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# *PHENOMENOLOGICAL THEORY OF CONCENTRATION INSTABILITY IN SEMICONDUCTORS*

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A theory of instability phenomena is developed on the basis of notions regarding a controllable electronic phase transition due to the dependence of local level depth on the free electron concentration. In order for this instability to be manifest in the volt–ampere characteristic (VAC), a "priming" concentration of free electrons produced by an electric field or power is required. The cases are considered when the priming carrier concentration is created by the Frenkel–Pool effect (thermoionization of centers made easier by an electric field) in a semi-insulator with donors, or by carrier injection into a dielectric with traps. The VAC obtained can explain the memory and switching phenomena observed, for example, in glassy semiconductors.[1-5] A thermodynamic analysis of the equilibrium state of a semiconductor with donors is performed, and a phase diagram of the states of semiconductor electron gas is plotted with the temperature and donor concentration as coordinates. The diagram describes the semiconductor–metal phase transition and yields, in particular, a natural explanation of the memory effect.

A summary of conclusions of the theory is presented and a comparison with the available experimental facts is carried out. It is suggested that experiments involving the field effect can be employed to distinguish the instability mechanism under consideration from those which essentially depend on the passage of current. Layers with opposite space-charge signs may alternate near the surface in a semi-insulator with donors in the case of the field effect; discontinuous changes in the dependence of longitudinal electric conductivity on external transverse field should be observed in this case.

## 1. INTRODUCTION

At the present time, interest is exhibited in metal—thin amorphous semiconductor layer–metal sandwich systems, in which S-shaped volt-ampere characteristics (VAC) and memory effects are observed.[1-5] These systems are quite promising for applications. Yet the physical mechanism of their action is not clear.

The observed instability phenomena, especially memory effects, are apparently difficult to interpret on the basis of the known instability mechanisms. The superheat mechanisms,[6] although not completely excluded, have low probability because of the very low mobility of the carriers. The double-injection mechanism[7] is also little likely, owing to the insensitivity of the VAC to the electrode material. In addition, a similar instability was observed in [8] in the case of field emission into vacuum from a tungsten needle coated with vitreous quartz doped with carbon. Such a measurement procedure, in principle, excluded double injection. We assume that these instability phenomena can be explained on the basis of the concept of an electronic phase transition due to the change of the concentrations of the free and bound carriers. Namely, we assume that the increase of the concentration of the free electrons leads to a shift and to a vanishing of the local levels (or the narrow band), described by the relation

$$E = E^0 - \frac{n}{\bar{n}} kT, \tag{1}$$

Here E is the activation energy of the local states, n is the density of the free electrons, and $\bar{n}$ is the characteristic density due to the decrease of E by kT.

The concentration effect may be connected, for example, with the screening of the local states by the free carriers.[9, 10] A relation similar to (1) was proposed in [11] on the basis of the mechanisms of antiferromagnetic ordering and lattice deformations to explain the semiconductor–metal transition in oxides and sulfides of transition metals.

Thus, expression (1) should be regarded as a general phenomenological relation, in which the value of the characteristic constant n is determined by the concrete form of the collective interaction.[1]

Of course, relation (1) is based on a model and describes only qualitatively the complicated situation that takes place, for example, as a result of the overlap of the wave functions of the local states and formation of the impurity band, both in the initial state at large center concentration, and in the case of the "pulling" of the local levels.

If the concentration effect operates in a system with sufficiently large center concentration, then any "priming" mechanism whereby the concentration of the free carriers is increased leads to the appearance of instability. In particular, if we talk of the instability of the VAC, such a mechanism may be injection of carriers

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[1] In the particular case when the concentration effect (1) is determined by the screening of hydrogenlike local centers by a nondegenerate gas of free electrons we have $\bar{n} = m\epsilon(kT)^2/2\pi\hbar^2 q^2$, where m is the effective mass of the electron.

from the contacts,[2] the Frenkel–Pool effect (thermoionization of the donors, facilitated by a strong electric field), autoionization of the donors, superheat processes (for example, impact ionization), ionization due to Joule heating, etc. We shall consider in detail as examples of the volume and contact "priming" mechanism, the Frenkel–Pool effect in a semi-insulator with donors, and the injection of carriers into a dielectric with traps. Both these phenomena are frequently observed in high-resistance layers, particularly in glass-like semiconductors.[14-17]

