CURRENT-VOLTAGE CHARACTERISTIC OF A SEMICONDUCTOR-DIELECTRIC HETEROCONTACT

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CURRENT-VOLTAGE CHARACTERISTIC OF A SEMICONDUCTOR-DIELECTRIC HETEROCONTACT

1. Studying currents in films of Al_2O_3 and SiO_x under emission from n-type cadmium sulfide, Müller and Zuleeg (1) observed, in the current-voltage characteristic (I-V characteristic), a cubic segment $j \propto V^3$ over a range of current variation of almost 3 orders of magnitude. An analogous result was obtained by Mark and Helfrich (2) on p-triphenyl under emission from a contact with a saturated solution of iodine in $0.1\,M$ sodium iodide. These experiments were interpreted as the result of the filling, by emitted carriers, of trapping levels in the dielectric. Assuming an exponential distribution of trapping levels over energies in the forbidden band,

$$\rho^* = \rho_0^* \exp\left[(\varepsilon^* - \varepsilon_1^*)/kT_c\right] \quad (\varepsilon_1^* \ll \varepsilon^* \ll \varepsilon_2^*), \quad \rho_0^* = \mathrm{const}; \quad T_c = \mathrm{const}, \quad (1)$$

one can obtain an approximate expression for the I-V characteristic in the form (3,4)

$$j^* = \frac{q\mu N_c^* V^{*\,T_c/T+1}}{L^* V_t^{*\,T_c/T}} \exp\left(-\frac{\varepsilon_c^* - \varepsilon_2^*}{kT}\right), \quad (2)$$

where $V_t^* = 4\pi q L^{*2} N_t^*/\alpha\beta\varkappa$ is the trap-filling voltage; L^* is the thickness of the dielectric layer; $\varkappa$ is the dielectric permittivity, and the values of the constants α and β lie within the limits $1 \le \alpha \le 2$ and $1/2 \le \beta \le 1$.

By an appropriate choice of the coefficient T_c in formula (2) one can obtain any power-law dependence of current on voltage. In particular, for $T_c = 2T$ the I-V characteristic (2) becomes cubic.

The possibility of describing any power-law dependence by means of one or another choice of the distribution of local levels, not controlled in a direct experiment, compels one to treat such an interpretation with caution, especially in those cases where, experimentally, $j \propto V^n$ with a small integer exponent is

Fig. 1

Figure 1: Fig. 1

observed over a sufficiently wide interval. This explanation raises still greater doubts when such a dependence is found in different materials and with different contacts. It is also easy to see that, according to this mechanism, only an accidental correspondence of the experimental temperature to the constant T_c can lead to a cubic I-V characteristic, and it is enough to change the temperature for this dependence to disappear.

A second possible mechanism leading to a cubic dependence of j on V may be a definite regime of double injection into the dielectric—electrons from the cathode and holes from the anode $^{(5,6)}$ (see also $^{(7)}$). However, the existence of double injection for the materials and contacts described in $^{(1,2)}$ appears unlikely.

It is shown below that the cubic law of emission currents in a dielectric can occur in the case when the emitting contact is not a metal but a semiconductor. It is possible that the results obtained in $^{(1,2)}$ are explained precisely by this.

2. The general solution of the problem of emission into a dielectric from a semiconductor heterocontact will be carried out separately. Here we shall consider

case of sufficiently large currents, when diffusion may be neglected in comparison with drift, and the current-voltage characteristic of the emission current in the dielectric is described by the Mott-Gurney formula $^{(8-10)}$

$$V = \frac{2\sqrt{2j}}{3}\left[(x_1 + L)^{3/2} - x_1^{3/2}\right]. \tag{3}$$

This formula is given here in dimensionless form; the units of length, current density, field strength, and potential are taken to be

$$x^*_{\text{deb}} = \sqrt{\varkappa kT/4\pi q^2 N_0^*}; \qquad qDN_0^*/x^*_{\text{deb}}; \qquad kT/qx^*_{\text{deb}}; \qquad kT/q. \tag{4}$$

The unit of concentration N_0^* may be introduced arbitrarily $^{(9)}$. Dimensional quantities are denoted by asterisks. Quantities referring to the semiconductor are marked by the index s. For definiteness we shall consider electron emission.

