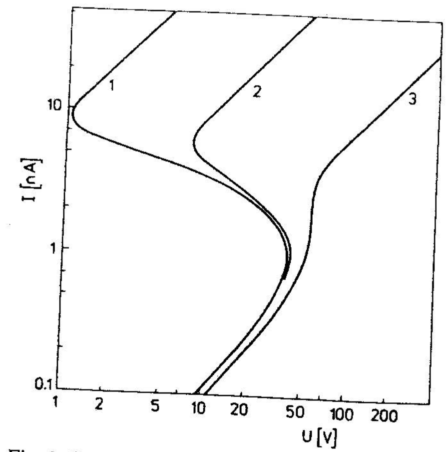

Fig. 1. Current-voltage characteristic described by the formula (5) with $b = 1\ (nA)^{-1}$, $R_1 = 10^{11}\ \Omega$, and $R_2 = 10^8\ \Omega$ (1), $10^9\ \Omega$ (2), $1.353 \times 10^{10}\ \Omega$ (3), respectively.

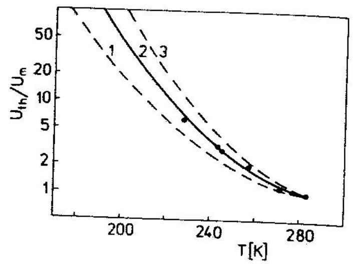

Fig. 2. The computed U_{th}/U_m versus T dependeces corresponding to R_2/R_1 given by the relation (8) with $T_0 = 283$ K. and $a = 10$ (1), 12.6 (2), 15 (3), respectively. The full circles correspond to the ratio of experimental values of U_{th} and U_m shown in Fig. 3 of the reference [3].

be rewritten into the form (5). The model of these authors has been criticized by Avak'yana and Arumjunjan [2]. However, we are of the opinion that also other microscopic models can be found which lead to the formula (5), since this phenomenological formula comprehends the general feature of the transition from high resistivity to low resistivity ohmic regions of the "S"-type current-voltage characteristic.

The low resistance state R_2 includes the series resistance of the circuit with the examined sample. Changing this resistance we get various characteristics, as it is illustrated in Fig. 1.

The ratio of the threshold to the sustain voltage is given by the formula

$$\frac{U_{th}}{U_m} = \frac{\exp(-bI_{th}) + R_2/R_1\, bI_{th}}{\exp(-bI_m) + R_2/R_1\, bI_m}. \qquad (7)$$

Let us denote the temperature at which $U_{th} = U_m$ as T_0. At this temperature $R_2/R_1 = \exp(-2)$. If we suppose that the resistance R_1 exponentially decreases with increasing temperature while the temperature dependence of R_2 is weaker, then the temperature dependence of the ratio R_2/R_1 can be expressed as

$$R_2/R_1 = \exp\left[-\frac{a(T_0 - T)}{T} - 2\right]. \qquad (8)$$

By numerical solution of Eq. (6) with R_2/R_1 given by the relation (8) with given values of constants T_0, a, we can find the values of bI_{th} and bI_m for various T. Then from (7) we get the temperature dependence of U_{th}/U_m. The results gained with $T_0 = 283$ K, $a = 10$, 12.6, 15, respectively, are shown in Fig. 2. The full circles in Fig. 2 correspond to the ratio of experimentally determined values of U_{th} and U_m on a semiinsulating GaAs(Cr) sample shown in Fig. 3 of our previous paper [3]. The value of the parameter "a" which fits the experimental data is 12.6, and the experimental value of T_0 is 283 K. Using these values we get from (8) that

$$R_2/R_1 \sim \exp(-3580K/T) = \exp(-0.30\ eV/k_B T). \qquad (9)$$

We suggest the following physical interpretation of this result. It is known that in semiinsulating GaAs(Cr) the chromium ions located on gallium lattice sites can be in various states depending on the number of donors [4, 5]. In the absence of donor impurities chromium atoms are in the state commonly designed Cr^{3+}. If donors are present, the Cr^{3+} ion can capture one electron and thus is converted to the Cr^{2+} ion with the energy level approximately 0.80 eV below the conduction band. Addition of more donors should allow chromium atoms to capture a second electron, which leads to the Cr^{1+} state with an energy level of about 0.5 eV below the conduction band. The injection of electrons into a semiinsulating GaAs(Cr) base can also lead to the conversion of Cr^{2+} to Cr^{1+} ions. We suppose that at low voltage the resistance of the investigated sample can be expressed as

$$R_0 = R_1 + R_2,$$

where

$$R_1 \sim \exp(+0.80\ eV/k_B T)$$

and

$$R_2 \sim \exp(+0.50\ eV/k_B T).$$

With an increasing current more Cr^{2+} ions will trap the injected electrons and become Cr^{1+} ions. Thus the regions with a resistivity proportional to $\exp(+0.80\ eV/k_B T)$ disappear with an increasing current, as it follows from the formula (5), and the ratio R_2/R_1 is given by the relation (9).

Thus we have proposed a new mechanism of the switching effect which can occur in some high-resistivity crystalline semiconductors in which, due to the capture of electrons, the impurity-ions are converted to the state of the lower activation energy.

We note that recently Chiang [6] has proposed the theory of threshold switching in amorphous thin films based on the assumption that in amorphous films there are two stable and reversible configurations I, II with conductivities g_1 and g_2, which coexist in approximate equilibrium and may transform into each other through an energy barrier $\Delta E = E_1 - E_2$ under electric excitation. The energy levels E_1 and E_2 of the configurations I and II may be elevated due to a current by the amount $k_1 I$ and $k_2 I$, respectively. His model leads to the steady current-voltage characteristic which can be approximated by the formula (5) if $g_2 \ll g_1$, $E_2 < E_1$, $k_1 < k_2$.

The above mentioned models have an electronic nature. Krempaský et al. [7] proposed a thermal model of the switching effect which also leads to the current-voltage characteristic described by the relation (5) if we include the series resistance of the circuit and neglect the quadratic term in the exponential function of their relation (10). This again confirms that the formula (5) can find a wide utilization.

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Received February 1st, 1980