## 2. THE FRENKEL–POOL EFFECT IN A SEMI-INSULATOR WITH DONORS

In a semiconductor with weakly ionized donors (semi-insulator), the role of the priming mechanism that supplies free carriers may be the Frenkel–Pool effect, namely thermoionization of the donors facilitated by a strong electric field. The problem is homogeneous and the system of equations defining the VAC consists (using dimensionless quantities) of an expression for the current

$$j = nF, \tag{2}$$

the electroneutrality equation

$$N_d - n_d - n = 0, \tag{3}$$

where the concentration of the filled donors is

$$n_d = \frac{N_d \theta(E_d)}{1 + (N_c/n)\exp(-E_d)} \tag{4}$$

Here $N_d$ is the donor concentration, $N_c$ is the effective density of the states in the conduction band,

$$\theta(E_d) = \begin{cases} 1, & E_d > 0 \\ 0, & E_d < 0 \end{cases}$$

The units of energy current, and field are

$$\tilde{E} = kT, \quad \tilde{j} = q\mu\tilde{N}\tilde{F}, \quad \tilde{F} = \frac{kT}{q\tilde{x}}, \quad \tilde{x} = \left(\frac{\varepsilon kT}{4\pi q^2 \tilde{N}}\right)^{1/2}. \tag{5}$$

Here q is the electron charge, $\mu$ the electron mobility, $\epsilon$ the dielectric constant, T the temperature, and $\tilde{N}$ an arbitrary unit of concentration.

The level shift, with allowance for the Frenkel–Pool effect, is written in the form

$$E_d = E_d^0 - (F/\bar{F})^{1/2} - n/\bar{n}, \tag{6}$$

where the characteristic field in dimensional units is given by $\bar{F}^* = \epsilon(kT)^2/q^3$. After simple transformations we can easily obtain an equation for the volt-ampere characteristics j(F):

$$\frac{j}{F}\left\{N_d[1-\theta(E_d)] - \frac{j}{F}\right\} + \left(N_d - \frac{j}{F}\right)N_c \exp(-E_d) = 0. \tag{7}$$

The equation $E_d = 0$ defines on the (j, F) plane a curve

$$j = \bar{n}F[E_d^0 - (F/\bar{F})^{1/2}], \tag{8}$$

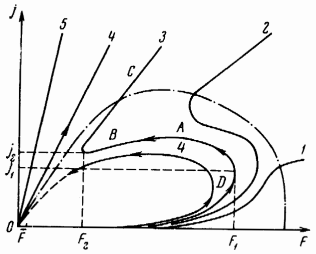

FIG. 1.

shown by the dash-dot curve of Fig. 1. Outside this curve is located the region of "metallic" conductivity, and the VAC has, in accordance with (7), the form

$$j = N_d F. \tag{9}$$

The region of semiconductor conductivity is bounded by the curve (8) and by the F axis. Inside this region, the VAC is described, in accordance with (7), by the equation

$$\left(\frac{j}{F}\right)^2 - \left(N_d - \frac{j}{F}\right)N_{cd}^0 \times \exp\left[\left(\frac{F}{\bar{F}}\right)^{1/2} + \frac{j}{\bar{n}F}\right] = 0, \tag{10}$$

where $N_{cd}^0 = N_c \exp(-E_d^0)$. An analysis of expression (10) enables us to find the characteristic J(F) plots inside the region (8). The total VAC are obtained by continuing these curves as straight lines (9) outside the region (8). A VAC family is shown qualitatively in Fig. 1. The parameter of the family is the donor concentration $N_d$, which increases with increasing number of the curve. Moving along a definite VAC in the direction indicated by the arrow in Fig. 1, the system passes through all the states with continuously increasing concentration of the free electrons n. This becomes obvious if the VAC are intersected by the straight lines $j/F = n = \text{const}$.