The difference between a semiconductor emitting contact and a metallic one consists in the fact that the field penetrates into the semiconductor and causes band bending in it. Therefore the boundary concentration of electrons in the dielectric n_0^* is not a constant, but depends on the current. As is seen from the corresponding band diagram (Fig. 1),

$$n_0^* = n_{s\infty}^* \exp\left[(-\Delta\chi^* - \varphi_1^*)/kT\right]. \tag{5}$$

Fig. 1

Here $n^*_{s\infty}$ is the equilibrium concentration of electrons in the semiconductor far from the contact, φ_1^* is the difference between the values of the electron affinity of the semiconductor and the dielectric, and the shift of the bottom of the conduction band in the semiconductor at the contact with the dielectric is equal to $^{(11,12)}$

$$\Delta\chi^* = 2kT\ \mathrm{ar\,sh}\left[\frac{qL^*_{\mathrm{deb}}}{2\sqrt{2}\,kT}\,\frac{\varkappa}{\varkappa_s}E_1^*\right]. \tag{6}$$

Noting that for a good contact, when the charge of the surface centers is small, $\varkappa E_1^* = \varkappa_s E_{1s}^*$, we see that, for emission from a semiconductor into a dielectric, the effect of the field on the semiconductor will manifest itself at E_1^* values $\varkappa$ times smaller than for emission into vacuum.

We take as the unit the equilibrium concentration of electrons in the dielectric at the contact with the semiconductor for $\Delta\chi^* = 0$,

$$N_0^* = n_{00}^* = n^*_{s\infty}\exp(-\varphi_1^*/kT). \tag{7}$$

Then the boundary condition at the emitting contact is written in the form

$$n_0 = \exp(-\Delta\chi) = \exp\left[-2\,\mathrm{ar\,sh}\,\frac{E_1}{2\sqrt{2}\lambda}\right] = \left[\sqrt{1+\frac{E_1^2}{8\lambda^2}} - \frac{E_1}{2\sqrt{2}\lambda}\right]^2, \tag{8}$$

where $\lambda = \sqrt{\varkappa_s/\varkappa}\,e^{\varphi_1/2}$. Substituting into (8) n_0 and E_1, corresponding to the Mott-Gurney solution,

$$n = \sqrt{j}/2(x_1+x); \qquad E = -\sqrt{2j}(x_1+x), \tag{9}$$

we determine the current function $x_1(j)$, entering the current-voltage characteristic (3),

$$x_1 = \frac{1}{2j}\left[\sqrt{x_1 j/4\lambda^2+1} - \sqrt{x_1 j}/2\lambda\right]^4. \tag{10}$$

Equations (3) and (10) constitute a parametric representation of the current-voltage characteristic $j = j(V,\lambda,L)$, with x_1 serving as the parameter. Formula (10) des-

gives the family $x_1(j,\lambda)$ for different values of λ. In the regions of small and large currents it may be written in the form

Fig. 2

Figure 2: Fig. 2

$$x_1 = j/2 \quad \text{for } j/\lambda \ll 1, \qquad x_1 = \lambda^{4/3}/\sqrt[3]{2j} \quad \text{for } j/\lambda \gg 1. \tag{11}$$

3. If in (3) $x_1(j,\lambda) \ll L$, then the current-voltage characteristic is approximated by the quadratic law

$$j = \frac{9}{8}\frac{V^2}{L^3}. \tag{12}$$

For $x_1(j,\lambda) \gg L$, from (3) it follows that

$$x_1 = \frac{1}{2j}\frac{V^2}{L^2},$$

which, together with (10), gives

$$j = \frac{V}{L}\left[\sqrt{\frac{1}{8\lambda^3}\frac{V^2}{L^2} + 1} + \frac{1}{2\sqrt{2}\lambda}\frac{V}{L}\right]^2. \tag{13}$$

Formula (13) permits a further approximation, namely

$$j = \frac{V}{L} \quad \text{for} \quad \frac{1}{2\sqrt{2}\lambda}\frac{V}{L} \ll 1, \tag{14}$$

$$j = \frac{1}{2\lambda^2}\frac{V^3}{L^3} \quad \text{for} \quad \frac{1}{2\sqrt{2}\lambda}\frac{V}{L} \gg 1. \tag{15}$$

It is not difficult to see that, when the regions of applicability are estimated with respect to currents rather than voltages, formula (14) corresponds to $j/\lambda \ll 1$, while formula (15) corresponds to $j/\lambda \gg 1$.

