VE320
Intro to Semiconductor Devices
Final RC PartI

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The Schottky Barrier Diode

In the chapter 7 and 8, we have considered the pn junction and assumed that the semiconductor material was the same throughout the structure. This type of junction is referred to as a homojunction. We developed the electrostatics of the junction and derived the current–voltage relationship. In this chapter, we consider the metal–semiconductor junction and the semiconductor heterojunction, in which the material on each side of the junction is not the same. These junctions can also produce diodes.

The Schottky Barrier Diode

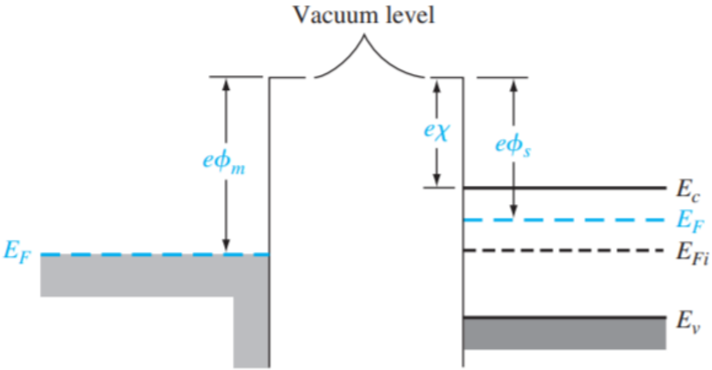


Figure: Energy-band diagram of a metal and semi conductor before contact

The Schottky Barrier Diode

Work function: energy difference between the vacuum energy level and the Fermi level
Electron affinity: energy different between the vacuum energy level and conduction band bottom edge
The parameter ϕ_m is the metal work function (measured in volts), ϕ_s is the semiconductor work function, and χ is known as the electron affinity.

The Schottky Barrier Diode

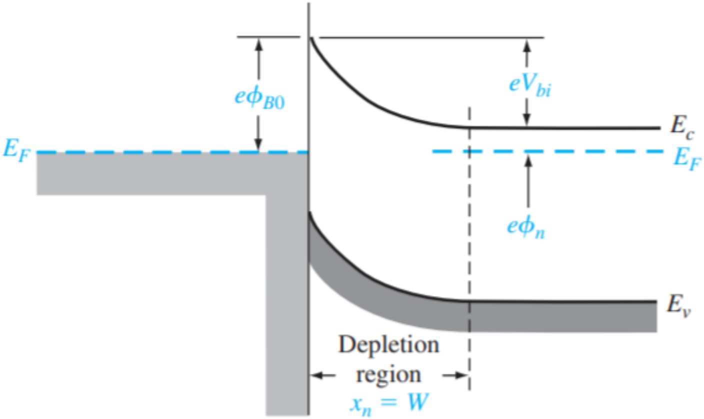


Figure: ideal energy-band diagram of a metal–n-semiconductor junction for $\phi_m > \phi_s$

The Schottky Barrier Diode

The parameter ϕ_{B0} is the ideal barrier height of the semiconductor contact, the potential barrier seen by electrons in the metal trying to move into the semiconductor. This barrier is known as the Schottky barrier and is given, ideally, by

$$\phi_{B0} = (\phi_m - \chi)$$

On the semiconductor side, V_{bi} is the built-in potential barrier. This barrier, similar to the case of the pn junction, is the barrier seen by electrons in the conduction band trying to move into the metal. The built-in potential barrier is given by

$$V_{bi} = \phi_{B0} - \phi_n$$

which makes V_{bi} a slight function of the semiconductor doping, as is the case in a pn junction.

Reverse-biased and Forward-bias Voltage

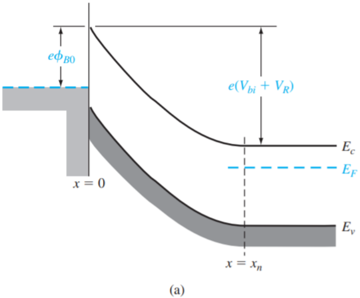


Figure: Ideal energy-band diagram of a metal–semiconductor junction (a) under reverse bias and (b) under forward bias

Reverse-biased and Forward-bias Voltage

If we apply a positive voltage to the semiconductor with respect to the metal, the semiconductor-to-metal barrier height increases, while ϕ_{B0} remains constant in this idealized case. This bias condition is the reverse bias. If a positive voltage is applied to the metal with respect to the semiconductor, the semiconductor-to-metal barrier V_{bi} is reduced while ϕ_{B0} again remains essentially constant. In this situation, electrons can more easily flow from the semiconductor into the metal since the barrier has been reduced. This bias condition is the forward bias. The energy-band diagrams for the reverse and forward bias are shown in Figures where V_R is the magnitude of the reverse-biased voltage and V_a is the magnitude of the forward-bias voltage.

