

## **III.6. METAL – SEMICONDUCTOR CONTACT BIAS**

### **1. Work purpose**

The determination of the potential difference that appears at the contact surface between a metal and a semiconductor, potential difference that is known under the name of contact, or diffusion, bias.

### **2. Theory**

When two substances are in contact, between them there is a charge carriers exchange that determines a modification of the properties both at the contact surface and in the depth. The practical use of semiconductors and the study of many physical phenomena taking place in their inner part, are related to the connection of the semiconductors in a circuit made up of different materials.

For a better understanding of the phenomena determined by the existence of the contact, the following should be studied:

- The variation of the semiconductor properties when an electric field is applied.
- The appearance of a potential difference at the metal – metal contact.
- The appearance of a potential difference at the metal – semiconductor contact.

The results of this type of analysis can be summarized as follows:

a) When a semiconductor is introduced in an external homogenous electric field, at a certain distance from the surface the electric field cancels as a result of the movement of the free charge carriers produced by this external field in the bulk. The field exists only in a surface layer, in which there is also a space charge. This space charge shields the external field and, as a consequence, the field does not penetrate inside the bulk.

b) In the space charge region, the energy bands are bent. If the bent goes up, then the surface layer is enriched with holes. If the bent goes down, the surface layer is enriched with electrons. In an intrinsic semiconductor, the conduction in the upper layers increases independent of the field direction. In a doped semiconductor, the conduction in the surface layer is increased if the external field extracts from the bulk the majority carriers and is decreased if the surface layer is enriched with minority carriers. The variation of the surface layer conduction is called field effect.

c) The width of the layer in which there is a bulk charge and an electric field and in which the energy bands are considerably bent, is characterized by a quantity  $L_D$ , called the Debye screening length:

$$L_D = \sqrt{\frac{\epsilon_0 \epsilon_r k_B T}{e^2 (n_0 + p_0)}}. \quad (1)$$

In an intrinsic semiconductor we have  $n_0 = p_0 = n_i$ , while in an extrinsic n-type semiconductor  $n_0 = N_d$ ,  $p_0 = n_i^2 / N_d \ll n_0$  (and analogous for a p-type semiconductor).

d) For a large enough value of the field intensity, the type of conduction in the surface layer can be modified. The domain in which the modification of the conduction type takes place is called p – n physical junction.

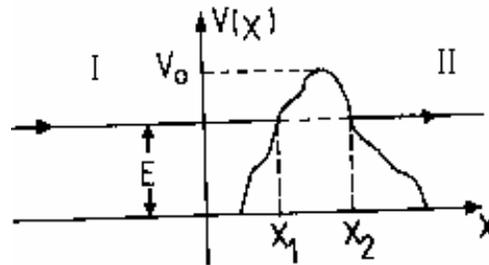
e) In a metal, the concentration of the free electrons is large and this is why the Debye screening length is much smaller than the interatomic distances.

f) When two metals are in contact, between two arbitrary external points of the different metals there is a potential difference, called external contact bias. The existence of the potential energy jump ensures the equality of the electron flow from one metal to another. Because of this equality, it results that through the contact there is a potential difference that is called internal contact bias. It determines the potential energy jump.

g) In the case when a semiconductor replaces one of the two metals, because there cannot be an electric field in the absence of a current inside the volume of a metal, the entire contact potential difference falls on the adjacent semiconductor surface layer. In this way, the energy bands bending and the space charge appearance are determined.

h) When two bodies are in contact, the electrons flows from the body with higher Fermi energy to the one with lower Fermi energy. The oriented flow disappears at the moment when the Fermi levels are equalized.

In this paper, we analyze and determine the contact bias that appears when the two substances put in contact are a metal and a semiconductor. This phenomenon can be better explained using the quantum theory of the tunnel effect. By a comparative analysis of the case of a particle with energy  $E$ , meeting a potential barrier as in Figure 1, (one-dimensional case), one can see that:



