SCHOTTKY EMISSION AND CURRENTS IN DIELECTRICS

PHYSICS

1967

SovietRxiv

Abstract

Full Text

UDC 539.294:537.3

PHYSICS

Academician of the Academy of Sciences of the Uzbek SSR É. I. ADIROVICH,
L. A. DUBROVSKII

SCHOTTKY EMISSION AND CURRENTS IN DIELECTRICS

1. The distinction between the problems of the current regime of a dielectric with a constant contact barrier φ_0^* and with lowering of the barrier by the field ([1,2])*

$$\varphi^* = \varphi_0^* - q\sqrt{-qE_1^*/\chi} \tag{1}$$

reduces to a change in the boundary conditions, which, when the Schottky effect is taken into account, assume, in dimensionless notation, the form*

$$n_0 = e^{\sqrt{-aE_1}}, \qquad n_L = n_2, \tag{2}$$

where

$$a = \frac{q^2}{\chi kT}\frac{1}{x^*_{\mathrm{Deb}}} = \frac{q^3}{\chi kT}\sqrt{\frac{4\pi n^*_{00}}{\chi kT}} = \frac{1}{4\pi x^{*3}_{\mathrm{Deb}} n^*_{00}}. \tag{3}$$

Consequently, the influence of the Schottky effect on the general solution of the problem of emission currents in a dielectric ([3])

$$n = \sqrt{\frac{9j^2u^2}{2}\left[\left(\frac{Z_{-2/3}(u)}{Z_{1/3}(u)}\right)^2 + 1\right]}; \qquad E = \sqrt[3]{6ju}\,\frac{Z_{-2/3}(u)}{Z_{1/3}(u)};$$

$$V = 2\ln\left|\frac{u_0^{1/3}Z_{1/3}(u_0)}{\gamma u_L^{1/3}Z_{1/3}(u_L)}\right| \tag{4}$$

is manifested in the fact that the current functions $C(j)$ and $B(j)$, entering into

$$Z_{1/3}(u) = \begin{cases} N_{1/3}(u) + BJ_{1/3}(u), & \text{for } C + jx > 0, \\ K_{1/3}(w) + B'I_{1/3}(w), & \text{for } C + jx < 0; \end{cases} \tag{5}$$

$$Z_{-2/3}(u) = \begin{cases} N_{-2/3}(u) + BJ_{-2/3}(u), & \text{for } C + jx > 0, \\ -i\left[K_{-2/3}(w) - B'I_{-2/3}(w)\right], & \text{for } C + jx < 0, \end{cases} \tag{6}$$

where

$$u = \frac{\sqrt{2}}{3|j|}(C + jx)^{3/2} = -i\,\frac{\sqrt{2}}{3|j|}(-C - jx)^{3/2} = -iw. \tag{7}$$

We shall consider the voltage range where

$$w_L \equiv \frac{\sqrt{2}}{3|j|}(-C + |j|L)^{3/2} \geq 5. \tag{8}$$

In this case (4)

$$B(j) \equiv -\sqrt{3} + \frac{2}{\pi}B'(j) \approx -\sqrt{3}, \tag{9}$$

i.e., it is practically independent of j, and only one current function $C(j)$ enters the expression for the current-voltage characteristic. This function is deter- is obtained from the boundary condition at the emitting contact, which leads to the equation

$$C\left[\left(Z_{-2/3}(u_0)/Z_{1/3}(u_0)\right)^2 + 1\right] = \exp\sqrt{-a\sqrt[3]{6ju_0}\,Z_{-2/3}(u_0)/Z_{1/3}(u_0)}, \tag{10}$$

where

$$u_0 = \frac{\sqrt{2}}{3|j|}\,C^{3/2} = -iw_0. \tag{11}$$

The system (10) and (11) determines C as a function of j for given values of L and a, i.e., for given values of L^* and φ_0^*.

---

* The notation and units are the same as in (3,4). The discussion is carried out for emission from a metal into the conduction band of a dielectric (electron emission), when the Schottky effect arises for $E_1^* < 0$. The unit of measurement of the concentration n_{00}^* corresponds to the electron concentration at the source (cathode) in the dielectric for a barrier height φ_0^*.