Ideal Junction Properties

The electric field can then be written as

$$\mathrm{E} = -\frac{eN_d}{\epsilon_s}(x_n - x)$$

$$|\mathrm{E}_{\mathsf{max}}| = \frac{eN_d x_n}{\epsilon_s}$$

The space charge region width

$$W = x_n = \left[\frac{2\epsilon_s (V_{bi} + V_R)}{eN_d}\right]^{1/2}$$

where V_R is the magnitude of the applied reverse-biased voltage.

Example 1

Determine the theoretical barrier height, built-in potential barrier, and maximum electric field in a metal-semiconductor diode for zero applied bias.

Consider a contact between tungsten and n-type silicon doped to $N_d = 10^{16}\ \mathrm{cm}^{-3}$ at $T = 300\ \mathrm{K}$.

Work functions of some elements

Element	Work function, ϕ_m
Ag, silver	4.26
Al, aluminum	4.28
Au, gold	5.1
Cr, chromium	4.5
Mo, molybdenum	4.6
Ni, nickel	5.15
Pd, palladium	5.12
Pt, platinum	5.65
Ti, titanium	4.33
W, tungsten	4.55

Work functions of some elements

Element	Electron affinity, χ
Ge, germanium	4.13
Si, silicon	4.01
GaAs, gallium arsenide	4.07
AlAs, aluminum arsenide	3.5

Example 1 Solution

The metal work function for tungsten (W) from Table 1 is $\phi_m = 4.55\ \mathrm{V}$ and the electron affinity for silicon from Table 2 is $\chi = 4.01\ \mathrm{V}$. The barrier height is then

$$\phi_{B0} = \phi_m - \chi = 4.55 - 4.01 = 0.54\ \mathrm{V}$$

where ϕ_{B0} is the ideal Schottky barrier height. We can calculate ϕ_n as

$$\phi_n = \frac{kT}{e} \ln\left(\frac{N_c}{N_d}\right) = 0.0259 \ln\left(\frac{2.8 \times 10^{19}}{10^{16}}\right) = 0.206\ \mathrm{V}$$

Then

$$V_{bi} = \phi_{B0} - \phi_n = 0.54 - 0.206 = 0.334\ \mathrm{V}$$

Example 1 Solution

The space charge width at zero bias is

$$x_n = \left[\frac{2\epsilon_s V_{bi}}{eN_d}\right]^{1/2} = \left[\frac{2(11.7)\left(8.85\times10^{-14}\right)(0.334)}{\left(1.6\times10^{-19}\right)\left(10^{16}\right)}\right]^{1/2}$$

or

$$x_n = 0.208\times10^{-4}\ \mathrm{cm}$$

Then the maximum electric field is

$$|\mathrm{E}_{max}| = \frac{eN_d x_n}{\epsilon_s} = \frac{\left(1.6\times10^{-19}\right)\left(10^{16}\right)\left(0.208\times10^{-4}\right)}{(11.7)\left(8.85\times10^{-14}\right)}$$

or finally

$$|\mathrm{E}_{max}| = 3.21\times10^{4}\ \mathrm{V/cm}$$

Junction capacitance

A junction capacitance can also be determined in the same way as we do for the pn junction. We have that

$$C' = eN_d \frac{dx_n}{dV_R} = \left[\frac{e\epsilon_s N_d}{2\left(V_{bi} + V_R\right)} \right]^{1/2}$$

where C' is the capacitance per unit area. If we square the reciprocal of Equation 1, we obtain

$$\left(\frac{1}{C'} \right)^2 = \frac{2\left(V_{bi} + V_R\right)}{e\epsilon_s N_d}$$

We can use Equation 2 to obtain, to a first approximation, the built-in potential barrier V_{bi}, and the slope of the curve from Equation 2 to yield the semiconductor doping N_d. We can calculate the potential ϕ_n and then determine the Schottky barrier ϕ_{B0}.