**Figure 1.** Arbitrary potential barrier.

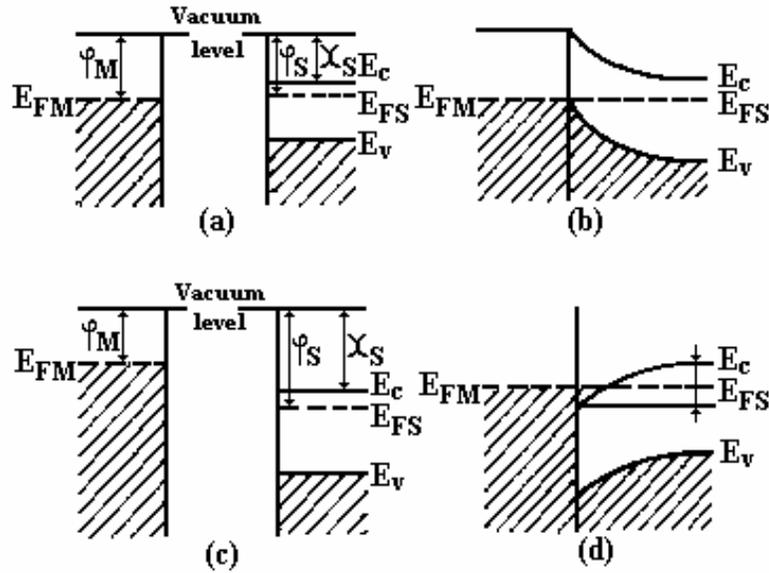
- From the classical mechanics point of view, the particle can arrive in the right side of the barrier (region II) if and only if  $E > V_0$  (where  $V_0$  is the barrier height); otherwise it is located in region I only.

- From the quantum mechanics point of view, a particle can cross the barrier, with a certain nonzero probability, even if  $E < V_0$ . This effect is known under the name of “tunnel effect”. The computations show that the transparency of the potential barrier with an arbitrary shape  $V=V(x)$  is given by the formula:

$$T = T_0 \exp \left[ -\frac{2}{\hbar} \int_{x_1}^{x_2} \sqrt{2m[V(x) - E]} dx \right], \quad (2)$$

where  $m$  and  $E$  represent the particle mass and energy, respectively.

For a better understanding, let us analyze the situation presented in Figure 2, where the energy levels for metal – vacuum and semiconductor – vacuum contacts are shown independently from one another, and let us define some characteristic quantities:



**Figure 2.** Energy levels diagram at M–S contact (n-type semiconductor).

a, b) –  $\varphi_M > \varphi_S$ . The contact is rectifying (the potential barrier appears);

c, d) –  $\varphi_M < \varphi_S$ . The contact is ohmic (no potential barrier in the conduction band).

- The vacuum levels represent the energy levels of a free electron in vacuum, having the kinetic energy equal to zero.

- The electronic affinity  $\chi_S$  represents the necessary energy needed by an electron to cross from the inferior limit of the conduction band to the vacuum level ( $\chi_{Ge} = 4,13$  eV,  $\chi_{GaAs} = 4,08$  eV,  $\chi_{Si} = 4,01$  eV).

- The extraction (or thermodynamic) work  $\phi$  is the difference between the vacuum level energy and the Fermi level energy ( $E_F$ ). For most metals and semiconductors, the extraction work is between 2 and 5 eV.

In the example given in Figure 2.a), the metal extraction work  $\phi_M$  is higher than the semiconductor extraction work  $\phi_S$  ( $\phi_M > \phi_S$ ). When the two bodies are put in contact, at the initial moment we have a non-equilibrium state. In the electronic exchange process, the preferential electron crossing direction will be from the substance with higher Fermi energy to the one with lower Fermi energy. This means that the electrons will cross from the semiconductor conduction band to the metal until the two Fermi levels are equalized, as in Figure 2.b).

Taking into account that the metal extraction work is higher than the semiconductor one ( $\phi_M > \phi_S$ ), more electrons will pass from the semiconductor towards the metal. Between the metal and the semiconductor there is a potential difference, given by:

$$U_D = \frac{\phi_M - \phi_S}{e}, \quad (3)$$

where  $e = 1,6 \cdot 10^{-19}$  C is the elementary charge. This potential difference is called contact or diffusion bias. Because of the energy barrier, the metal-semiconductor contact with  $\phi_M > \phi_S$  has rectifying properties and it is ohmic only when  $\phi_M < \phi_S$  in the case of a n-type semiconductor, as in Figure 2.d) (and the reverse for a p-type semiconductor).

The contact bias can be deduced from the temperature dependence of the saturation current  $I_s$ , or of the differential resistance  $R_d$ , which depends on  $I_s$ . The current intensity that flows through a metal-semiconductor structure (M – S), can be deduced as in the case of a vacuum diode, the computation being based on the thermoelectronic emission laws.

If the metal-semiconductor structure (M – S) is directly polarized by applying a voltage  $U$ , then the thermoelectronic current that flows from the semiconductor to the metal is given by:

$$I_{S \rightarrow M} = \frac{en_0\bar{v}}{4} \exp\left[-\frac{e(U_D - U)}{k_B T}\right], \quad (4)$$

where  $n_0$  is the majority carrier concentration in the semiconductor,  $\bar{v}$  is the electron mean velocity,  $k_B = 8.62 \cdot 10^{-5}$  eV/K is the Boltzmann constant, and  $T$  is the temperature.