In the region of weak fields $F < \bar{F}$ all the j(F) plots are linear. At small $N_d < \bar{n}$ the concentration effect is negligible and the resultant VAC is the one customarily obtained for the Frenkel–Pool effect (curve 1). With increasing $N_d$, the VAC retain their monotonic character up to $N_d = (3 + 2\sqrt{2})\bar{n}$, when a VAC with one vertical tangent appears. In the region

$$(3 + 2\sqrt{2})\bar{n} < N_d < \left(E_d^0 - \ln\frac{N_c}{\bar{n}}\right)\bar{n}$$

there appear VAC of the usual S-type (curve 2) and of the S-type with a section AB in which the current decreases (curve 3). The negative differential resistance on the VAC of the type of curve 2 appears as a result of the concentration dependence of the level depth. The coordinates of the extremal points for the VAC of the usual S-type and of the S-type with decreasing current are determined by the expressions

$$F_1 = \left[\ln\frac{n_1^2}{(N_d - n_1)N_{cd}^0} - \frac{n_1}{\bar{n}}\right]^2 \bar{F}, \quad j_1 = n_1 F_1, \tag{11a}$$

$$F_2 = \left[\ln\frac{n_2^2}{(N_d - n_2)N_{cd}^0} - \frac{n_2}{\bar{n}}\right]^2 \bar{F}, \quad j_2 = n_2 F_2, \tag{11b}$$

where

$$n_{2,1} = \frac{N_d + \bar{n}}{2} \pm \sqrt{\frac{(N_d + \bar{n})^2}{4} - 2N_d\bar{n}}. \tag{12}$$

When $N_d \gg 6\bar{n}$ we get $n_2 \approx N_d - \bar{n}$ and $n_1 \approx 2\bar{n}$. We note immediately that expression (11a) determines the

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[2] The concentration instability occurring upon injection was considered by us briefly in [12] for the simplest "capacitor" model of space-charge limited currents (SCLC). In a somewhat later paper [13] a relation similar to (1) was postulated with a reference to [11] for a description of the effects of switching in glass-like semiconductors. It was assumed there that the current transport is by the Zener mechanism.

coordinates of the threshold point $(F_1, j_1)$ in the case of loop-like VAC (see below).

When moving along the curve 3, the state of the semi-insulator changes in the following manner: on the section OA the Fermi quasilevel lies above the donor level. The donors are weakly ionized and their attraction to the bottom of the conduction band is connected mainly with the action of the Frenkel–Pool effect. On the section AB, owing to the concentration mechanism, the donor level $E_d$ moves rapidly towards the edge of the conduction band and crosses the Fermi quasi-level. Therefore the concentration of the free electrons n increases catastrophically. In order for the system to be able to pass continuously through all the possible states, the field F in the semi-insulator should decrease, and strongly enough so that the current also decreases (if the donor concentration $N_d$ is large enough).

On the section BC, the pulling of the donor level towards the edge of the conduction band at a result of both mechanisms terminates, the concentration n changes little, and the VAC becomes gradually ohmic, with metallic conductivity beyond the limits of the dashed region.

The interval

$$\left(E_d{}^0 - \ln\frac{N_c}{\bar{n}}\right)\bar{n} < N_d < \frac{4}{e^2}\frac{\bar{n}^2}{N_{cd}{}^0}$$

corresponds to loop-like VAC such as curve 4. It is remarkable that these curves have states with different conductivity at zero field. This leads to a possible mechanism of "electric" memory, observed for example in amorphous materials.[3,5]

Finally, when $N_d \geq 4\bar{n}^2/e^2N_{cd}^0$, the equilibrium concentration of the free electrons turns out to be sufficient for the vanishing of the bound states, and VAC are realized of the type of the straight line 5, corresponding to "metallic" conductivity.

The described VAC were obtained under the assumption that the space-charge density $\rho(n) = 0$; this assumption is violated, for example, if the concentration at the contacts differs from the concentrations in the interior of the sample. Allowance for the space charge greatly modifies the unstable sections of the VAC. It can be shown that the contact conditions forbid the existence of part of the segment OD on curve 4 (the dashed line in Fig. 1). At the same time, a new branch of the VAC, emerging from the origin can appear in some interval of contact concentrations and for definite sample parameters.

