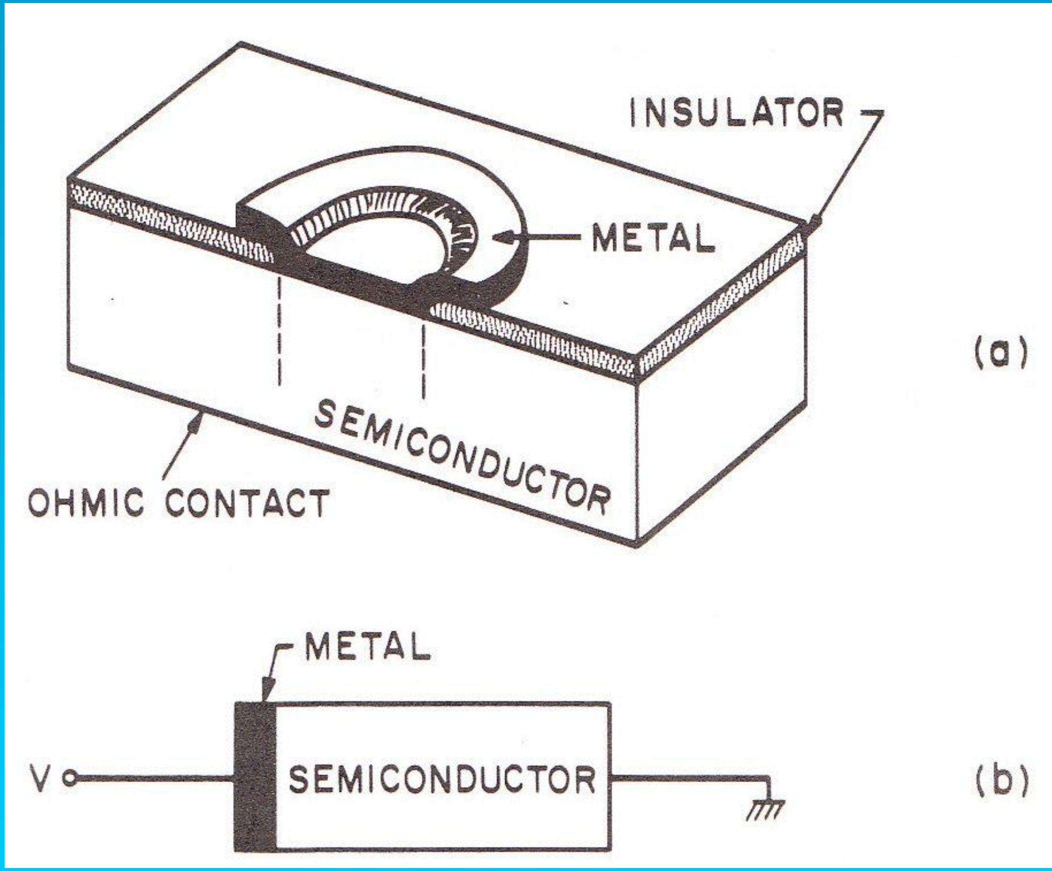
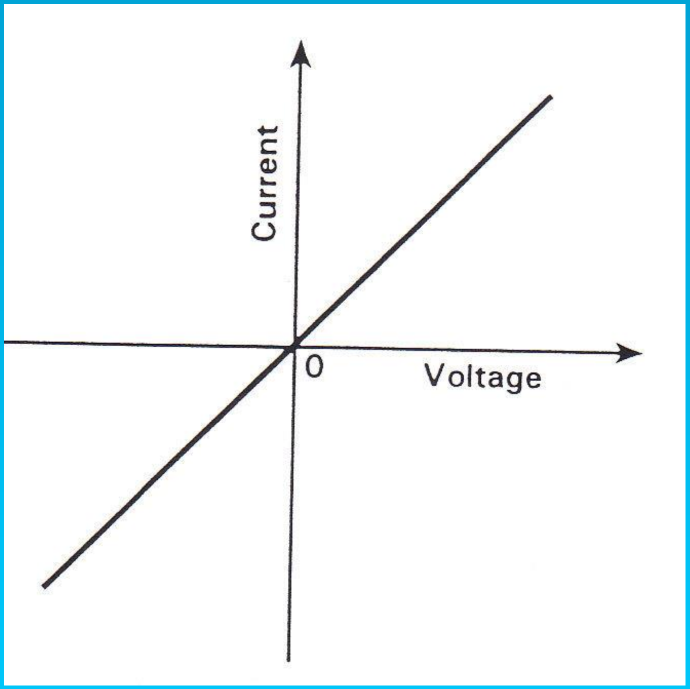
Metal-semiconductor contacts

