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CAPACITANCE VOLTAGE CHARACTERISTICS

Muminov Islombek Arabboyevich, Maqsudova Gavxaroy Nasiriddinovna,
To‘lqinboyeva Muxlisaxon, Mirzayeva Xadichaxon Mo‘sajon qizi.
Fergana State University

Annotation: This study investigates the Schottky barrier diode, specifically on n-type materials, drawing parallels with the abrupt p^+n diode for analytical purposes. The solution of the Poisson equation enables the determination of critical parameters such as the depletion width (W) for an externally applied voltage to the metal (V), with N_d representing the doping level of the n-type semiconductor. By summing the contributions of each allowed electron, this research provides insights into current calculations in the Schottky barrier diode, laying the foundation for its practical applications.

Keywords: schottky barrier diode, depletion width, depletion capacitance, electric field profile, metal-semiconductor junction, n-type semiconductor, poisson equation, thermionic emission, electron distribution, current flow, schottky barrier height, energy bands, zero bias operation.

Once the Schottky barrier height is known, the electric field profile, depletion width, depletion capacitance, etc., can be evaluated the same way we obtained the values for the p-n junction. The problem for a Schottky barrier on an n-type material is identical to that for the abrupt p^+n diode, since there is no depletion on the metal side. One again makes the depletion approximation; i.e., there is no mobile charge in the depletion region and the semiconductor is neutral outside the depletion region. Then the solution of the Poisson equation gives the depletion width W for an external voltage applied to the metal V

$$W = \left[\frac{2\varepsilon(V_{bi}-V)}{eN_d}\right]^{1/2} \quad (1)$$

Here N_d is the doping of the n-type semiconductor. Note that there is no depletion on the metal side because of the high electron density there. The potential V is the applied potential, which is positive for forward bias and negative for reverse bias. Consider the Schottky barrier band diagram shown on figure 1 at zero bias. The Schottky barrier between a metal and semiconductor is shown in equilibrium (at zero bias) with the electron distribution shown on the right

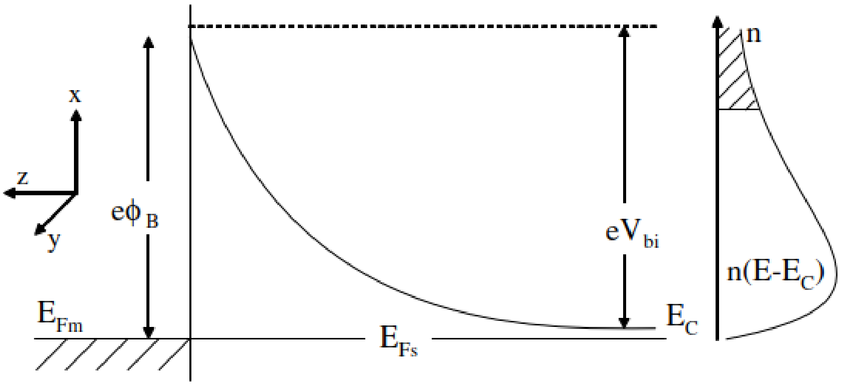

Figure 1: Schottky Barrier in equilibrium

Also shown is the electron distribution:

$$n(E-E_C) = 2f(E-E_C)\cdot N(E-E_C) \tag{2}$$

similar to the case of a $p-n$ junction, the factor of 2in accounting for electron spin. Thermionic emission assumes that all electrons in the semiconductor with kinetic energy in the $+z$ direction greater than $eV_{bi}(E_z > eV)$ and $k_z > 0$, are capable of surmounting the barrier and contributing to current flow from the semiconductor to the metal, $J_{s\to m}$. Note that the total kinetic energy $E-E_C = E_x + E_y + E_z$. At thermal equilibrium the current from the metal to the semiconductor, $J_{m\to s}$, will be equal in magnitude and opposite in sign to $J_{s\to m}$, making the net current zero. To calculate $J_{s\to m}$ one needs to sum the current carried by every allowed electron:

$$J_{s\to m} = e\sum \;\; n\,(E-E_c)\cdot v_z \tag{3}$$

for $E_z > eV_{bi}$ and $v_z > 0$. The methodology employed is to calculate the number of electrons at energy E in a volume of k-space $(dk)^3$, multiply the number with the electron velocity in the direction along the barrier, and sum or integrate over energy. Assuming a crystal of length L, periodic boundary conditions yield allowed k values given by

$$k = 2\pi N \tag{4}$$

where N is an integer and the separation between allowed k's is $\Delta k = 2\pi/L$. The number of electrons in a volume element dk_x, dk_y, dk_z is therefore

$$dN = 2f(E-E_C)\frac{dk_x dk_y dk_z}{\Delta k^3} \tag{5}$$

Assuming $(E-E_C) \gg E_F$ and writing $E-E_F = E-E_C+E_C-E_F$ gives

$$dN = 2\,\exp\left(\frac{-\left((E-E_C)+(E_C-E_F)\right)}{k_B T}\right)\frac{dk_x dk_y dk_z}{\Delta k^3} \tag{6}$$