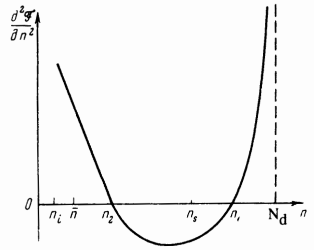

FIG. 2. Plot of the function $\partial^2\mathfrak{F}/\partial n^2$.

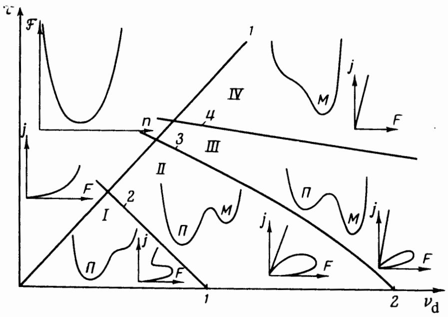

FIG. 3. State diagram of an electron gas in a semi-insulator with donors. The free energy $\mathfrak{F}$(n) and the VAC [j(F)], which are characteristic of each region, are shown.

## 3. MEMORY EFFECT

For a deeper understanding of the memory effect, let us carry out a thermodynamic analysis of the stability of different possible states of a semi-insulator with donors in the absence of current.

It is easy to verify that the expression for the free energy (we use henceforth dimensional quantities)

$$\mathcal{F} = \mathcal{F}_0 + nE_d{}^0 - \frac{n^2}{2\bar{n}}kT - N_d kT\ln\frac{N_d}{N_d - n} + nkT\ln\frac{n^2}{(N_d - n)N_c} - nkT \tag{13}$$

leads to the equation of state

$$\frac{\partial\mathcal{F}}{\partial n} = E_d + kT\ln\frac{n^2}{(N_d - n)N_c} = 0,\quad E_d = E_d{}^0 - \frac{n}{\bar{n}}kT, \tag{14}$$

from which follows an expression for the concentration n, identical with that obtained from (3) and (4). According to Sec. 2, when

$$\bar{n}\ln\frac{\bar{n}}{N_{cd}{}^0} < N_d < \frac{4}{e^2}\frac{\bar{n}^2}{N_{cd}{}^0}$$

Eq. (14) has three roots corresponding to the extrema of $\mathcal{F}$:

$$n = n_i \approx (N_d N_{cd}{}^0)^{1/2},$$

$$n = n_s \approx 2\bar{n}\ln(\bar{n}/n_i),\quad n = N_d.$$

The stability of these states is determined by the sign of the second derivative

$$\frac{\partial^2\mathcal{F}}{\partial n^2} = \frac{kT}{\bar{n}}\frac{n^2 - n(N_d + \bar{n}) + 2N_d\bar{n}}{n(N_d - n)} \tag{15}$$

a plot of which is shown in Fig. 2. The roots of the equation $\mathcal{F}''(n) = 0$ are given by expression (12). It is seen from the figure that the states with $n = n_1$ and $n = N_d$ correspond to minima of $\mathcal{F}$, and the state with $n = n_s$ corresponds to a maximum of $\mathcal{F}$. The stability or metastability of the semiconducting ($n = n_i$) and metallic ($n = N_d$) state is determined by the sign of the expression

$$\Delta\mathcal{F} = \mathcal{F}(N_d) - \mathcal{F}(n_i) = N_d\left[E_d{}^0 - \frac{N_d}{2\bar{n}}kT\left(1 + \frac{n_i{}^2}{N_d{}^2}\right) + kT\ln\frac{N_d{}^2}{(N_d - n_i)N_c} - kT\left(1 - \frac{n_i}{N_d}\right)\right].$$

Figure 3 shows qualitatively a diagram of states obtained on the basis of an analysis of relations (13)–(16), and plotted in the coordinates $\tau = kT/E_d^0$ and $\nu_d = N_d/\bar{n}$. Here $\bar{n} = \bar{n}E_d^0/kT$ is the free-electron concentration, at which the bound states disappear. We assume that the product $\bar{n}E_d^0/kT$ does not depend on the temperature. Above the line 1 ($\nu_d = (3 + 2\sqrt{2})\tau$), according to (15), there is located a region in which $\mathcal{F}''(n) > 0$, i.e., the free energy F(n) has no inflection points and possesses only one minimum. The VAC corresponding to this region have no singularities.