The integrated circuit must be accessible to the "outside world" through conducting pads for testing with metal probes and for bonding to metal pins to complete the packaged chip. While doped silicon and polysilicon conduct electricity, they are of limited use for interconnections, mainly because of their large resistance and lack of interconnecting flexibility. Therefore, at least one low-resistance conductor film must be deposited and patterned to contact and interconnect the different regions on the chip.

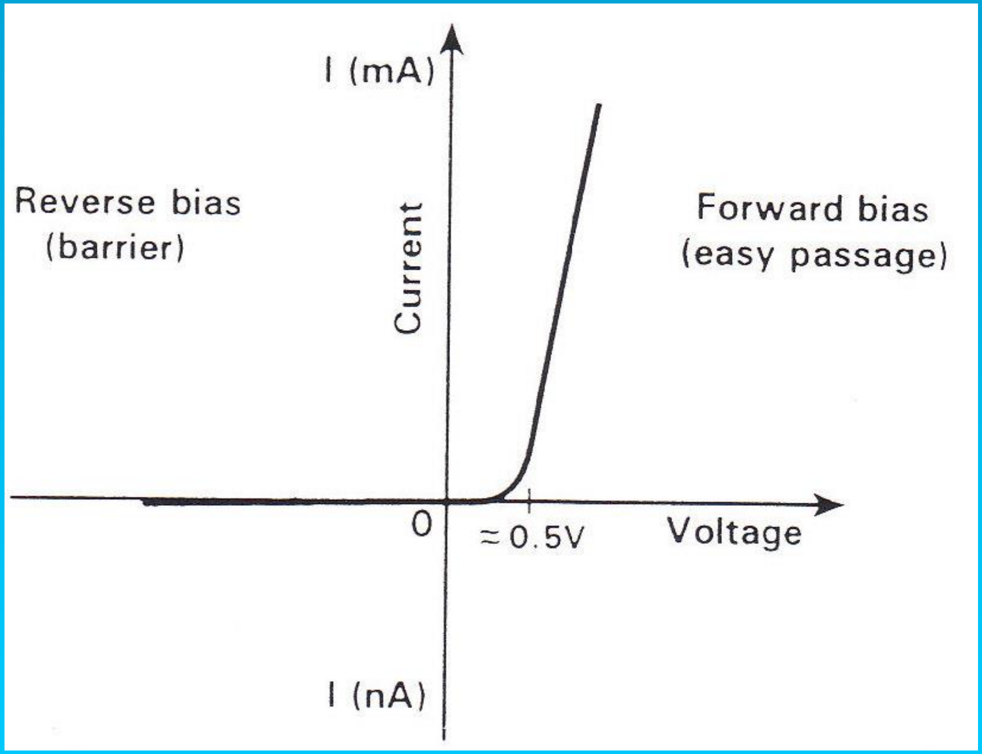
When contact is made between two dissimilar materials, a contact potential (barrier) typically develops at the interface between the materials. Contacts between metals and semiconductors can be categorised as non-rectifying (ohmic) and rectifying (Schottky barrier type diodes).