2. To study and compare the current functions $C(j)$ with and without allowance for the Schottky effect, we write the boundary condition (2) at the emitting contact in the form of three equations (see also the expression for n in (4), where $\sqrt[3]{9j^2u_0^2/2} = C$):

$$E_1 = -\frac{1}{a}\ln^2 n_0; \qquad C\left[1 + \left(\frac{Z_{-2/3}(u_0)}{Z_{1/3}(u_0)}\right)^2\right] = n_0; \qquad u_0 = \frac{\sqrt{2}}{3|j|}C^{3/2}. \quad (12)$$

These expressions, together with the first integral of the system of kinetic equations (see (3)),

$$n_0 - E_1^2/2 = C \quad (13)$$

make it possible to eliminate u_0, E_1, and n_0, and to represent C as a function of j for given L and a. Making the change of variables

$$j = \tilde{j}n_0^{3/2}; \qquad C = \tilde{C}n_0; \qquad E_1 = \tilde{E}_1 n_0^{1/2}, \quad (14)$$

we arrive at the system

$$1 - \frac{1}{2a^2}\frac{\ln^4 n_0}{n_0} = \tilde{C}; \qquad \frac{1}{\tilde{C}} = 1 + \left(\frac{Z_{-1/3}(u_0)}{Z_{1/3}(u_0)}\right)^2; \qquad u_0 = \frac{\sqrt{2}}{3|\tilde{j}|}\tilde{C}^{3/2}, \quad (15)$$

the last two equations of which coincide with the equations for $C(j)$ in the absence of the Schottky effect (see (3), (4)), while the first equation describes the relation of $\tilde{C}$ to the change in the boundary concentration n_0, which is absent if the electric field does not affect the contact barrier ($a = 0$; $n_0 = 1$). Consequently, the function $\tilde{C}(\tilde{j})$, found from the last two equations (15), coincides with the function $C(j)$ calculated in (4) for the problem of emission currents with constant work function from the source. This makes it possible to find $\tilde{C}(\tilde{j})$ directly for any prescribed value of $\tilde{j}$. Knowing $\tilde{C}(\tilde{j})$, we then find, with the aid of the first equation (15), the corresponding value of n_0 for any specified a (Fig. 1). For convenience in considering the regions of positive values of $\tilde{C}$, the scales for $\tilde{C} > 0$ and for $\tilde{C} < 0$, and also for $|\tilde{j}| < 1.825$ and for $|\tilde{j}| > 1.825$, have been chosen differently. Since for $|\tilde{j}| < 0.688$ the contact field in the dielectric is $E_1 > 0$ and there is no Schottky emission, the origin along the $|\tilde{j}|$ axis is taken to be $|\tilde{j}| = 0.688$.

For all $a \neq 0$, the interval of variation of $\tilde{C}$ is bounded and lies between $\tilde{C} = 1$ and

Fig. 1

Figure 1: Fig. 1

$$\tilde{C}' = 1 - 128/a^2 e^4. \tag{16}$$

The region of possible values of $\tilde{j}$ is also bounded by the quantity $\tilde{j}'$ corresponding to $\tilde{C}'$. The extrema of $\tilde{C}'$ of all curves of the family $\tilde{C}(n_0)$ lie at $n_0 = e^4$. As n_0 changes from 1 to e^4, $\tilde{C}$ changes from 1 to $\tilde{C}'$, and $\tilde{j}$ from 0.688 to $\tilde{j}'$; with further increase of n_0, the same segment of the curve $\tilde{C}(\tilde{j})$ is traversed in the reverse direction.

Let us consider $a_{\text{cr}} = 8\sqrt{2}e^{-2}$. For $a < a_{\text{cr}}$, $\tilde{C}(\tilde{f})$ vanishes twice at the point $|\tilde{j}| = 1.825$, once decreasing and the second time increasing. The corresponding roots n_{01} and n_{02} are determined from the equation

$$\ln^4 n_0 = 2a^2 n_0. \tag{17}$$

For $a = a_{\text{cr}}$, $n_{01} = n_{02} = e^4$, and for $a > a_{\text{cr}}$ $\widetilde{C}$ remains positive for all values of n_0.

The investigation carried out of the functional relation between n_0, $\widetilde{C}$, and $\tilde{j}$ makes it possible to easily construct the family of curves $C(j)$, determined by equation (10) (right-hand side of Fig. 2). The transition from $\tilde{j}$ and $\widetilde{C}$ to j and C for a given a is accomplished by means of formulas (14). The roots of $C(j)$ for $a < a_{\text{cr}}$ are

Fig. 1

$$|j_1| = 1.825\, n_{01}^{3/2}; \qquad |j_2| = 1.825\, n_{02}^{3/2}. \tag{18}$$

Since as $n_0 \to \infty$, $\widetilde{C} \to 1$, and $|\tilde{j}| \to 0.688$, asymptotically $C \to n_0$, while $|j| \to 0.688\, n_0^{3/2} \approx 0.688\, C^{3/2}$; hence it follows that the common asymptote of the family $C(j)$ is the curve

$$C = 1.284\, |j|^{2/3}. \tag{19}$$

In Fig. 2 on the left the family of curves $C(n_0)$ is shown:

$$C = n_0 - \frac{1}{2a^2} \ln^4 n_0. \tag{20}$$

Let us note that, in addition to $a = a_{\text{cr}} = 1.53$, at which C becomes positive everywhere, there is one more special value, $a'_{\text{cr}} = 1.64$, at which the extrema on

Fig. 2.

