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THE TEMPERATURE AND COMPENSATION DEPENDENCE OF THE THRESHOLD VOLTAGE FOR SWITCHING EFFECT DUE TO THE POOLE-FRENKEL AND SCREENING EFFECTS WITH APPLICATION TO CHROMIUM DOPED GaAs STRUCTURES

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In the present paper relations are found for the switching threshold and for the sustain electric fields in the case when the current controlled negative resistance in a partly compensated crystalline semiconductor is due to the combined screening and the Poole-Frenkel effects. The main attention is paid to the temperature and compensation dependences of these fields. It is shown that there exists a critical temperature above which negative resistance cannot occur. The theoretical results are successfully applied to the temperature dependences of the static threshold voltage of GaAs(Cr) structures measured at dark in the temperature range 90—230 K.

ТЕМПЕРАТУРНАЯ И КОМПЕНСАЦИОННАЯ ЗАВИСИМОСТИ ПОРОГОВОГО НАПРЯЖЕНИЯ И ПЕРЕКЛЮЧЕНИЯ, ОБУСЛОВЛЕННОГО ЭКРАНИРИЮЩИМ ЭФФЕКТОМ И ЭФФЕКТОМ ПУЛЯ-ФРЕНКЕЛЯ ПРИМЕНЕНИЕМ К СТРУКТУРАМ GaAs С ПРИМЕСЬЮ ХРОМА

В работе найдены зависимости порогового напряжения переключения и незатухающих электрических полей в случае, когда регулируемое током отрицательное сопротивление в частично компенсированных полупроводниках обусловлено сочетанием экранирующего эффекта и эффекта Пуля-Фенкеля. Главное внимание при этом уделено температурной и компенсационной зависимостям этих полей. Показано, что существует критическая температура, выше которой отрицательное сопротивление не может наблюдаться. Полученные теоретические результаты успешно применены к температурным зависимостям статического порогового напряжения структур GaAs(Cr), измеренным в темноте для области температур 90—230 K.

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I. INTRODUCTION

Sandomirski et al. [1] have proposed a model for the switching effect in semiconductors due to electron concentration and electric field dependences of the donor ionization energy. Several papers of one of the authors of the present paper are also devoted to this model [2—5]. However, according to our knowledge, this model has not yet been applied in any concrete case. From the experimental point of view the temperature dependences of the voltage which limit the range of negative resistance of the "S"-type current-voltage characteristics can be used for the verification of the particular model, since various mechanisms leading to the switching effect are distinguished not only by various values of the threshold and sustain fields but also by their temprerature dependences. We therefore concentrate in the present paper upon the theoretical temperature dependences of the threshold (E_{th}) and sustain (E_s) electric fields in the model based on the release of electrons from donors (or electron traps) enhanced by an electric field and by the screening influence of conduction electrons. The main reason for the "S"-type current-voltage characteristic is the electric field dependence of the carriers concentrations. When the switching effect occurs due to the rapid rise of electron concentration n at such high electric fields that the electron drift velocity becomes saturated, the turning points of the "S" characteristics are given by the relation

$$\left(\frac{\mathrm{d}E}{\mathrm{d}n}\right)_{n=n_{th},\,n_s}=0, \tag{1}$$

where n_{th} and n_s are the threshold and sustain electron concentrations, respectively. The electric fields at which $n=n_{th}$ and $n=n_s$ are denoted as E_{th} and E_s, respectively.

Since the considered model is based on the delocalization of electrons by an applied electric field, it is obvious that the substantial change of electron concentration is possible in the low temperature range when only few electrons are thermally delocalized. This means that the condition

$$\frac{\varepsilon_D^0}{k_B T}\gg 1, \tag{2}$$

where ε_D^0 is the ionization energy of unscreened donors in low applied electric fields, should hold. The screening effect of conduction electrons on the donor ionization energy at low temperature and low electric fields is rather weak. However, with an increasing electric field the screening effect in the considered model becomes essential, since the Poole-Frenkel effect alone never leads to the switching effect.

Using reasonable approximations we shall derive (in Sect. II) the formula for the temperature and compensation dependences of the threshold and sustain fields which we shall apply (in Sect. III) to our own experimental results gained on the semi-insulating GaAs(Cr) structures in the dark in the temperature range 90—230 K.