INSULATOR
METAL
SEMICONDUCTOR
OHMIC CONTACT
(a)
METAL
V
SEMICONDUCTOR
(b)

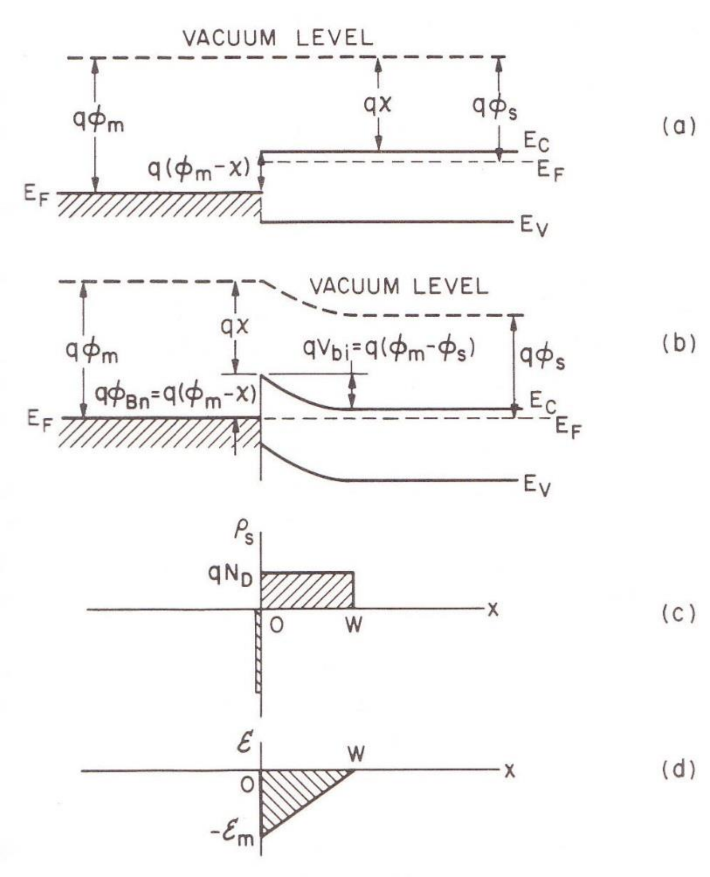
Ohmic contact



Schottky contact

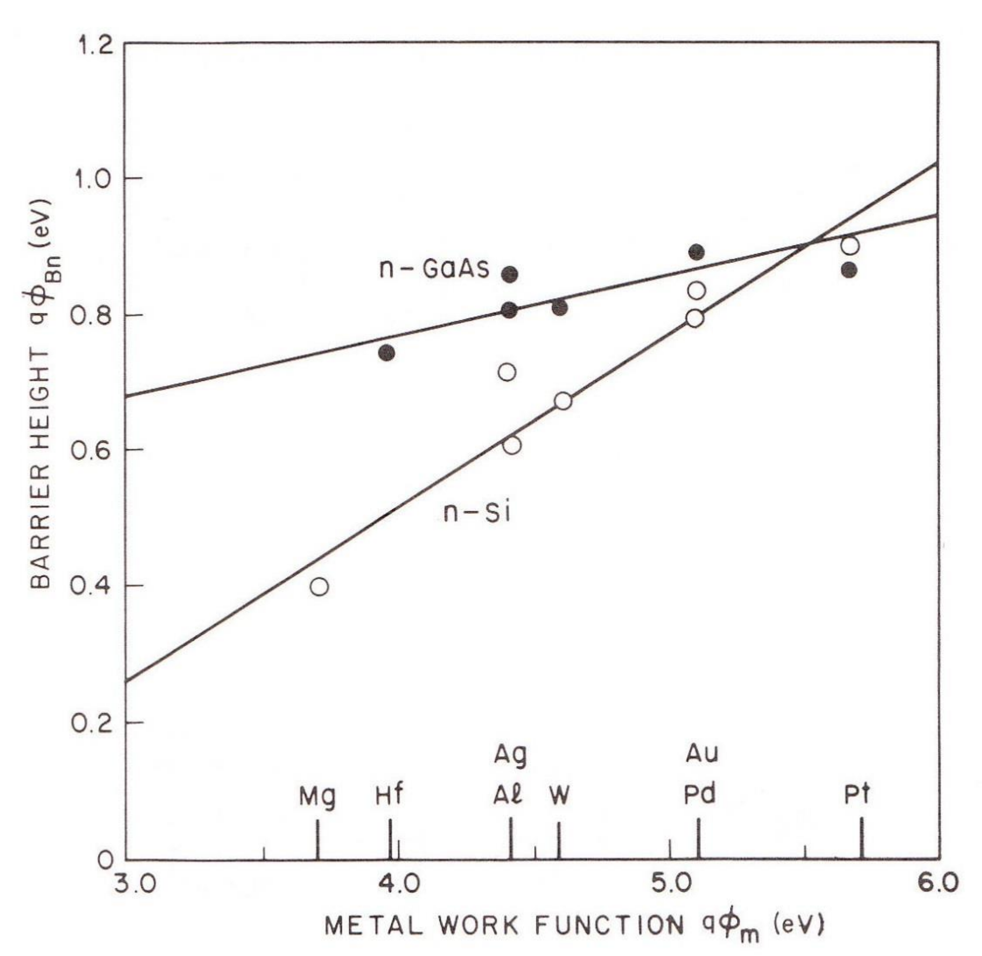


Band diagrams for a physical understanding of contact formation

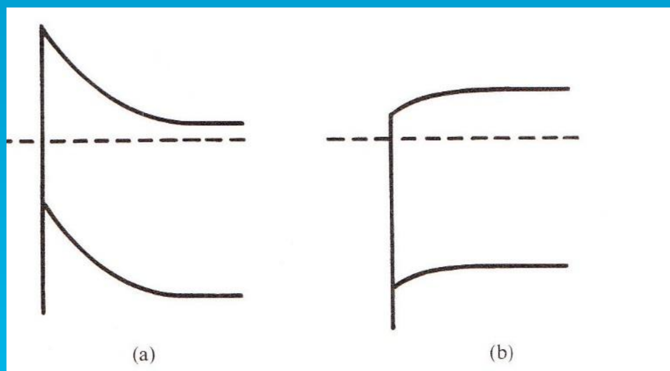


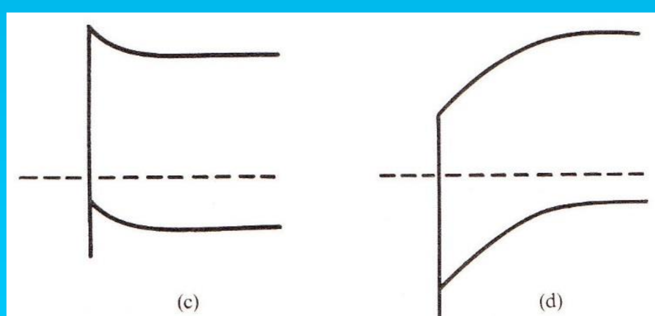
- $q\varphi_m$ – work function of metal – energy difference between Fermi level and vacuum level
- $q\varphi_s$ – work function of semiconductor
- $q\chi$ - electron affinity – energy difference between the conduction band edge and the vacuum level in the semiconductor
- $qV_{bi} = q(\varphi_m - \varphi_s)$

