A SEMICONDUCTOR-DIELECTRIC HETEROCONTACT WITH A POTENTIAL TRAP FOR ELECTRONS IN THE NEAR-CONTACT LAYER

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Abstract

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A SEMICONDUCTOR–DIELECTRIC HETEROCONTACT WITH A POTENTIAL TRAP FOR ELECTRONS IN THE NEAR-CONTACT LAYER

1. The contact of a dielectric with a semiconductor is described by the following system of equations*:

in the semiconductor (for $x<0$) in the dielectric (for $x>0$)

$$\begin{aligned} \frac{dE}{dx} &= -n+1, & \chi\frac{dE}{dx} &= -n, \\ \frac{dn}{dx} &= j-nE; & \frac{dn}{dx} &= \frac{1}{\mu}j-nE. \end{aligned} \tag{1}$$

For definiteness, we consider an electron semiconductor. We denote by ε_c the bottom of the conduction band and set $\varepsilon_c=0$ in the bulk of the semiconductor. Under equilibrium conditions ($j=0$)

$$n=\begin{cases} e^{-\varepsilon_c}, & \text{in the semiconductor;} \\ m^{3/2}e^{-\varepsilon_c}, & \text{in the dielectric.} \end{cases} \tag{2}$$

In this case the current equations in system (1) are satisfied identically, while $E=-d\psi/dx=d\varepsilon_c/dx$.

Finding the first integrals of equations (1), we obtain

$$E=\begin{cases} \sqrt{2\left(C_1+\varepsilon_c+e^{-\varepsilon_c}\right)}, & \text{in the semiconductor;} \\ \sqrt{\dfrac{2m^{3/2}}{\chi}\left(C_2+e^{-\varepsilon_c}\right)}, & \text{in the dielectric.} \end{cases} \tag{3}$$

Noting that for $x\to-\infty$, $E\to0$, $\varepsilon_c\to0$, and for $x\to+\infty$, $E\to0$, $\varepsilon_c\to W+\varphi_1$, we determine the constants C_1 and C_2 in formulas (3): $C_1=-1$;

Fig. 1. Semiconductor-dielectric heterocontact: a—when $\varphi_s > \varphi_d$; b—when $\varphi_s < \varphi_d$

Figure 1: Fig. 1. Semiconductor-dielectric heterocontact: a—when $\varphi_s > \varphi_d$; b —when $\varphi_s < \varphi_d$

$C_2 = -e^{-W-\varphi_1}$. Here $W = W_d - W_s$ is the difference between the electron work functions from the dielectric and from the semiconductor, and $\varphi_1 = \varphi_s - \varphi_d$ is the difference between the values of the electron affinity of the semiconductor and the dielectric.

Substituting the expressions obtained for n and E into the boundary conditions at the contact (4),

$$n_0 = m^{1/2} n_{0s} e^{-\varphi_1}; \qquad \chi E_1 = E_{1s}; \qquad n_{0s} = e^{-\Delta\chi_0}, \tag{4}$$

we obtain

$$\left(\Delta\chi_0 - 1 + \chi m^{3/2} e^{-W-\varphi_1}\right) e^{\Delta\chi_0} = m^{1/2}\chi e^{-\varphi_1} - 1; \qquad \varepsilon_{c0} = \Delta\chi_0 + \varphi_1 + \ln m. \tag{5}$$

The first of these equations determines $\Delta\chi_0$—the bending of the conduction band in the semiconductor at the boundary with the dielectric; the second determines the position of the bottom of the band in the dielectric at the contact with the semiconductor, ε_{c0}.

For all nonmetallic bodies with dielectric properties $W + \varphi_1 \gg 1$, and, consequently, in the first equation (5) one may always neglect the term $\chi m^{3/2} e^{-W-\varphi_1}$. It is thereby shown that the magnitude of the work

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* The notation and units are the same as in ($^{1-4}$). As the units of concentration, effective mass, mobility, and dielectric permittivity, the values of these quantities in the bulk of the semiconductor are taken.

exit from the dielectric practically does not affect the form of the band diagram of the semiconductor-dielectric contact in the immediate vicinity of the contact. In particular, the contact band bending in the semiconductor does not depend on W. On the contrary, the magnitude of the electron affinity substantially affects the near-contact picture.