II. THEORY

In our previous paper (5) we computed the electric field dependences of the current density $j=env_d$ in a partly compensated n-type semiconductor when the electron concentration in the stationary state is given by the relation

$$\frac{n(n+N_A)}{N_D-N_A-n}=\frac{1}{2}N_c\exp\left(-\frac{\varepsilon_D}{k_B T}\right) \tag{3}$$

and the donor ionization energy of the screened coulombic centrum in the applied electric field is given by the relation

$$\varepsilon_D(n,E)=\varepsilon_D^0\left[(1-\varkappa a_1\exp(-\varkappa a_1)-4\frac{E/E_0}{[E/E_0+\frac{1}{2}(\varkappa a_1)^2]^{1/2}}\right]. \tag{4}$$

Here $\varkappa$ is the Debye-Hückel screening parameter,

$$\varkappa a_1=\left(\frac{e^2 n}{\epsilon k_B T}\right)^{1/2} a_1=\left(8\pi a_1^3 n\frac{\varepsilon_D^0}{k_B T}\right)^{1/2}, \tag{5}$$

$$\varepsilon_D^0=\frac{e^2}{8\pi\epsilon a_1}=\frac{\hbar^2}{2m^* a_1^2} \tag{6}$$

is the ionization energy of the unscreened donor in the weak electric field, m^* is the electron effective mass, ϵ is the effective dielectric constant, a_1 is the effective Bohr radius,

$$E_0=\frac{e}{4\pi\epsilon a_1}=\frac{2\varepsilon_D^0}{e\hbar}(2m^*\varepsilon_D^0)^{1/2}, \tag{7}$$

$$N_c=2(m^* k_B T/2\pi\hbar^2)^{3/2}=\frac{1}{4\pi^{3/2}a_1^3}\left(\frac{k_B T}{\varepsilon_D^0}\right)^{3/2}. \tag{8}$$

N_D and N_A are the donor and acceptor concentrations, respectively.

In the case of low screening, i.e. if

$$(\varkappa a_1)^2\ll 1, \tag{9}$$

and a high electric field, i.e. if

$$E/E_0\gg\frac{1}{2}(\varkappa a_1)^2, \tag{10}$$

the screening influence of the conduction electrons on the ionization energy can be expressed as

$$\varepsilon_D(n)=\varepsilon_D^0\left[1-2\varkappa a_1+\frac{3}{2}(\varkappa a_1)^2\right] \tag{11}$$

and the maximum barrier lowering due to the applied electric field is

$$\Delta\varepsilon=\varepsilon_D^0\left(\frac{16E}{E_0}\right)^{1/2}=\left(\frac{e^3}{\pi\epsilon}\right)^{1/2}E^{1/2}, \tag{12}$$

which is the well-known Poole-Frenkel formula.

At sufficiently low temperature, when $n/N_D \ll K=N_A/N_D$, the relation (3) can be approximated by

$$n=\frac{1}{2}N_c\,\frac{1-K}{K}\exp\left(-\frac{\varepsilon_D(n)}{k_BT}\right)\frac{2+\cosh(\Delta\varepsilon/k_BT)}{3}, \tag{13}$$

where the orientational dependence of the barrier lowering due to the applied electric field has been taken into account in an approximation introduced by Adamec and Calderwood [6]. However, if

$$\frac{\Delta\varepsilon}{k_BT}=\frac{\varepsilon_D^0}{k_BT}\left(\frac{16E}{E_0}\right)^{1/2}\gg 1, \tag{14}$$

we can write

$$\frac{2+\cosh(\Delta\varepsilon/k_BT)}{3}\doteq\frac{1}{6}\exp\left[\frac{\varepsilon_D^0}{k_BT}\left(\frac{16E}{E_0}\right)^{1/2}\right]. \tag{15}$$

Then the electric field dependence of the electron concentration is given by the transcendental equation

$$n=\frac{1}{64\pi^{3/2}a_1^3}\left(\frac{k_BT}{\varepsilon_D^0}\right)^{3/2}\frac{1-K}{K}\exp\left(-\frac{\varepsilon_D}{k_BT}\right), \tag{16}$$

where

$$\varepsilon_D=\varepsilon_D^0\left[1-2\varkappa a_1+\frac{3}{2}(\varkappa a_1)^2-\left(\frac{16E}{E_0}\right)^{1/2}\right]>0. \tag{17}$$

The calculated na_1^3 versus $16E/E_0$ dependences in the case $\varepsilon_D^0/k_BT=25$, and $K=0.01$ or 0.14, are shown in Fig. 1. As can be seen from this figure the range of negative values of dn/dE is limited either by the values of E_s and E_{th}, or by the value $E(\varepsilon_D=0)$ and E_{th}. The voltages which limit the region of negative differential resistance in the current-voltage characteristics are denoted as V_{th} and V_m, where $V_{th}=E_{th}d$ and V_m is equal either to E_sd or to $E(\varepsilon_D=0)d$, d being the distance between contacts on the sample.