As is evident from the analysis carried out, the applicability of one or another approximate form of the current-voltage characteristic requires the fulfillment of several inequalities which, depending on the values of the parameters λ and L, may be satisfied in different current regions or may prove to be incompatible altogether. Determination of the regions of applicability of the approximate expressions obtained above for the current-voltage characteristic, (12), (13), (14), and (15), is aided by consideration of the graphs shown in Fig. 2.

Fig. 2

Along the abscissa axis to the right are plotted the values $\mathcal{L} = \lambda L/2\sqrt{2}$, and along the ordinate axis downward—the values of λ. The scale on both axes is logarithmic; consequently, along the λ-axes the values $0.22\varphi_1 + \frac{1}{2}\ln\chi/\chi_s$ are plotted on a linear scale. It is easy to see that $\mathcal{L} = L^*/\sqrt{2\chi^2 kT/\chi_s \pi q^2 n_{s\infty}}$ and does not depend on φ_1. Consequently, if χ_s and χ are constant, then for a dielectric layer of a given thickness L^* the quantity $\mathcal{L}$ does not depend on λ.

Introduce the change of variables

$$x_1 = 2\sqrt{2}\lambda y_1; \qquad j = \sqrt{2}\lambda i; \qquad L = 2\sqrt{2}\lambda L'. \tag{16}$$

In this case the family of current functions (10) is transformed into a single universal function

$$y_1 = \frac{1}{4i}\left[\sqrt{y_1 i + 1} - \sqrt{y_1 i}\right]^4, \tag{17}$$

independent of λ. This curve is shown in Fig. 2 in the second quadrant. It is obvious that the conditions $x_1 \ll L$ and $x_1 \gg L$ may, respectively, be replaced by the conditions $y_1 \ll L'$ and $y_1 \gg L'$.

The family $L' = \frac{1}{\lambda^2}\mathcal{L}$ for different values of λ is given in the first quadrant, and the family $i(\lambda)$ for different values of j in the third quadrant.

The shaded region in the third quadrant corresponds to $j < 10 n_0^{3/2}$ and lies outside consideration, since the condition of validity of the initial current-voltage characteristic (3) is the inequality $j \geq 10 n_0^{3/2}$ ([9], [13]). In the shaded region of the first quadrant $\lambda < 1$, which corresponds to $\varphi_1 < 0$ (if $\chi_s = \chi$), i.e., to a semiconductor with a smaller electron affinity than the dielectric. This case is also not considered in the present paper.

The change in the form of the current-voltage characteristic in various ranges of emission-current values is conveniently traced by choosing some definite $\mathcal{L}$ (i.e., by specifying the thickness of the dielectric layer L^*) and varying λ. For $\lambda = \lambda_1$, $L' \gg y_1$ for all values of i (straight line 1). This means that, outside the shaded region, the quadratic law is valid everywhere. For $\lambda = \lambda_2$ (straight line 2), in the region $i_3 < i < i_7$ the current-voltage characteristic is quadratic; then, in the interval $i_7 < i < i_9$, it is described parametrically by equations (3) and (10), and then for $i > i_9$ it is again quadratic. For $\lambda = \lambda_3$, the various approximations of the current-voltage characteristic replace one another in the following sequence: $j \propto V^2/L^3$ ($i_1 < i < i_2$); the Mott-Gurney formula (3) for x_1 specified by equation (10) ($i_2 < i < i_5$); $j \propto V/L$ ($i_5 < i < i_6$); formula (13) ($i_6 < i < i_8$); $j \propto V^3/L^3$ ($i_8 < i < i_{10}$).

Fig. 3

For numerical estimates we choose parameters corresponding to the experimental data given in work ([1]) (Fig. 3): $n^*_{s\infty} = 10^{12}$ cm^{-3}; $L^* = 10^{-5}$ cm;

Fig. 3

Figure 3: Fig. 3

$\varphi_1^* = 0.2$ eV; $\mu = 100$ cm^2/V $\cdot$ s; $S = 10^{-2}$ cm^2. According to (15), the cubic dependence should begin at $J^* \sim 10^{-6}$ A, $V^* = 7$ mV, and should remain valid when the current changes by approximately 7 orders of magnitude.

The physical meaning of the appearance of the cubic and second quadratic regions at large values of j is that, as the applied voltage is increased, the field penetrating into the semiconductor leads to a continuous growth of the interfacial concentration. This effect is qualitatively similar to the Schottky effect, in which the ohmic region of the current-voltage characteristic also disappears in the region of large currents (^{13}).

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