Region I, bounded by the curves 1 and 2 ($\nu_d = n_s/\bar{n}$, i.e., $\nu_d = 1 - \tau \ln(\nu_c/\tau)$, $\nu_c = N_c/\bar{n}$) and the abscissa axis is a region of only semiconductor (S) states. (The free energy has one minimum with $n = n_i$ and inflection points, and the VAC corresponding to this region have an S-shape.) In region II, bounded by curves 1, 2, 3 ($\Delta\mathcal{F} = 0$, $N_d \approx 2n_s$) and the abscissa axis, there exist on the $\mathcal{F}(n)$ curve two minima with $n = n_i$ (stable semiconductor (S) state) and $n = N_d$ (metastable metallic (M) state). In region III under curve 4 ($n_i = \bar{n}$, i.e., $\nu_d = (\tau^2/\nu_c)\exp(1/\tau)$) the situation is reversed. Regions II and III correspond to loop-like VAC. Region IV is characterized by a free energy that has inflection points at single maximum with $n = N_d$ (metallic state). The corresponding VAC have an ohmic character with concentration $n = N_d$.

The existence on the phase diagram of regions II and III with two stable states makes it possible to explain in natural fashion the memory effect. Indeed, in region II the semiconducting minimum of the free energy lies below the metallic minimum. Therefore, if the system is converted by the electric field into a metastable metallic state, it can be easily returned to a more stable state, i.e., one can say that the system has a readily erasable (reversible memory). In region III, the metallic minimum is stable and the return of the system to the initial semiconducting state (erasure) calls, generally speaking, for a special action (irreversible memory). We note that by varying the temperature and concentration of the donors it is possible to transfer the sample from one band to another, and consequently from a state "without memory" into a state with "memory" and vice versa.

The switching effect due to the presence of an S-type VAC and loop-type VAC (Sec. 2) is an electronic phase transition of first order, controlled by the electric field that transfers the system from regions I and II into region IV. In the case when the double shift is due to the screening by the free carriers, the switching effect can be interpreted as a Mott phase transition[18] induced by the Frenkel–Pool effect. In fact, assume that in the absence of the external field there is satisfied the Mott condition of stability of the semiconducting state:[19]

$$r_{\text{scr}}(N) / a_{\text{car}} > \lambda, \tag{17}$$

where for Debye screening, $r_{\text{scr}} = (\epsilon kT/4\pi q^2 N)^{1/2}$, $a_{\text{car}}$ is the characteristic dimension of localization of the wave function (the Bohr rays at F = 0), and $N = N_d$ is the total concentration of the free and bound electrons, and $\lambda$ = const (~1).

The Frenkel–Pool effect leads to a decrease of the activation energy and to an increase of $a_{\text{car}}$:

$$a_{\text{car}} = \frac{\hbar}{\{2mE_d(F)\}^{1/2}} = \frac{\hbar}{\{2m[E_d{}^0 - (F/\bar{F})^{1/2} kT]^{1/2}}. \tag{18}$$

Substituting $r_{\text{scr}}$ and $a_{\text{car}}$ in (17), we obtain the critical field at which the "metallic" and semiconducting states are equally stable (equal sign in (17)):

$$F_{\text{cr}} = \bar{F}\left[\frac{E_d{}^0}{kT} - \frac{N_d}{\bar{n}}\lambda^2\right]^2, \quad \bar{n} = \frac{m\varepsilon(kT)^2}{2\pi\hbar^2 q^2}. \tag{19}$$

It is easy to verify that when $\lambda = 1/\sqrt{2}$ the value of $F_{\text{cr}}$ coincides with the corresponding expression obtained for the critical field from a thermodynamic analysis with allowance for the level shift by the Frenkel–Pool effect.

## 4. INJECTION INTO A DIELECTRIC WITH TRAPS

The qualitative physical picture of instability upon injection into a dielectric with traps, with allowance for the concentration effect, is as follows. The electrons injected into the dielectrics are distributed between the conduction band and the trap level. At a definite voltage, when the concentration of the free electrons becomes sufficiently large, the concentration effect leads to a decrease of the depth of the level and to a cascade-like increase of the electron concentration in the conduction band as a result of the release of the traps. It is obvious that this effect leads to an S-type VAC.