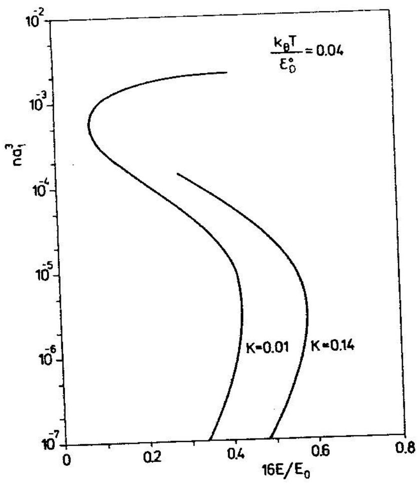

Fig. 1. The calculated na_1^3 versus the $16\ E/E_0$ dependences in the case $k_BT/\varepsilon_D^0=0.04$ and $K=0.01$ or 0.14.

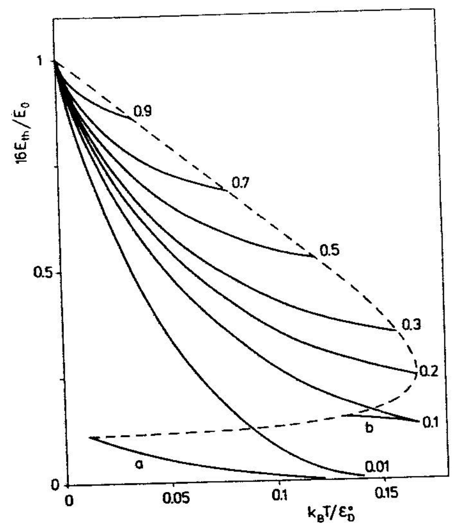

Fig. 2. The calculated $16\ E_{th}/E_0$ versus the k_BT/ε_D^0 dependences for various values of K. The dashed curve corresponds to Eq. (23). The curves "a" and "b" correspond to the $16\ E_a/E_0$ dependences for $K=0.01$ and 0.1, respectively.

The derivative of eq. (16) with respect to n, using condition (1), gives the equation

$$144\pi^2\left(\frac{\varepsilon_D^0}{k_BT}\right)^2(a_1^3n)^2+8\pi\left[3-\frac{\varepsilon_D^0}{k_BT}\right]a_1^3n+\left(\frac{k_BT}{\varepsilon_D^0}\right)^2=0, \tag{18}$$

which has two positive roots

$$n_{s,th}=\frac{1}{36\pi a_1^3}\frac{k_BT}{\varepsilon_D^0}\left[1-3\frac{k_BT}{\varepsilon_D^0}\pm\left(1-6\frac{k_BT}{\varepsilon_D^0}\right)^{1/2}\right], \tag{19}$$

corresponding to the fields E_s and E_{th}, respectively, if

$$\frac{\varepsilon_D^0}{k_BT}\geqslant 6. \tag{20}$$

(The minus sign in front of the square root term in (19) belongs to n_{th}.)

With the use of the relation (19) we get from (16)

$$\frac{16E_{s,th}}{E_0}=\left\{1-\frac{k_BT}{\varepsilon_D^0}\ln\left[\frac{1}{8\sqrt{\pi}}\frac{1-K}{K}\left(\frac{k_BT}{\varepsilon_D^0}\right)^{1/2}\frac{1}{(\varkappa_{s,th}a_1)^2}\right]-2\varkappa_{s,th}a_1+\frac{3}{2}(\varkappa_{s,th}a_1)^2\right\}^2, \tag{21}$$

where $\varkappa_{s,th}a_1$ is (in accordance with relation (5) and (19))

$$\varkappa_{s,th}a_1=\left[\frac{2}{9}\left(1-3\frac{k_BT}{\varepsilon_D^0}\pm\left(1-6\frac{k_BT}{\varepsilon_D^0}\right)^{1/2}\right)\right]^{1/2}. \quad (22)$$

$(\varkappa_{th}a_1)^2$ reaches the maximum value of 1/9 at the temperature $T_c=\varepsilon_D^0/6k_B$. At low temperatures, when $k_BT/\varepsilon_D^0 \ll 1$, there approximately holds $(\varkappa_{th}a_1)^2 = (k_BT/\varepsilon_D^0)^2$. Thus the condition (9) is for the threshold concentration well fulfilled if condition (2) holds. On the other hand, $(\varkappa_s a_1)^2$ varies from 4/9 at $T=0$ to 1/9 at $T=T_c$.

