# Metal-Semiconductor Contact

There are two types of metal-semiconductor contact:

1. Metal-semiconductor rectifying contact
2. Metal-semiconductor ohmic contact

## Metal-semiconductor rectifying contact (Schottky barrier diode)

Metal-semiconductor rectifying contact or Schottky barrier diode. In most cases the rectifying contacts are made on n-type semiconductor. The parameter $\Phi_M$ is the work function of the metal (measured in volts), $\Phi_s$ is the work function of the semiconductor, and $\chi$ is the electron affinity. The work functions of various metals are given in Table.14.1 and the electron affinities of several semiconductors are given in Table.14.2. for Schottky contact $\Phi_M > \Phi_s$.

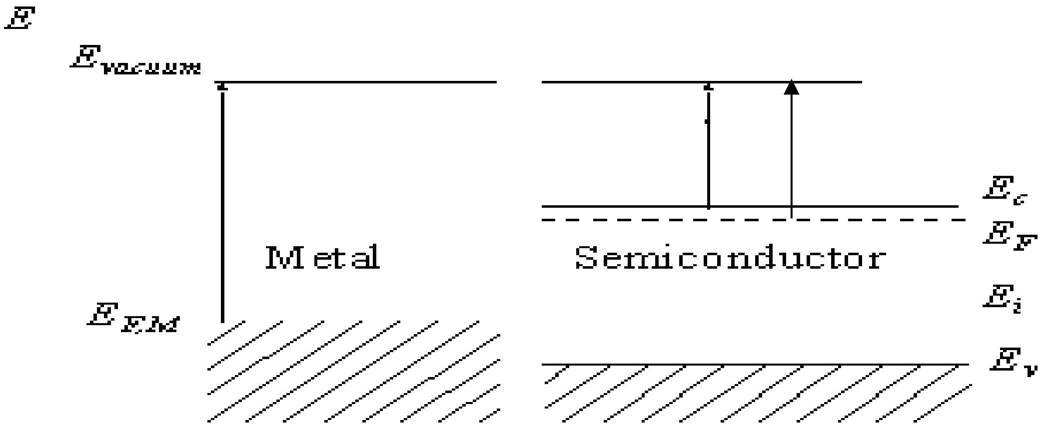
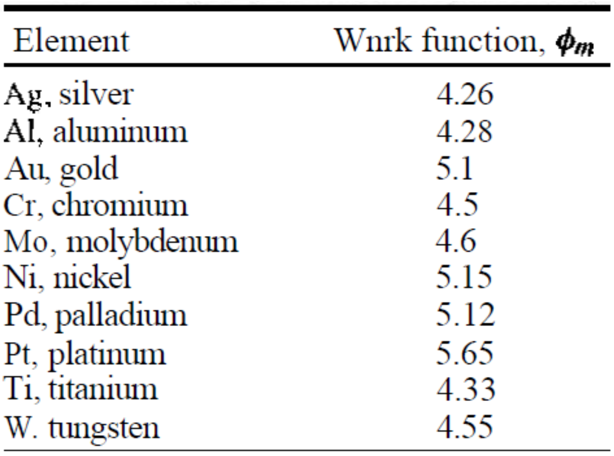
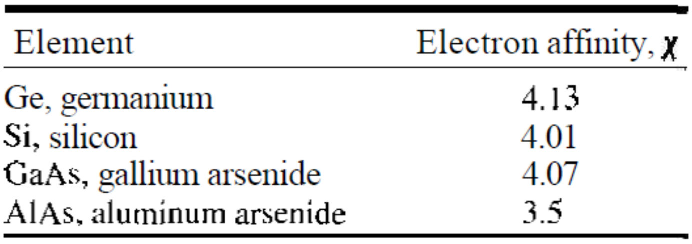


*Fig. 14.1 Energy-band diagram of a metal and semiconductor before contact;*



| Element | Wnrk function, $\phi_m$ |
|---|---|
| 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 |

*Table 14.1 Work functions of some elements*



| Element | Electron affinity, $\chi$ |
|---|---|
| Ge, germanium | 4.13 |
| Si, silicon | 4.01 |
| GaAs, gallium arsenide | 4.07 |
| AlAs, aluminum arsenide | 3.5 |

*Table 14.2 Electron affinity of some semiconductors*

The ideal thermal equilibrium metal-semiconductor energy band diagram, for this situation is shown in the figure. Before contact, the Fermi level in the semiconductor was above that in the metal. In order the Fermi level to becomes a constant through the system in thermal equilibrium, electrons from the semiconductor flow into lower energy state in the metal. Positively charged donor atoms remain in the semiconductor, creating a space charge region.