Current–Voltage Relationship

$$J = J_{sT}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

where J_{sT} is the reverse-saturation current density and is given by

$$J_{sT} = A^* T^2 \exp\left(\frac{-e\phi_{Bn}}{kT}\right)$$

The parameter $A*$ is called the effective Richardson constant for thermionic emission.

Richardson constant

Calculate the ideal Richardson constant for a free electron.

$$A^* = \frac{4\pi e m_n^* k^2}{h^3}$$

Assume $m_n^* = m_o$, then

$$A^* = \frac{4\pi \left(1.6 \times 10^{-19}\right) \left(9.11 \times 10^{-31}\right) \left(1.38 \times 10^{-23}\right)^2}{\left(6.625 \times 10^{-34}\right)^3}$$

$$= 1.20 \times 10^6 \ \mathrm{A/K^2 \cdot m^2}$$

$$\Rightarrow A^* = 120 \ \mathrm{A/K^2 \cdot cm^2}$$

Example 2

(a) Calculate the ideal reverse-saturation current densities of a Schottky barrier diode and a pn junction diode.
Consider a tungsten barrier on silicon with a measured barrier height of $e\phi_{Bn} = 0.67\mathrm{eV}$. The effective Richardson constant is $A^* = 114\ \mathrm{A/K^2 - cm^2}$. Let $T = 300\ \mathrm{K}$.

Example 2 Solution

We have for the Schottky barrier diode

$$J_{sT} = A^* T^2 \exp\left(\frac{-e\phi_{Bn}}{kT}\right) = (114)(300)^2 \exp\left(\frac{-0.67}{00050}\right)$$
$$= 5.98 \times 10^{-5}\ \mathrm{A/cm^2}$$

For a pn junction,

$$J_s = 3.66 \times 10^{-11}\ \mathrm{A/cm^2}$$

The ideal reverse-saturation current density of the Schottky barrier junction is orders of magnitude larger than that of the ideal pn junction diode.

Example 2

(b) Calculate the forward-bias voltage required to induce a forward-bias current density of 10 $\mathrm{A/cm^2}$ in a Schottky barrier diode and a pn junction diode.

Example 2 Solution

For the Schottky barrier diode, we have

$$J = J_{sT}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

Neglecting the (-1) term

$$V_a = \left(\frac{kT}{e}\right)\ln\left(\frac{J}{J_{sT}}\right) = V_t \ln\left(\frac{J}{J_{sT}}\right) = (0.0259)\ln\left(\frac{10}{5.98\times 10^{-5}}\right)$$
$$= 0.312\ \mathrm{V}$$

For the pn junction diode, we have

$$V_a = V_t \ln\left(\frac{J}{J_s}\right) = (0.0259)\ln\left(\frac{10}{3.66\times 10^{-11}}\right) = 0.682\ \mathrm{V}$$

A comparison of the two forward-bias voltages shows that the Schottky barrier diode has a turn-on voltage that, in this case, is approximately 0.37 V smaller than the turn-on voltage of the pn junction diode.

1. Metal–Semiconductor and Semiconductor Heterojunctions
   - The Schottky Barrier Diode
   - Metal–Semiconductor Ohmic Contacts

Ohmic Contacts

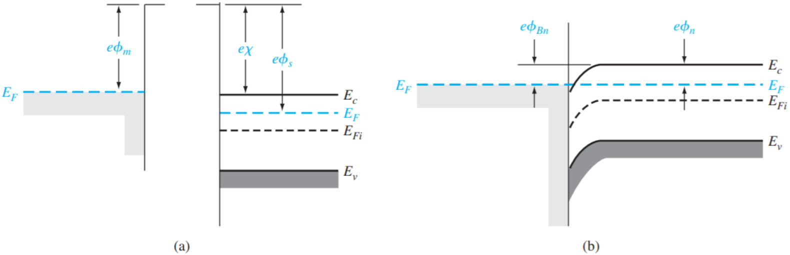


Figure: Ideal energy-band diagram (a) before contact and (b) after contact for a metal-n-type semiconductor junction for $\phi_m < \phi_s$.