The metal – semiconductor current is:

$$I_{M \rightarrow S} = \gamma \exp\left(-\frac{eU_D + E_{FS}}{k_B T}\right), \quad (5)$$

where  $\gamma$  is a constant, and  $E_{FS}$  is the semiconductor Fermi energy. At thermodynamic equilibrium ( $U = 0$ ) we have  $I_{S \rightarrow M} = I_{M \rightarrow S}$  and, from (4) and (5), we obtain:

$$\gamma = \frac{en_0\bar{v}}{4} \exp\left(\frac{E_{FS}}{k_B T}\right). \quad (6)$$

By replacing (6) in (5) it results:

$$I_{M \rightarrow S} = \frac{en_0\bar{v}}{4} \exp\left(-\frac{eU_D}{k_B T}\right). \quad (7)$$

The current that flows through M-S structure is equal to the net difference of the thermoelectric currents (4) and (7):

$$I = I_{S \rightarrow M} - I_{M \rightarrow S} = I_s \left[ \exp\left(\frac{eU}{k_B T}\right) - 1 \right], \quad (8)$$

where

$$I_s = \frac{en_0\bar{v}}{4} \exp\left(-\frac{eU_D}{k_B T}\right). \quad (9)$$

By differentiating the relation (8), we obtain the differential resistance:

$$R_d = \left( \frac{dI}{dU} \right)^{-1} = \frac{k_B T}{e I_s} \exp\left( -\frac{eU}{k_B T} \right) = \frac{4k_B T}{en_0 \bar{v}} \exp\left[ \frac{e(U_D - U)}{k_B T} \right]. \quad (10)$$

Taking into account that  $\bar{v}_e = \sqrt{\frac{8k_B T}{\pi m_e^*}}$  ( $m_e^*$  being the electron effective mass), we can write that, for a n-type semiconductor:

$$\frac{R_d}{T^{1/2}} = \text{const} \exp\left[ \frac{e(U_D - U)}{k_B T} \right]. \quad (11)$$

Applying a logarithm, we obtain:

$$\log\left[ \frac{R_d}{T^{1/2}} \right] = ct + \frac{e(U_D - U)}{k_B} \cdot \frac{1}{T}. \quad (12)$$

For a polarization bias  $U = U_0$ , if  $R_d$  is measured as a function of temperature and one plots  $\log(R_d/T^{1/2}) = f(1/T)$ , then a straight line is obtained and, from its slope, we can determine the contact bias:

$$U_D = U_0 + \frac{k_B}{e} \cdot \frac{\Delta[\log(R_d/T^{1/2})]}{\Delta(1/T)}. \quad (13)$$

### 3. Experimental set-up

The experimental set-up (see Figures 3 and 4) consists of:

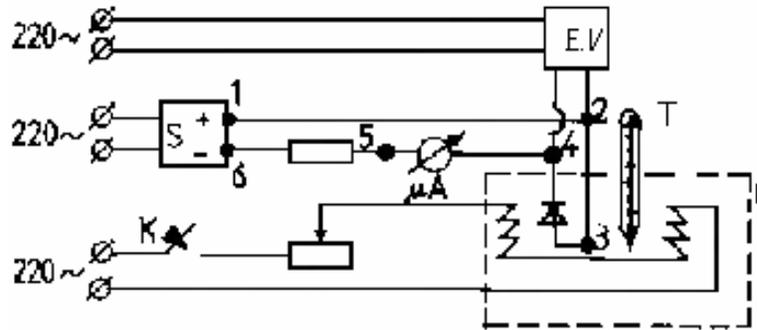
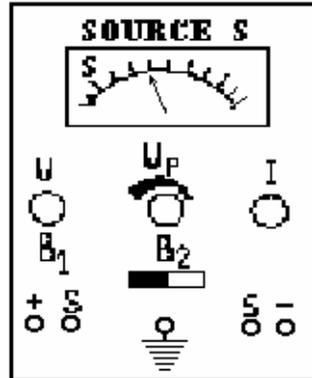


Figure 3. Draft of the experimental set-up.

- a germanium diode (EFD - 314) with wolfram contact;
- a stabilized voltage source S;

- an electronic digital voltmeter EV(E 303, DIGITAL VOLTMETER);
- a microammeter  $\mu\text{A}$ ;
- a furnace F, whose heating can be controlled using a rheostat;
- an industrial thermometer T.