In the case of a homocontact ($\varphi_1 = 0,\ \varkappa = 1,\ m = 1$), $\Delta\chi_0 = 1$. This case is essentially an $n-i$ contact (or a $p-i$ contact) (^{5,6}). For $\varphi_1 > 0$, a heterojunction is created at the semiconductor-dielectric contact,

Fig. 1. Semiconductor-dielectric heterocontact: *a*—when $\varphi_s > \varphi_d$;
b—when $\varphi_s < \varphi_d$.

shown in Fig. 1a, while for $\varphi_1 < 0$ it is the heterojunction shown in Fig. 1b. In the first of these two cases the semiconductor has a greater electron affinity than the dielectric; in the second, a smaller one. Phenomena at the semiconductor-dielectric heterocontact for $\varphi_1 > 0$ were considered in Ref. (^{4}). The present article investigates the heterocontact for $\varphi_1 < 0$, i.e., such a heterocontact in which a potential well arises in the dielectric, serving as an energy trap for conduction electrons.

Let us first show that the bottom of this potential trap ε_{c0} lies below the bottom of the conduction band in the unperturbed semiconductor and, consequently, that the electron concentration in the dielectric near the contact may be very high. Writing the first equation (5) in the form

$$\frac{1}{\varkappa m^{1/2}}\left[\Delta\chi_0 - 1 + e^{-\Delta\chi_0}\right] - 1 = e^{|\varphi_1| - \Delta\chi_0}, \tag{6}$$

we see that for $|\varphi_1| \gtrsim 1 + \varkappa m^{1/2}$, $\Delta\chi_0 < -\varphi_1$, i.e., $\varepsilon_{c0} \lesssim 0$.

2. Let us now consider how the potential trap in the near-contact layer of the dielectric affects the current-voltage characteristic (I-V characteristic) of the semiconductor-dielectric-metal (s-d-m) structure. For the case in which the semiconductor serves as the source and the metal as the drain (the forward current direction), we write the I-V characteristic in the form (^{2})

$$V \simeq \frac{2\sqrt{2}}{3j}\left[-C(j) + jL\right]^{3/2}. \tag{7}$$

The current function $C(j)$ must be determined from the boundary conditions at the source.

In Schottky emission from the metal (^{3}), and also in emission from a semiconductor with greater electron affinity than the dielectric ($\varphi_1 > 0$) (^{4}), the boundary condition was a definite functional relation between

n_0 and E_1, which made it possible to find $C(j)$ by means of the sequence of operations:

$$n_0 \to C \to \tilde{C} \to \tilde{j} \to j$$

(excluding E_1 from the first integral $C(n_0, E_1)$ with the aid of the boundary condition $E_1 = E_1(n_0)$, we determine $C(n_0)$; from $C(n_0)$ we find $\tilde{C}(n_0) = C/n_0$; knowing $\tilde{C}(n_0)$, we obtain $\tilde{j}(n_0)$, using the universal function $\tilde{C} = \tilde{C}(\tilde{j})$ (2); the function $\tilde{j}(n_0)$ makes it possible to find $j(n_0) = \tilde{j} n_0^{3/2}$; bringing into correspondence the values of j and C for one and the same n_0, we find the current function $C(j)$). In the problem under consideration the boundary condition proves to be more complicated and leads to an expression of the form $F(E_1, n_0, j) = 0$, i.e., to a dependence of E_1 not only on n_0, but also on j. The equation $F(E_1, n_0, j) = 0$ is obtained as a result of eliminating E_{1s} and n_{0s} from the first two formulas (4) and from the first integral of equations (1) in the semiconductor. The appearance of j in the boundary condition is connected with the fact that, in the case $\varphi_1 < 0$, in the semiconductor under forward currents the depleted layer is preserved (large positive Δx), and therefore the slope of the quasi-Fermi level cannot be neglected.

Eliminating E_1, j, and C from the system

$$F(E_1, n_0, j) = 0; \qquad j = \tilde{j} n_0^{3/2}; \qquad C = \tilde{C} n_0; \qquad n_0 - \frac{\chi E_1^2}{2} = C, \tag{8}$$

we arrive at an equation relating n_0, $\tilde{j}$, and $\tilde{C}$. The current function $C(j)$ is found by means of the following operations:

$$\begin{tikzcd} & & & C \\ \tilde{j} \arrow[r] & \tilde{C} \arrow[r] & n_0 \arrow[ur] \arrow[dr] & \\ & & & j \end{tikzcd} \quad . \tag{9}$$

In the region $0 \leq j \leq 0.2$ this function is shown graphically in Fig. 2 ($m = 1$; $\mu = 1$; $\chi = 1$; $|\varphi_1| > 10$). For comparison, the same figure gives the function $C(j)$ for a metallic source (curve 2), which creates in the dielectric a near-boundary electron concentration n_0 equal to the electron concentration in the bulk of the semiconductor $n_{s\infty}$. As is seen from Fig. 2, these functions differ little, and, consequently, a semiconductor source with $\varphi_1 < 0$ behaves similarly to a well-emitting metallic contact (a contact with a small work function into the dielectric). For $j > 0.2$ the calculation of $C(j)$ for the forward branch of the current-voltage characteristic was not carried out, since at $j \sim 0.2$ the barrier at the semiconductor-dielectric boundary Δx^* becomes of the order of kT/q.