The current density contributed by these electrons is

$$J_z = -ev_z\frac{dN}{L^3} \tag{7}$$

if $k_z > 0$ and $E_z > eV_{bi}$. Note that all values of E_x and E_y are allowed as they represent motion in the $x-y$ plane which is not constrained by the barrier in the $+z$ direction. Note that

$$(E_x - E_C) = \frac{\hbar^2 k_x^2}{2m^*} \tag{8}$$

with similar relationships for $(E_y - E_C)$ and $(E_z - E_C)$. Also employing the condition $(E_z - E_c) > eV_{bi}$ yields a minimum value of

$$k_{\min} = \sqrt{eV_{bi}\left(\frac{2m^*}{\hbar^2}\right)} \tag{9}$$

Also,

$$v_z = \frac{\hbar k_z}{m^*} \tag{10}$$

Therefore,

$$J_z = \frac{-e}{(2\pi)^3}\int_{-\infty}^{+\infty} d\,k_x \int_{-\infty}^{+\infty} d\,k_y \int_{k_{\min}}^{+\infty} \frac{\hbar k_z}{m^*} dk_z \cdot$$

$$2\exp\left[-\frac{\left(E_x + E_y + E_z\right)}{k_B T}\right]\exp\left[-\frac{E_C - E_F}{k_B T}\right]\exp\left(\frac{E_C}{k_B T}\right)$$

$$= -\frac{2e}{(2\pi)^3}\int_x \cdot \int_y \cdot \int_z \exp\left(-\frac{E_C - E_F}{k_B T}\right) \tag{11}$$

where

$$\int_x = \int_y = \int_{-\infty}^{\infty} \exp\left(\frac{\hbar^2 k_x^2}{2m^* k_B T}\right) dk_x = \frac{\sqrt{2\pi m^* k_B T}}{\hbar} \tag{12}$$

and

$$\int_z = \int_{k_{\min}}^{\infty} \exp\left(-\frac{\hbar^2 k_z^2}{k_B T}\right) \cdot \frac{\hbar k_z}{m^*} \cdot dk_z \tag{13}$$

$$= \frac{k_B T}{\hbar}\exp\left(-\frac{\hbar^2 k_{\min}^2}{k_B T}\right) = \frac{k_B T}{\hbar}\exp\left(\frac{-eV_{bi}}{k_B T}\right) \tag{14}$$

Therefore,

$$J_z = \frac{4\pi}{(2\pi\hbar)^3} \cdot e m^* k_B^2 T^2 \exp\left(-\frac{\left(eV_{bi} + (E_C - E_F)\right)}{k_B T}\right) \tag{15}$$

or

$$J_z = A^* T^2 \exp\left(\frac{-e\varphi_B}{k_B T}\right) = J_{s\to m}(V = 0) \tag{16}$$

where

$$A^* = \frac{4\pi e m^* k_B^2}{2\pi\hbar^3} = 120\ A\ sm^{-2} K^{-2} \times \frac{m^*}{m_0} \tag{17}$$

is the Richardson constant and $\varphi_B = V_{bi} + (E_C - E_F)$, the barrier seen by electrons in the metal of the Schottky barrier height. We have calculated $J_{s\to m}$ at $V = 0$. The analysis can be easily extended to a forward bias of V_F, the only change being replacing the barrier, V_{bi} by the new barrier $V_{bi} - V_F$. This changes I_z to

$$I_z = \frac{k_B T}{\hbar}\exp\left(-\frac{eV_{bi}}{k_B T}\right)\exp\left(\frac{eV_F}{k_B T}\right) \tag{18}$$

or

$$J_{s\to m}(V = V_F) = J_{s\to m}(V = 0)\exp\left(\frac{eV_F}{k_B T}\right) \tag{19}$$

Since the current flow from the metal to the semiconductor is unchanged:

$$J(V = V_F) = J_{s\to m}(V = V_F) - J_{m\to s}(V = V_F) \tag{20}$$

$$= A^* T^2 \exp\left(\frac{-q\varphi_B}{k_B T}\right)\left[\exp\left(\frac{eV_F}{k_B T}\right) - 1\right] \tag{21}$$

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