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POSSIBLE TYPE OF INSTABILITY IN MONOPOLAR INJECTION

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Submitted 18 December 1968
ZhETF Pis. Red. 9, No. 3, 201 - 203 (5 February 1969)

We shall show that the effect of vanishing of local levels upon screening by free carriers, predicted theoretically in [1] and observed experimentally in [2], can lead, in the case of monopolar injection from the contact (i.e., in the space-charge-limited current mode - SCLC), to an S-shaped current-voltage characteristic.

We consider a thin dielectric layer of thickness L, in which there is a high concentration N_t of monoenergetic electron traps of depth E_t. The electrons injected from the contact are distributed among the traps and the conduction band. The free electrons screen the traps and E_t decreases. At a critical voltage $V = V_1$ at which the concentration of the free electrons becomes sufficiently large, $n = n_1$, a cascade-like decrease of E_t and an increase of n set in as a result of the release of the electrons from the trap, and a region of negative conductivity appears on the current-voltage characteristic. This process is in essence a Mott transition due to the injection [3].

Let us obtain the current-voltage characteristic of the dielectric diode under consideration within the framework of the simplest SCLC model [4]. The initial system of equations is:

$$j = q\mu n(V/L), \tag{1}$$

$$CV/qL = n + n_t, \tag{2}$$

$$n_t = \frac{nN_t\,\theta(E_t)}{n + N_{ct}};\quad N_{ct} = N_c e^{-E_t/kT} = N_{ct}^{o} e^{n/\bar{n}};\quad \theta(z) = \begin{cases} 1, & z > 0 \\ 0, & z < 0 \end{cases}, \tag{3}$$

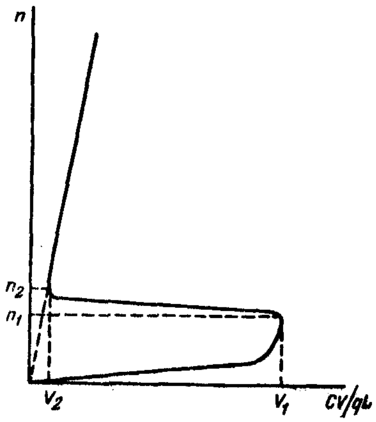
$$E_t = E_{to} - kT\frac{n}{\bar{n}};\quad \bar{n} \approx \frac{m\epsilon(kT)^2}{2\pi^3\hbar^2 q^2}, \tag{4}$$

where j is the current density, μ the electron mobility, $C = \epsilon/4\pi L$ the interelectrode geometric capacitance, ε the dielectric constant, q and m the charge and mass of the electron, N_c the effective density of states in the conduction band. The phenomenological expression (4) for the level shift can be obtained by analytically approximating the the numerical curve obtained in [5]. Substituting (3) in (2) and differentiating the expression term by term with respect to n, we have respectively

$$CV/qL = n + [nN_t\,\theta(E_t)/(n + N_{ct}^{o} e^{n/\bar{n}}, \tag{5}$$

$$\frac{C}{qL}\frac{dV}{dn} = 1 + N_t\left\{\frac{N_{ct}^{o} e^{n/\bar{n}}(\bar{n} - n)}{(n + N_{ct}^{o} e^{n/\bar{n}})^2}\,\theta(E_t) - \frac{n}{n + N_{ct}^{o} e^{n/\bar{n}}}\,\delta(E_t)\right. . \tag{6}$$

Substituting n(V) as given by (5) in Eq. (1), we obtain the current-voltage characteristic j(V). It follows from (6) that there is always a region $dV/dn < 0$ corresponding to the region of negative conductivity on the current-voltage characteristic. A qualitative plot of the function $n(CV/qL)$ is shown in the figure. The corresponding characteristic points are:



$$n_1 = \bar{n}\left(\frac{E_{to}}{kT} - \ln\frac{N_c}{\bar{n}}\right); \quad (7a) \qquad V_1 = \frac{qL}{C}\left[\bar{n}\left(\frac{E_{to}}{kT} - \ln\frac{N_c}{\bar{n}}\right) + \frac{N_t}{2}\right]; \quad (7b)$$

$$n_2 = \bar{n}E_{to}/kT; \quad (7c) \qquad V_2 = \frac{qL}{C}\bar{n}E_{to}/kT. \quad (7d)$$

We note that owing to the level shift the usual region of sharp increase of the current on the current-voltage characteristic of the space-charge-limited currents assumes an S-shape form in this case, i.e., $V_1 \approx V_{tf}$ - the voltage at which the traps are filled.