The system of equations describing injection into a dielectric layer of thickness L consists of an expression for the current, in which we retain in accordance with the usual SCLC approximation[20] only the drift term (2), and the Poisson equation

$$dF/dx = -n - n_t. \tag{20}$$

The position of the trap level is given by the relation (1), $E_t = E_t^0 - n/\bar{n}$, and the concentration of the filled traps $n_t$ is given by formula (4), in which the index d must be replaced by t. The unit length $\tilde{x}$ is given in (5). The boundary condition is chosen to be the condition of the "virtual" cathode, F(0) = 0.

We assume for the characteristic values of the concentrations the following inequality, which is reasonable for dielectric layers with defects, and which are optimal for the development of the instability process: $N_t \gg \bar{n}, N_{ct}^0$. We approximate the function (4) with allowance for (1) in different regions of variation of n by means of straight-line segments. When $\bar{n} > N_{ct}^0$ and the concentration effect (screening) develops after complete filling of the traps (deep traps), we have

$$n_t = \begin{cases} pn, & n < N_{ct}{}^0, \\ N_t, & N_{ct}{}^0 < n < n_s, \\ 0, & n > n_s \end{cases} \tag{21}$$

where

$$p = N_t / N_{ct}{}^0, \quad N_{ct}{}^0 = N_c \exp(-E_t{}^0), \quad n_s \approx \bar{n} \ln(\bar{n}/N_{ct}{}^0)$$

is the effective concentration of the free electrons at which the trap levels are released as a result of screening.

If $\bar{n} < N_{ct}^0$, then the screening sets in already in the case of weak filling of the traps (shallow traps), and then

$$n_t = \begin{cases} pn, & n < n_s', \\ 0, & n > n_s', \end{cases} \tag{22}$$

where $n_s' = 2\bar{n}$.

Let us solve the problem for the case of deep traps. Since the electron concentration in the dielectric decreases in the direction from the cathode to the anode, it follows, generally speaking, that within the limits of the dielectric layer there will exist three regions: $0 \le x \le x_0$—region with "vanished" trap levels, $x_0 \le x \le x_1$—

region with completely filled traps, and $x_1 \le x \le L$—region with weakly filled traps. The characteristic points $x_0$ and $x_1$ are determined by the equations

$$n(x_0) = n_s, \quad n(x_1) = N_{ct}^0. \tag{23}$$

In the case of weak currents, all three regions are realized. With increasing current, the points $x_1$ and $x_0$ shift to the anode and vanish gradually, so that in the case of sufficiently strong currents the entire volume of the dielectric becomes "free" of the trap levels.

Accordingly, the entire current interval also breaks up into three sections:

$$0 \leqslant j \leqslant j_1, \quad j_1 \leqslant j \leqslant j_0, \quad j_0 \leqslant j.$$

The characteristic currents are determined by the relations

$$x_1(j_1) = L, \quad x_0(j_0) = L. \tag{24}$$

Solving the system of equations under the assumed approximations for all three regions of the dielectric, and joining together the solutions at the points $x_0$ and $x_1$, we obtain expressions for the limiting points $x_0$ and $x_1$, the characteristic currents $j_1$ and $j_0$, the field distribution F, and the dependence of the current on the external voltage V. We present only the VAC:

$$U = \begin{cases} J^2\left\langle \frac{3}{8}\frac{p}{g}\left(\frac{1}{J_1}-1\right)+\frac{3}{2}\left(\frac{1}{J_1}-\frac{1}{3}\right)+\frac{g^3}{p}\left\{\left[\frac{p}{g^2}\left(\frac{1}{J}-\frac{1}{J_1}\right)+1\right]^{3/2}-1\right\}\right\rangle, & J \leqslant J_1 \\ J^2\left\langle \frac{3}{8}\frac{p}{g}\left(\frac{1}{J}-1\right)+\frac{3}{2}\left(\frac{1}{J}-\frac{1}{3}\right)\right\rangle, & J_1 \leqslant J \leqslant 1, \\ J^{1/2}, & J \geqslant 1 \end{cases} \tag{25}$$

where

$$U = \frac{V}{V_0}, \quad J = \frac{j}{j_0}, \quad V_0 = \frac{4}{3}n_sL^2, \quad j_0 = 2n_s^2L,$$

$$J_1 = \frac{j_1}{j_0} = \frac{1}{1+2g^2/p}, \qquad p = \frac{N_t}{N_{ct}^0}, \qquad g = \frac{n_s}{N_{ct}^0}.$$

Here the current J is assumed to be positive.