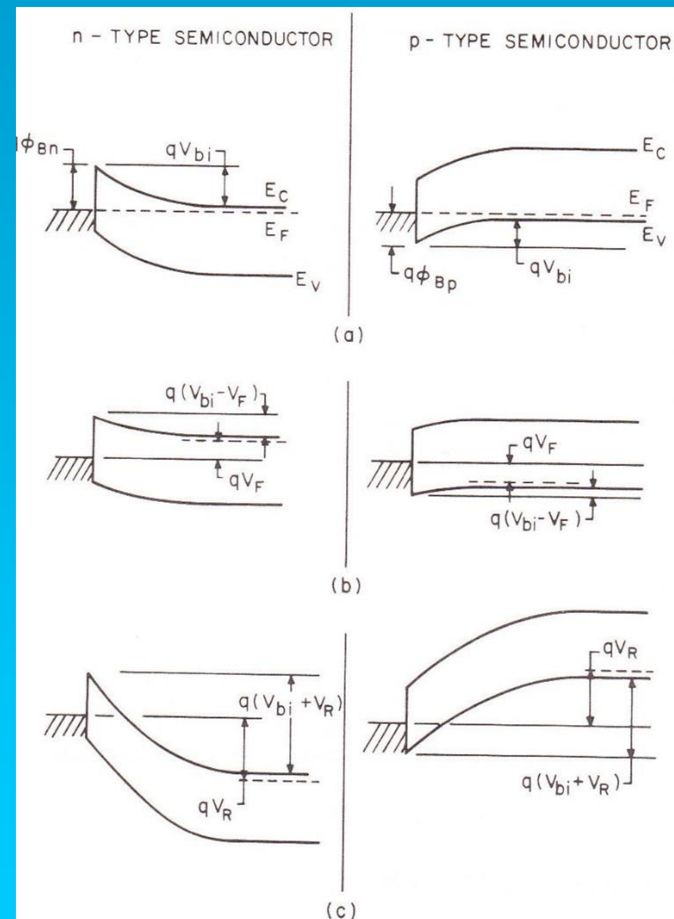
Measured barrier height for metal-Si and metal GaAs contacts



N- and p- type semiconductor





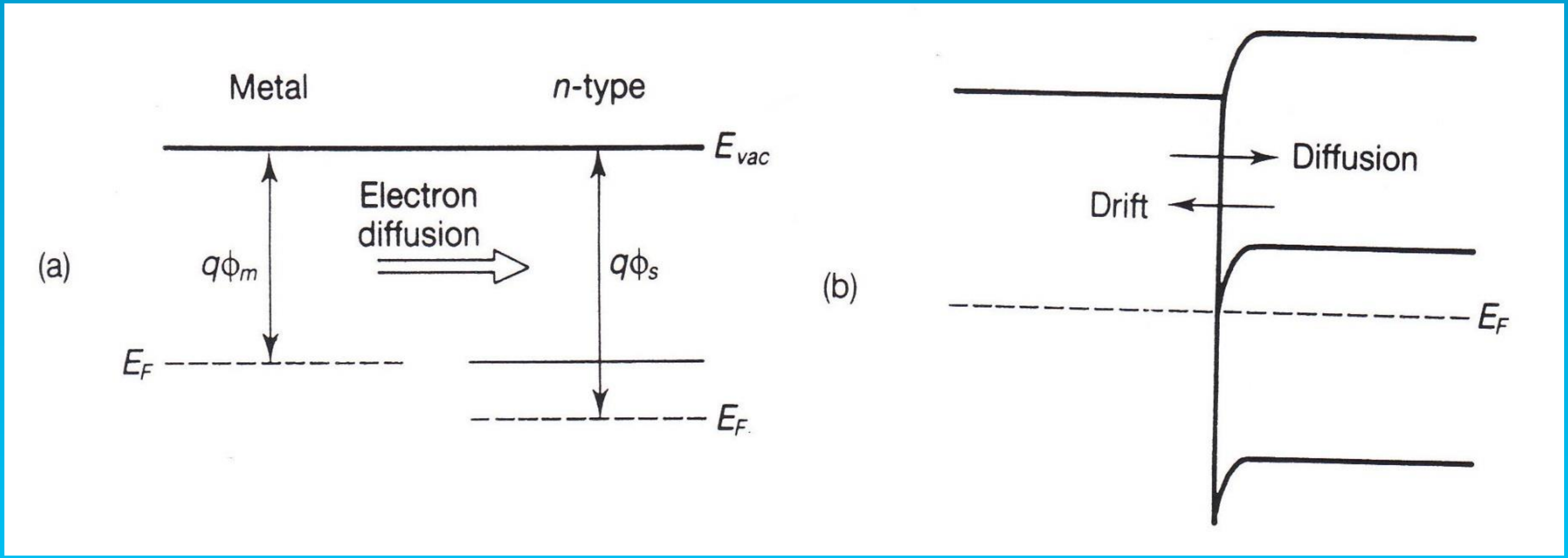


Ohmic contact

- Ohmic contact – allows current to flow in either direction with contact resistance as low as possible, a few milli-ohms.