An estimate of the characteristic time of fluctuation development in the instability region yields:

$$\Delta t \sim \frac{\tau_{to} e^{-E_{to}/kT}}{[N_t/(2\pi \ln N_c/\bar{n}) - 1]}, \qquad (8)$$

where $\tau_{to} = [\langle vS_t\rangle N_c]^{-1}$, v - the thermal velocity of the electron, and S_t is the trap capture cross section.

A similar Mott transition (metallization upon injection) can be realized also in a system with high concentration of weakly-ionized donors. If this concentration is sufficiently high, then the system is unstable and goes over into a state with high conductivity even when V = 0. In other words, it turns out that $V_2 < 0$.

Effects of similar nature can arise as a result of the action of contact fields and the field effect (metallization of the near-contact or near-surface region, or else of the entire high-resistance layer if the latter is sufficiently thin).

Of course, similar phenomena can occur also in combination with impact ionization, double injection, the Pool-Frenkel effect, etc., leading to an S-shaped current-voltage characteristic and to metallization of the system.

Let us estimate the thickness of the dielectric layer at which metallization by injection is possible, using formula (7b). Putting $V_1/L = 5 \times 10^6$ V/cm, $N \approx 10^{19} - 10^{21}$ cm^{-3} $> n(E_{to}/kT)$, we get $L \approx 10^{-5} - 10^{-7}$ cm. Thus, this effect can apparently be realized in very thin layers with large defect concentration.

It can be assumed that the known phenomenon of switching in glass-like semiconductors[6] is connected with metallization by injection, facilitated by the Pool-Frenkel effect.

The authors thank V. L. Bonch-Bruevich for useful discussions.

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QUANTUM KINETIC EQUATION FOR ELECTRONS IN A HIGH-FREQUENCY FIELD

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Submitted 2 January 1969
ZhETF Pis. Red. 9, No. 3, 204 - 206 (5 February 1969)

The general derivation of the kinetic equation [1] is based on the separation of the action of the external field on the electron from the effect of the collisions with the scatterers. It is assumed that the electron moves between collisions under the influence of the field like a classical particle with a dispersion law determined by the band structure of the semiconductor, and that the electron scattering probability does not depend on the field. Accordingly the kinetic equation takes the form

$$\frac{\partial f}{\partial t} + eE\frac{\partial f}{\partial p} = \int \frac{d^3p}{(2\pi)^3}\left[W(p', p)f(p') - W(p, p')f(p)\right], \tag{1}$$

where the right side contains the collision term and the left side the force term. $f(\vec{p})$ is the electron momentum distribution function, $\vec{E}$ is the electric field, which in general depends on the time, and e is the electron charge. $W(\vec{p}', \vec{p})$ is the probability of transition from the state $\vec{p}'$ to the state $\vec{p}$, and is in general the sum of terms of the form

$$|M(p', p)|^2\delta[\epsilon(p') - \epsilon(p) \pm \epsilon_{p',p}], \tag{2}$$

where $M(\vec{p}', \vec{p})$ is the matrix element of the operator of interaction between the electron and the scatterer, $\epsilon(\vec{p})$ is the electron energy, and $\epsilon_{p',p}$ is the energy lost or acquired by the electron on scattering.

The purpose of the present paper is to derive a quantum-kinetic equation for electrons in a homogeneous high-frequency field $\vec{E}(t) = \vec{E}_0\cos\omega t$ under conditions when the field quantum energy $\hbar\omega$ is comparable with the average electron energy $\bar{\epsilon}$.

We derive the equation using an example with electrons having a quadratic dispersion. Defining the electric field in terms of the vector potential $\vec{A}(t) = -(\vec{E}_0 c/\omega)\sin\omega t$, where c is the speed of light, and solving the Schrodinger equation ($\hbar = 1$)

$$i\frac{\partial\psi}{\partial t} = \epsilon(p, t)\psi; \quad \epsilon(p, t) = \frac{\left[p - \frac{e}{c}A(t)\right]^2}{2m}, \tag{3}$$

we obtain the wave function of the electron in the field

$$\psi_p(r, t) = \exp\{ipr - i\int_0^t \epsilon(p, t')dt'\}. \tag{4}$$

Under conditions when $\omega\tau \gg 1$ (τ - free-path time), the canonical momentum $\vec{p}$ is a good quantum number, since it is altered only by the collisions. It is therefore natural to write the kinetic equation for the distribution function of the electrons with respect to the canonical momentum, $F(\vec{p})$ (we use the same letter for the canonical and kinematic momenta, since the corresponding distribution functions are denoted by different symbols).