The physical meaning of the result obtained consists in the fact that in the potential well in the near-contact layer of the dielectric a high electron concentration is created, which ensures large TOPZ densities through the dielectric.

3. Under reverse currents in the s.-d.-m. system, the metallic electrode serves as the source. In this case the depletion in the near-boundary layer of the semiconductor increases, and the applied voltage V_{pr} is divided between the dielectric and the semiconductor. Order-of-magnitude estimates show that for $V_{\text{pr}} \gtrsim 2kT/q$ the main voltage drop occurs across the blocking layer of the semiconductor. Neglecting, under these conditions, electron diffusion in this layer, the current can be written in the form $j = n_{s0} E_{1s}$. Using the boundary conditions and the first integrals of the system of kinetic equations (1), we arrive at the following expression for the reverse branch of the current-voltage characteristic of the s.-d.-m. system:

Fig. 2 and Fig. 3

Figure 2: Fig. 2 and Fig. 3

$$j = \frac{\sqrt{2}\, e^{\varphi_1}}{\chi m^{1/2}}\, (V_{\text{pr}} + V_k)^{3/2}. \tag{10}$$

Here V_k is the sum of the contact voltage drops in the system, including Δx_0, and j and V_{pr} in (10) are taken to be positive.

The forward and reverse branches of the current-voltage characteristic of the s-d-m structure are shown in Fig. 3. Let us note that, for $V_{\text{pr}} \gg V_{\text{k}}$, the reverse current through the dielectric-semiconductor contact is proportional to $V_{\text{pr}}^{3/2}$, and not to $\sqrt{V_{\text{pr}}}$, as at a metal-semiconductor contact (7). The rectification coefficient is equal to

$$K = 9\varkappa m^{1/2} e|\varphi_1|\sqrt{V_{\text{pr}}}/8\sqrt{2}\, L^3. \tag{11}$$

For $\varphi_1^* = 0.7$ eV, $\varkappa = 1$, $L = 100$, and $V^* = 5$ V, the rectification coefficient is $K \sim 10^7$.

4. The analysis carried out shows that a heterocontact of a dielectric with a semiconductor having a lower electron affinity than the dielectric leads to the formation of a potential trap for electrons in the near-contact layer of the dielectric. This trap changes the forward branch of the current-voltage characteristic only slightly and the reverse branch substantially. As a result, the possibility opens up of creating dielectric diodes with a high rectification coefficient without applying blocking metallic contacts.

Fig. 2. Current function $C(j)$ for emission from a semiconductor (1) and from a metal (2) in the case of forward currents

Fig. 3. Current-voltage characteristic of an s-d-m diode structure ($\varphi_1^* = 0.7$ eV, $L = 100$).
1 —forward branch; 2 —reverse branch

This circumstance is also significant because the high-resistivity character of crystals and films is usually ensured by compensation of the doping impurity by deep traps. When a blocking metallic contact with a dielectric is created, these traps are exposed, forming a narrow space-charge layer of donors. This leads to considerable leakage currents and considerable near-contact capacitances (8). An s-d-m structure with a potential trap is free of these drawbacks, since it does not require a blocking metallic contact.

It is undoubtedly of interest to consider the influence of a potential trap for electrons on the operating modes of more complex solid-state systems with semiconductor-dielectric heterojunctions.

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1. É. I. Adirovich, FTT, **2**, 1410 (1960).
2. É. I. Adirovich, L. A. Dubrovsky, DAN, **164**, 771 (1965).
3. É. I. Adirovich, L. A. Dubrovsky, DAN, **173**, 1032 (1967).
4. É. I. Adirovich, L. A. Dubrovsky, DAN, **178**, 68 (1968).
5. É. I. Adirovich, Yu. S. Ryabinkin, K. V. Temko, ZhTF, **28**, 55 (1958).
6. W. Shockley, R. C. Prim, Phys. Rev., **90**, 753 (1953).
7. T. E. Pikus, *Fundamentals of the Theory of Semiconductor Devices*, Moscow, 1965, p. 81.
8. R. S. Muller, R. Zuleeg, J. Appl. Phys., **35**, 1550 (1964).

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