**Figure 4.** Front panel of the source.

#### 4. Working procedure:

1. Identify the draft components. The voltmeter E.V., the furnace F and the source S should be in the Stop position (for the source S the button B<sub>2</sub> from Figure 4 should be turned to the left up to the maximum). Then the apparatus are plugged in at 220V a. c.
2. The stabilized source S is turned on, turning just a little bit to the right the potentiometer B<sub>2</sub> (the rotation will be stopped as soon as a click sound is heard).
3. The digital voltmeter is turned on.
4. The diode is directly polarized with a low voltage  $U_0$  ( $U_0 = 0,02 - 0,04$  V), by turning the button B<sub>1</sub> of the source. The voltage is read using the digital voltmeter E.V. (on the 20V scale).
5. The furnace is turned on.
6. The voltage  $U_0$  applied on the diode is kept constant using the potentiometer B<sub>1</sub>.

7. Read the values of  $t$  ( $^{\circ}\text{C}$ ),  $U_0$  (V) and  $I$  ( $\mu\text{A}$ ), varying the temperature from the room temperature up to  $65 - 70$   $^{\circ}\text{C}$ , in steps of  $5$   $^{\circ}\text{C}$ . When the temperature goes to  $65 - 70$   $^{\circ}\text{C}$ , stop the heating process by turning off the furnace and read  $t$ ,  $U_0$  and  $I$  in the reverse (cooling) process, at the same temperatures. The results obtained should be summarized in Table 1.

**Table 1**

$t$ ( $^{\circ}\text{C}$ )	$U_0$ (V)	$I_h$ ( $\mu\text{A}$ )	$I_c$ ( $\mu\text{A}$ )	$I_m$ ( $\mu\text{A}$ )	$R_d$ ( $\Omega$ )	T (K)	$1/T$ ( $\text{K}^{-1}$ )	$\log(R_d/T^{1/2})$

### 5. Experimental data processing

1. Compute the mean value for the current,  $I_m = \frac{I_n + I_c}{2}$  at each temperature.
2. Compute  $R_d = U_0 / I_m$  at each temperature.
3. Draw the plot for  $\log(R_d / T^{1/2}) = f(1/T)$ . Determine  $U_D$  taking into account the slope of the straight line obtained and the relation (13).

We have to remark that:

- The accuracy of  $U_0$  depends of the precision of keeping the voltage constant when applied on diode.
- The polarization voltage applied on the diode should be low, in order not to destroy the contact potential barrier.
- For such a polarization, one can obtain values of the differential resistance of the order of  $10^3 \Omega$ .
- The voltmeter will be set up on the scale of 20 V because only in this case we can keep constant (with a high accuracy) a voltage of the order of  $10^{-2}$  V ( $U_0 = 0.02; 0.03; \dots; 0.04; 0.05$  V).

To determine the slope of a straight line given by the general equation  $y = ax + b$ , one can apply the least square method. We use the following notations:  $y = \log(R_d/T^{1/2})$ ,  $x = 1/T$ ,  $a = e(U_D - U_0)/k_B$ . Neglecting the errors due to the variable  $x$  and according to the least square method, the estimated values  $\bar{a}$  and  $\bar{b}$  of the quantities  $a$  and  $b$  can be obtained using the relations:

$$\bar{a} = \frac{n \sum x_i y_i - \sum x_i \sum y_i}{n \sum x_i^2 - (\sum x_i)^2}, \quad \bar{b} = \frac{\sum x_i^2 \sum y_i - \sum x_i \sum x_i y_i}{n \sum x_i^2 - (\sum x_i)^2}, \quad (14)$$

where  $y_i$  represents the dependent variable corresponding to the independent variable  $x_i$  and  $n$  represents the number of pairs  $\{x_i, y_i\}$  experimentally measured. The estimates of the  $a$  and  $b$  variances are:

$$s_{\bar{a}}^2 = \frac{n}{n \sum x_i^2 - (\sum x_i)^2} s_y^2, \quad s_{\bar{b}}^2 = \frac{\sum x_i^2}{n \sum x_i^2 - (\sum x_i)^2} \cdot s_y^2, \quad (15)$$

where  $s_y$  is the  $y$  mean square deviation, which can be calculated using the formula:

$$s_y^2 = \frac{\sum (y_i - \bar{b} - \bar{a}x_i)^2}{n(n-1)}. \quad (16)$$

The unknown quantity  $a$  have to be expressed as a function of its estimate and of the variance estimate as follows:

$$a = \bar{a} \pm s_{\bar{a}}. \quad (17)$$

The quantity  $U_D = f(a)$  will be given in the form:

$$U_D = \bar{U}_D \pm s_{\bar{U}_D}, \quad (18)$$

where

$$s_{\bar{U}_D}^2 = \left( \frac{\partial U_D}{\partial a} \right)_{a=\bar{a}}^2 s_{\bar{a}}^2. \quad (19)$$