The qualitative form of the VAC (25) is shown in Fig. 4 (curve 1) for the case of very deep traps, when $n_s^2 \gg N_tN_{ct}^0$ ($g^2 \gg p$). The coordinates of the extrema are determined here by the expressions

$$V_1 = \frac{3}{8}\frac{p}{g}V_0, \quad j_1 = \frac{1}{2}\frac{p}{g^2}j_0 \ll j_0, \quad V_2 = V_0, \quad j_2 = j_0. \tag{26}$$

In dimensional notation

$$V_0^* = \frac{16\pi q n_s^* L^{*2}}{3\varepsilon}, \qquad j_0^* = \frac{8\pi q^2\mu n_s^{*2}L^*}{\varepsilon},$$

$$V_1 = \frac{2\pi q N_t^* L^{*2}}{\varepsilon}, \qquad j_1^* = \frac{4\pi q^2\mu N_t^* N_{ct}^{0*} L^*}{\varepsilon}.$$

For the case of shallow traps, using expression (22) for $n_t(n)$ and proceeding in the same manner as in the analysis of the deep traps, we obtain expressions for the VAC:

$$U = \begin{cases} J^2\left\langle 1+\frac{1}{p}\left\{\left[1+p\left(\frac{1}{J}-1\right)\right]^{3/2}-1\right\}\right\rangle, & 0 \leqslant J \leqslant 1 \\ J^{1/2}, & J \geqslant 1 \end{cases}. \tag{27}$$

The coordinates of the extremal points are

$$V_1 = \frac{3\sqrt{3}}{16}p^{1/2}V_0, \qquad j_1 = \frac{j_0}{4}, \qquad V_2 = V_0 = \frac{4}{3}n_s'L^2,$$

$$j_2 = j_0 = 2n_s'^2L. \tag{26a}$$

The qualitative form of this VAC is shown in Fig. 4 (curve 2). We note that (27) is obtained from (25) if we put in the latter $g = 1$ ($N_{ct}^0 = n_s$), and with it $J_1 = 1$.

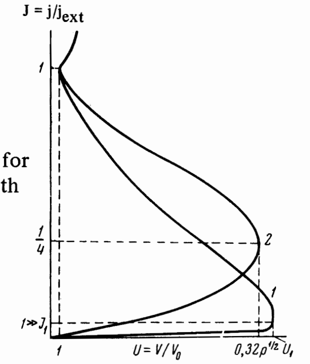

FIG. 4. Volt-ampere characteristics for the case of injection into a dielectric with traps: 1—deep traps, 2—shallow traps.

For the capacitor model of the SCLC, considered in [12], the threshold voltage corresponded to the average electron concentrations which the entire sample "metallizes." For the investigated model with distributed resistance, the threshold voltage corresponds, naturally, to metallization of only part of the sample, for example in the limiting case of a large number of shallow traps, only to one quarter of the sample.

If the concentration effect is due to screening, switching can be regarded as a Mott transition upon injection.

Indeed, as a result of the increase of the concentration of the electrons in the system and the decrease of the screening radius, the inequality sign in the Mott condition (17) is reversed, i.e., a transition to the "metallic" state becomes possible.

## 5. CONSEQUENCES OF THE THEORY. CRITICAL EXPERIMENT

It is useful to list the characteristic consequences of the developed theory and to indicate some obvious qualitative considerations that should be reflected in experiments.

1. The Frenkel–Pool mechanism. According to Sec. 2, in this case the high-resistance branch of the VAC should follow the usual Frenkel law

$$I \propto V \exp\left[-\frac{E_d^0 - q\sqrt{qV/\varepsilon L}}{kT}\right].$$

In the conducting state $I \propto V$ and depends on the temperature like the mobility. The threshold and the residual voltages $V_1$ and $V_2$ are proportional to L. However, if the contact concentrations of the electrons are lower than the concentrations in the volume for the conducting state, then $V_2$ may become independent of L. According to (11a), the threshold voltage decreases with increasing temperature.