We have also to remember that ε_D should be always positive. This leads to the condition

$$\frac{16E_{s,th}}{E_0}\leqq\left[1-2\varkappa_{s,th}a_1+\frac{3}{2}(\varkappa_{s,th}a_1)^2\right]^2. \quad (23)$$

With this restriction, the temperature dependences of E_{th} and E_s for various compensation ratios are shown in Fig. 2. The dashed curve corresponds to eq. (23). It can be seen that in any case (in our model) the negative resistance cannot occur above the temperature T_c. The critical temperature decreases with increasing compensation ratio for $K>0.2$. The threshold field increases with decreasing temperature. The temperature dependence of E_s in Fig. 2 is shown only for $K=0.01$ *and* $K=0.1$, since for higher compensation ratios ε_D becomes negative before the turning point E_s of the "S" characteristic is reached, as shown in Fig. 1. The lower the compensation ratio is, the lower are the temperatures for which the derived formulas are applicable, since we have used the formula for electron concentration which is valid if

$$\frac{a_1^3n}{a_1^3N_D}\ll K, \quad (24)$$

and $a_1^3N_D$ should be less than 0.3 to avoid the Mott transition without the applied electric field.

III. THE TEMPERATURE DEPENDENCE OF THE STATIC THRESHOLD VOLTAGE OF GaAs(Cr) STRUCTURES

We measured the static threshold voltage V_{th} and minimum voltage V_m for the occurrence of negative resistance in semiinsulating GaAs(Cr) samples in the dark in the temperature range 90—300 K. The samples were prepared from GaAs(Cr) slices of a thickness of about 100 μm with an area 2 × 2 mm^2 by alloying In contacts with an area of 0.2 mm^2 on both sides. Due to alloying, the actual distance among the contacts (d) was smaller that the original thickness of the slice. The experimental values of the threshold voltage in a typical sample are marked in Fig. 3 by full circles. The curve denoted by V_{th} corresponds to the formula

$$V_{th}=E_{th}d, \quad (25)$$

where E_{th} is given by the formula (21), and the following values of parameters were used: $m^*=0.067m_0$ (electron effective mass in GaAs), $\varepsilon_D^0=0.2$eV, $K=0.14$, $d=40$ μm.

The value of 0.2 eV corresponds to the donor (or electron trap) level, the occupation of which in illuminated GaAs(Cr) is according to Vorob'ev et al. [7] very sensitive to the applied electric field. In a paper by Martin et al. [8] several

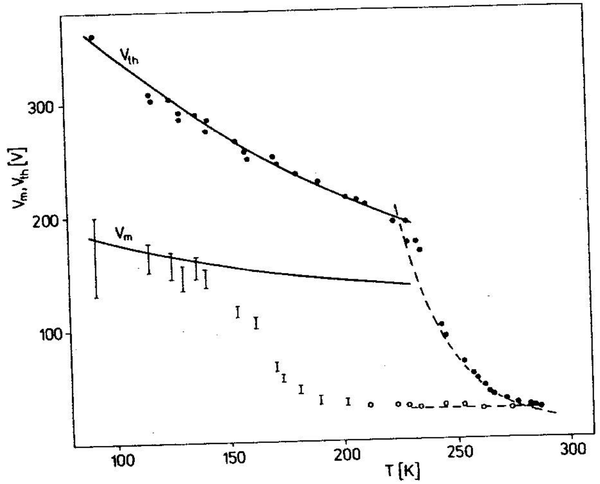

Fig. 3. Temperature dependences of V_{th} and V_m in a GaAs(Cr) structure. Experimental values of V_{th} are denoted by full circles. Experimental values of V_m are denoted by empty circles or vertical abscissa. Curves V_{th} and V_m were calculated with the following values of parameters: $\varepsilon_D^0=0.2$ eV, $m^*=0.067m_0$, $K=0.14$. $d=40$ μm.

electron traps in GaAs samples prepared by various technologies are identified with activation energies in the range 0.17—0.225 eV. We suppose that at a low electric field in semiinsulating GaAs(Cr) in the dark the 0.2 eV traps are empty but with increasing injection become partly occupied. A further rise of the electric field can lead to the switching effect due to the delocalization of electrons trapped on this level according to the mechanism discussed in this paper.