The parameter $\phi_B$ 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 obtained from:

$$\phi_B = \Phi_M - \chi$$ , for n-type semiconductor

On the semiconductor side, $V_{bi}$ is the built-in potential barrier, this is the barrier seen by electrons in the conduction band trying to move into the metal. The built-in potential barrier is given by:

$$V_{bi} = \phi_B - \frac{E_c - E_F}{e}$$

, for n-type semiconductor

$$\phi_n = \frac{E_c - E_F}{e} = \frac{kT}{e} \ln\left(\frac{N_c}{N_d}\right)$$

Where $E_c$ is the bottom edge of the conduction band, $E_F$ is the Fermi level in n-type semiconductor and $e$ is the electron charge.

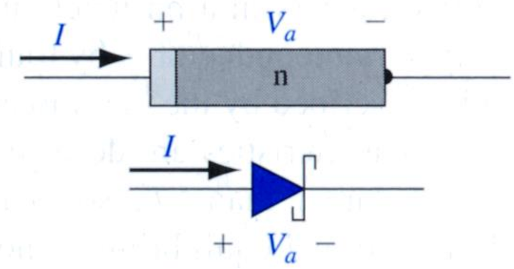


*Fig.14.2 Symbol of Schottky diode*

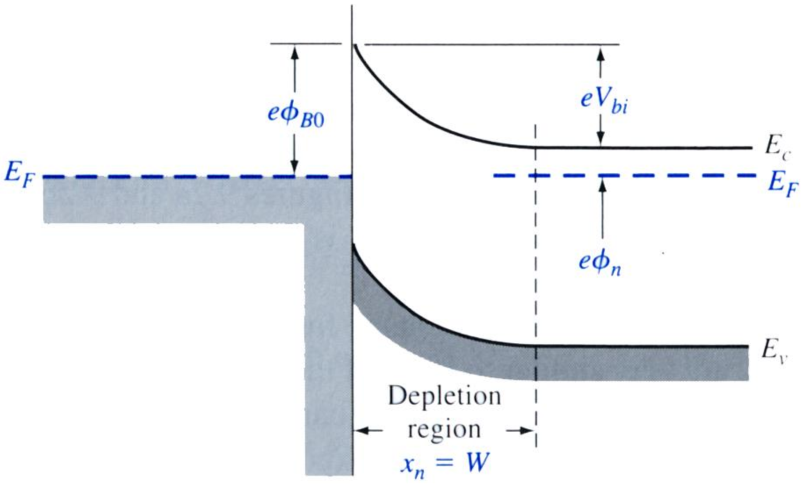


*Fig.14.3 ideal energy-hand diagram of a metal-n-semiconductor junction for $\Phi_M > \Phi_S$.*

## Forward and reverse bias

As a positive voltage is applied to the metal with respect to the semiconductor, the semiconductor-to-metal barrier $V_{bi}$ is reduced while $\phi_B$ remains constant. In this situation, the barrier seen by the electrons in the semiconductor is reduced so majority carrier electrons flow more easily from the semiconductor into the metal. The current mechanism here is due to the flow of majority carrier electrons.