Figure 2: Fig. 2.

the curves $C(n_0)$ and $C(j)$ disappear, and these curves become monotonically increasing.

Let us also note that, for the graphical representation of the dependences under study in different ranges of values of C, a uniform scale is used along the ordinate axis in the region $|C| < 1$, and a logarithmic scale in the regions $|C| > 1$.

By comparing the values of n_0 and j corresponding to one and the same C, we can find the dependence of the emission current in the dielectric on the boundary concentration n_0 and on the magnitude of the electric field at the cathode E_1.

3. Knowledge of the functions $C(j; a)$ makes it possible to obtain in explicit form the general solution (4) of the kinetic problem and to find the current-voltage characteristics of emission currents in the dielectric with allowance for the Schottky effect. The radical changes in the function $C(j)$, caused by the action of the field on the contact barrier (cf. the curves $C(j)$ for $a = 0$ and $a \neq 0$ in Fig. 2), indicate that this effect plays an essential role in dielectric elec-

tronics. Let us show this explicitly by the example of currents $|\tilde{j}| > 10$, where the solution (4) is written in elementary functions (^{3})

$$n = \sqrt{\frac{|j|}{2(x_1 + x)}}; \qquad E = -\sqrt{2|j|(x_1 + x)}; \qquad V = \frac{2\sqrt{2|j|}}{3}\left[(x_1 + L)^{3/2} - x_1^{3/2}\right]. \tag{21}$$

The current function entering into these formulas, $x_1(j) \equiv -C(j)/|j|$, is equal to

$$x_1 = \frac{|j|}{2} \exp\left[-\sqrt[4]{32a^2|j|x_1}\right]. \tag{22}$$

From the last expression (21) it follows that in the regions $x_1(j) \ll L$ and $x_1(j) \gg L$ the current-voltage characteristic respectively takes the form

$$|j| = \frac{9}{8}\frac{V^2}{L^3}; \qquad V = \sqrt{2|j|x_1}\,L. \tag{23}$$

In the absence of the Schottky effect ($x_1 = |j|/2$) the first region corresponds to the SCLC regime, and the second to the ohmic regime: $j = V/L$. With

Fig. 2.

Schottky emission, the quadratic law is retained in the SCLC region, while for $x_1(j) \gg L$, from (22) and (23), instead of Ohm' s law we obtain the formula

$$|j| = \frac{V}{L} \exp \sqrt{a \frac{V}{L}}, \tag{24}$$

which, following the works of Stockmann (5) and Simmons (6), is interpreted as an expression describing Schottky emission in a dielectric. However, the influence of the Schottky effect is not limited to removal of saturation with respect to concentration in the region of large currents, but plays a much more substantial role; in particular, Schottky emission broadens the region of applicability of the quadratic SCLC law and makes possible, in principle, the appearance of a second quadratic section after the region (24), etc. These results, caused by the change in the form of the function $C(j)$ and by its nonmonotonic character, will be considered in detail in a subsequent communication.

Physico-Technical Institute
Academy of Sciences of the Uzbek SSR

Received
16 I 1967

CITED LITERATURE

1. M. I. Elinson, G. F. Vasil' ev, *Autoelectronic Emission*, Moscow, 1958, p. 28.
2. A. I. Gubanov, *Theory of the Rectifying Action of Semiconductors*, Moscow, 1956, p. 122.
3. E. I. Adirovich, *FTT*, **2**, 1410 (1960).
4. E. I. Adirovich, L. A. Dubrovsky, *DAN*, **164**, 771 (1965).
5. F. Stockmann, *Phys. Stat. Sol.*, **3**, 221 (1963).
6. I. G. Simmons, *Phys. Rev. Lett.*, **15**, 967 (1965).

Note: Figure translations are in progress. See original paper for figures.

Source: Math-Net.Ru and CyberLeninka. Machine translation. Verify with the original.