With the same values of the parameters we computed the temperature dependence of the voltage V_m which corresponds to $\varepsilon_D=0$. (the curve denoted by V_m in Fig. 3). The large discrepency from experimental results may be due to the heating effect connected with the transition to the low resistivity state. While the reproducibility of V_{th} measurements at the given temperature was very good, at low temperature we could determine only a rough value of V_m, as indicated in Fig. 3.

At temperatures below 230 K, k_BT/ε_D^0 is smaller than 0.1. The electric field

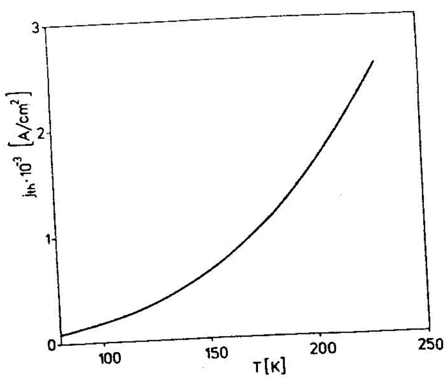

Fig. 4. The calculated temperature dependence of j_{th} corresponding to the curve V_{th} in Fig. 3.

corresponding to the curve V_{th} in Fig. 3 varies from 9×10^4 v/cm (at 90 K) to 5×10^4 V/cm (at 220 K). These values are lower than the value of the electric field necessary for the impact ionization of the 0.2 eV donor in GaAs (this is according to [7] about 10^5 V/cm), but are high enough for the saturation of the electron drifts velocity in GaAs. This justifies the use of condition (1) for the determination of the threshold voltage on the measured current-voltage characteristic. According to Houston and Evans [9] the saturated electron drift velocity in GaAs is given by the relation

$$v_{sat} = 2\left(\frac{2}{3\pi}\right)^{1/2} \frac{\hbar\omega_{ij}}{M} \left(\frac{\exp\frac{\hbar\omega_{ij}}{k_B T} - 1}{\exp\frac{\hbar\omega_{ij}}{k_B T} + 1}\right)^{1/2} \quad (26)$$

with $\omega_{ij} = 4.54 \times 10^{13}$ rad/sec and $M = 0.35$ m_0. Using thas relation and the relation (19) with $\varepsilon_D^0 = 0.2$ eV, $a_1 = \hbar/(2m^*\varepsilon_D^0)^{1/2} = 1.68 \times 10^{-7}$ cm, we get for the threshold current density

$$j_{th} = e n_{th} v_{sat} \quad (27)$$

the temperature dependence shown in Fig. 4. As can be seen, the values of j_{th} are rather high (1.2×10^2 A/cm^2 at 90 K and 2.2×10^3 A/cm^2 at 220 K). Since the currents corresponding to V_{th} below 230 K were less than 10^{-9} A, our model can be consistent only if the current flowed through a very narrow filament (diameter of 10^{-6} cm). We have not been able to resolve this problem experimentally.

In the temperature range above 230 K the conditions under which the formula (21) holds are not well fulfilled. However, the experimental results in this range suggest that another mechanism of switching effect becomes predominant, because the temperature dependence of the threshold voltage is quite different. This mechanism is distinguished by an exponential decrease of the threshold voltage and an exponential increase of the threshold current with increasing temperature.

IV. CONCLUSION

We have shown that by the use of reasonable approximations an analytical formula can be found for the switching voltage in a model based on the concentration and electric field dependences of the donor ionization energy. According to this formula the threshold voltage slowly decreases with increasing temperature. The threshold voltage is sensitive to the compensation ratio K. The threshold current density is rather high and slowly increases with increasing temperature. The high threshold current density suggests that a non-ohmic current flows through a narrow filament.

The main condition for the application of our model is $k_B T/\varepsilon_D^0 \ll 1$. This demands either a very low temperature or sufficiently deep donors. We have shown that our theoretical results can be successfully applied to some GaAs(Cr) structures in the temperature range 90—230 K, due to the presence of electron traps with an ionization energy of about 0.2 eV, which have been identified in GaAs by other authors.

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