The switching kinetics is determined by the self-accelerating (as a result of the concentration effect) process of ejection of electrons, and the total duration of this process, characterized by the switching delay time, turns out to be

$$\tau_{\text{scr}} \approx \frac{\bar{n}}{N_d}\frac{1}{\langle Sv\rangle N_c}\exp\left[\frac{E_d^0}{kT} - q\frac{(qV/\varepsilon L)^{1/2}}{kT}\right], \tag{28}$$

where v is the thermal velocity of the carriers, S is the cross section for capture by the donor centers, and $V > V_1$. We see from (28) that $\tau_{\text{del}}$ decreases rapidly with increasing overvoltage $V - V_1$. The switching time proper is determined by the ejection from very shallow "drawn" centers.

It is obvious that an alternating signal with frequency $1/\tau_{del}$ will not switch a system into the conducting state even when $V > V_1$. It is also clear that the presence of $\tau_{del}$ is connected with the finite time of ejection of the electrons when the levels are drawn, and this inertia of the system becomes manifest in the form of an inductive contribution to the reactive part of the impedance. More accurately, one should speak of a negative capacitance that is observed directly, in particular, in [21]. It follows naturally from this model that the memory effect, the mechanism of which was discussed in detail in Sec. 3 do exist.

Apparently the laws considered above are in best agreement with the experimental data obtained in [3, 5, 22].

2. Injection mechanism. According to Sec. 4, this mechanism on the high-frequency branch is characterized by VAC of the SCLC type in the presence of traps and by the presence of a conduction activation energy that depends on the voltage; in the conducting state, the activation energy should be zero, and the VAC should follow the SCLC law—quadratic in the case of unlimited injection from the contact, and linear if the current is limited by the contact.[20] Similar regularities of the switching effects were observed in tetracene.[23]

If follows also from this model that the threshold voltage $V_1$ depends quadratically on the sample thickness L. In the case of unlimited injection, the residual voltage is $V_2 \propto L^2$, and if the current is limited by the contact we have $V_2 \propto L$ and $V_2$ depends on the temperature like the contact concentration $n_{cont}$. In the case of deep traps the threshold voltage $V_1$ is independent of the temperature, whereas the threshold current increases exponentially ($\propto \exp(-E_t/kT)$), and in the case of shallow traps $V_1$ decreases exponentially with increasing temperature ($\propto \exp(E_t/2kT)$) and $J_1$ increases weakly with temperature.

The characteristic features of the considered instability mechanism should become manifest also in the dynamic properties of the system. Namely, at an alternating-signal frequency exceeding the reciprocal time of capture by the traps, and at an amplitude $V > V_2$, the injected electrons remain in the conduction band, so that the conducting state is immediately realized. It can be shown that in thin samples there can exist several conduction states, i.e., memory effects are possible.

3. Field effect. As the critical experiment for the identification of the concentration instability, an experiment is proposed with a field effect, making it possible to "cut off" all the instability mechanisms that are directly connected with the flow of current and with dissipation of energy.

An analysis shows that under the conditions of concentration instability there should be observed singularities compared with the usual field effect that becomes manifest in the distribution of the space charge and in the anomalous dependence of the longitudinal conductivity on the external transverse electric field $\sigma(F_{ext})$.

In systems with a memory effect, in which several equilibrium conductivity states exist, there should alternate near the surface layers with different signs of the space charge, and jumps should be observed on the $\sigma(F_{ext})$ dependence. The latter are connected with the fact that as the limiting field is monotonically varied, the continuity of the electric induction cannot be satisfied upon continuous variation of the concentration of the free electrons at the boundary.

Jumps of two types are possible. If the semiconductor is in a metastable state, then the entire sample can be switched by a transverse electric field into an absolutely stable state. On the other hand, if the sample was in an absolutely stable state, say semiconducting, then this jump is connected with the formation of only a near-surface metallic conductivity channel.

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