Ohmic Contacts

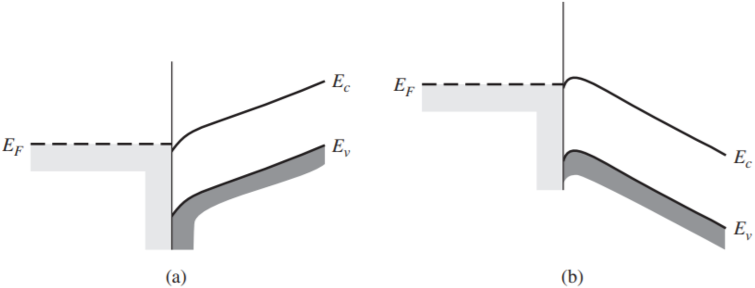


Figure: Ideal energy-band diagram of a metal-n-type semiconductor ohmic contact (a) with a positive voltage applied to the metal and (b) with a positive voltage applied to the semiconductor

Ohmic Contacts

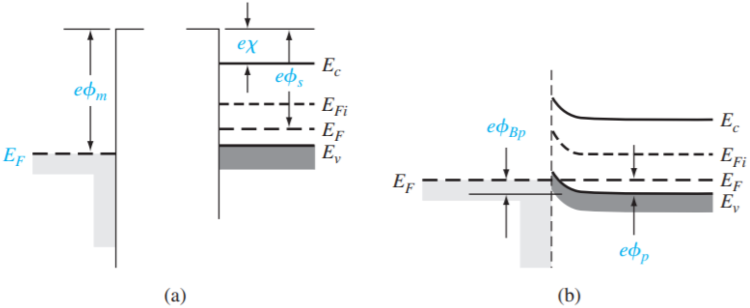
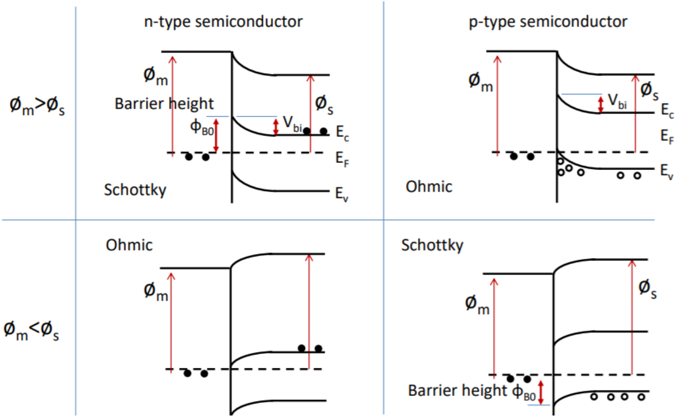


Figure: Ideal energy-band diagram (a) before contact and (b) after contact for a metal-p-type semiconductor junction for $\phi_m > \phi_s$.

Ohmic Contact and Schottky Contact

If $\phi_m > \phi_s$ for the metal-n-type semiconductor contact, and if $\phi_m < \phi_s$ for the metal-p-type semiconductor contact, we may not necessarily form a good ohmic contact.



Example 3

(a) Consider a metal-semiconductor junction formed between a metal with a work function of $4.8\mathrm{eV}$, and semiconductor Ge with an electron affinity of $4.13\mathrm{eV}$ and a bandgap of $0.66\mathrm{eV}$. The doping concentration in Ge is $N_\mathrm{d} = 2 \times 10^{14}\ \mathrm{cm}^{-3}$ and $N_\mathrm{a} = 6 \times 10^{14}\ \mathrm{cm}^{-3}$. Assume $T = 300\ \mathrm{K}$. Sketch the zero bias energy-band diagram. Is this an Ohmic contact or a Schottky contact? Determine the Schottky barrier height if it is a Schottky contact.

(b) If the metal work function is changed to $4.4\mathrm{eV}$, sketch the zero bias energy-band diagram. Is this an Ohmic contact or a Schottky contact? Determine the Schottky barrier height if it is a Schottky contact.

Example 3 Solution

(a) Plot

$$p_0 = N_a - N_d = N_v \exp\left(\frac{-(E_F - E_v)}{kT}\right) \Rightarrow E_F - E_v = 0.249\mathrm{eV}$$

It's Ohmic.

Example 3 Solution

(b) Plot

$V_{bi} = 0.141\ \mathrm{V}, \quad \phi_{Bo} = 0.39\ \mathrm{V}$

It's Schottky.

END

Thanks