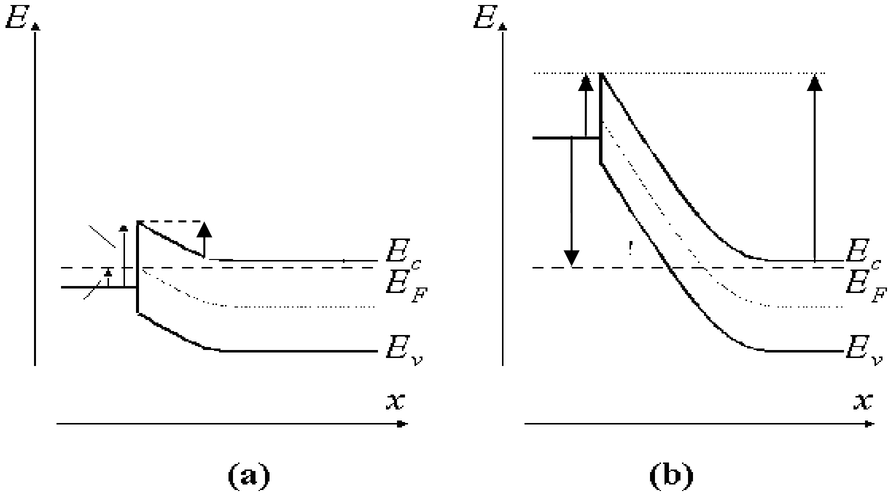


*Fig.14.4 Ideal energy-band diagram of a metal-semiconductor junction (a) under reverse bias and (b) under forward bias.*

In reverse bias situation a positive voltage is applied to the semiconductor with respect to the metal, the semiconductor-to-metal barrier height increases, while $\phi_B$ again remains essentially constant. The potential across the semiconductor now increases, yielding a larger depletion region and a larger electric field at the interface. The barrier, which restricts the electrons to the metal, is unchanged so that the flow of electrons is limited by that barrier independent of the applied voltage. The metal-semiconductor junction with positive barrier height has therefore a pronounced rectifying behavior.

A large current exists under forward bias, while almost no current exists under reverse bias.

The space charge width, W is given by

$$W = x_d = \left\{ \frac{2\varepsilon_s \left(V_{\mathrm{bi}} + V_R\right)}{eN_d} \right\}^{1/2}$$

The maximum electric field is given by

$$E_{\max} = \frac{eN_d x_d}{\varepsilon_s}$$

**Example**

Calculate the barrier height, built in potential and maximum electric field in a metal-semiconductor diode for zero applied bias. Consider a contact between tungsten and n-type silicon $N_d=10^{22}/\mathrm{m}^3$ at T=300K.

Solution

The metal work function for tungsten (W) from the Table 1, $\varphi_M$=4.55V and the electron affinity for silicon from Table 2 is $\chi$=4.01V.

The barrier height is then

$$\phi_B = \Phi_M - \chi = 4.55 - 4.01 = 0.54V$$

$$V_{bi} = \phi_B - \phi_n$$

$$\phi_n = \frac{kT}{e}\ln\left(\frac{N_c}{N_d}\right) = 0.0259\ln\left(\frac{2.8\times10^{25}}{10^{22}}\right) = 0.206V$$

$$V_{bi} = 0.54 - 0.206 = 0.33V$$

The space charge width at zero bias is

$$W = x_d = \left\{ \frac{2\varepsilon_s V_{\mathrm{bi}}}{eN_d} \right\}^{1/2} = \left\{ \frac{2\times 11.7\times 8.85\times 10^{-12}\times 0.33}{1.6\times 10^{-19}\times 10^{16}} \right\}^{1/2}$$

$$W = x_d = 0.207\mu m$$

$$E_{\max} = \frac{eN_d x_d}{\varepsilon_s} = \frac{1.6\times 10^{-19}\times 10^{22}\times 0.207\times 10^{-6}}{11.7\times 8.85\times 10^{-12}} = 3.2\times 10^{6} V/m$$

**Current vs. Voltage Relation**

The current versus voltage relationship for a Schottky barrier diode to be like the exponential behavior of the pn junction diode. The forward bias current is in the direction from metal to semiconductor; it is an exponential function of forward bias voltage $V$ and given by the following equation known as the Richardson equation.

$$I = I_s\left(e^{eV/\eta kT} - 1\right)$$

Where $I_s$ is the saturation current and given by,

$$I_S = AA^{*}T^{2}e^{-e\phi_B/kT}$$

$A^*$ is the Richardson constant and given by,

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

$A$ is the area, $k$ is the Boltzmann’s constant, $T$ is the temperature, $\eta$ is the ideality factor. As we see the saturation current is determined by thermionic emission of majority carriers over a potential barrier.