2 cases:

1) $\varphi_m < \varphi_s$



- Electrons in metal sees no field → diffuse across to semiconductor
- Electrons in semiconductor sees field → drift to metal

2) $\varphi_m > \varphi_s$

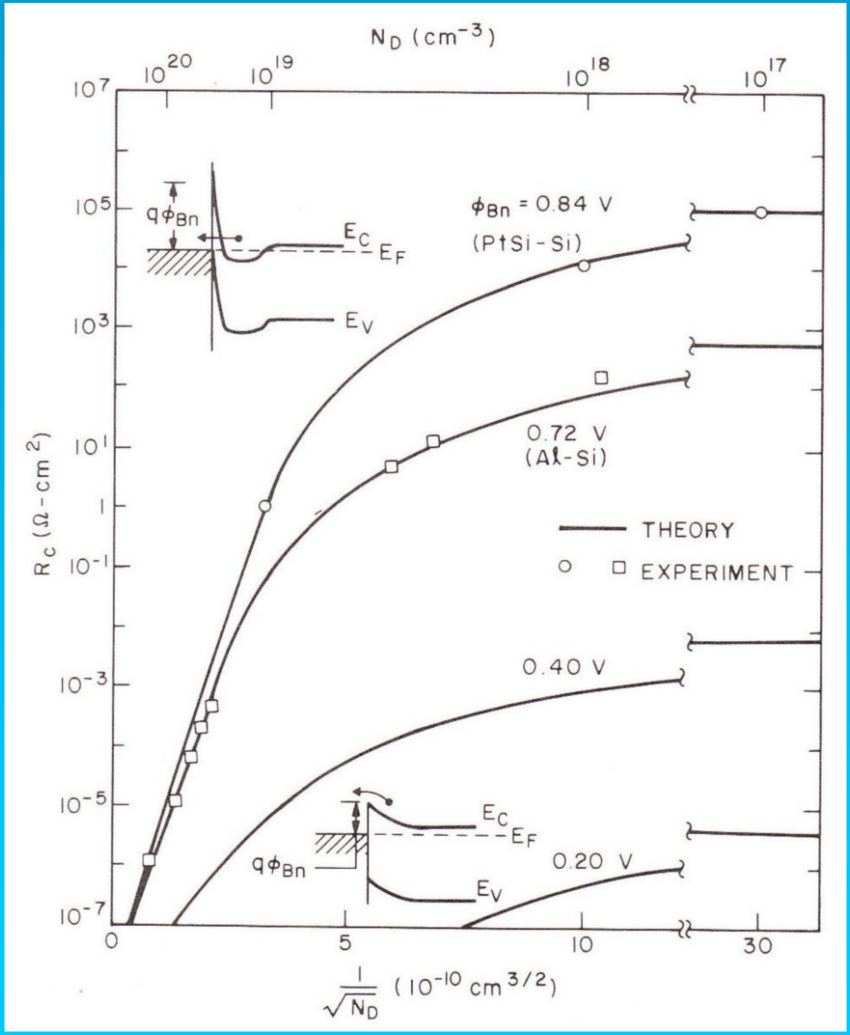
In this case, the specific contact resistance R_c depends on doping.

R_c (ohm-cm^2) = $(dJ/dV)^{-1}$ at $V=0$

For metal-semiconductor contacts with low doping concentrations, the thermionic-emission current dominates the current transport. R_c has an exponential dependence on the barrier height.

- For contacts with high dopings, the barrier becomes very narrow and the tunnelling current becomes dominant. In this case, R_c varies with the ratio of the barrier height and $(N_D)^{½}$.

Contact resistance as a function of doping



For example, Al on Si, NiGe/Au or In on GaAs :

Work function φ_m :

Al – 4.3eV

Ni – 4.78eV

In – 3.97eV

Electron affinity :

GaAs – 4.07eV

Si- 4.05eV

Contact resistance depends on relative metal semiconductor work functions, chemical reactions and temperature of contact formation.

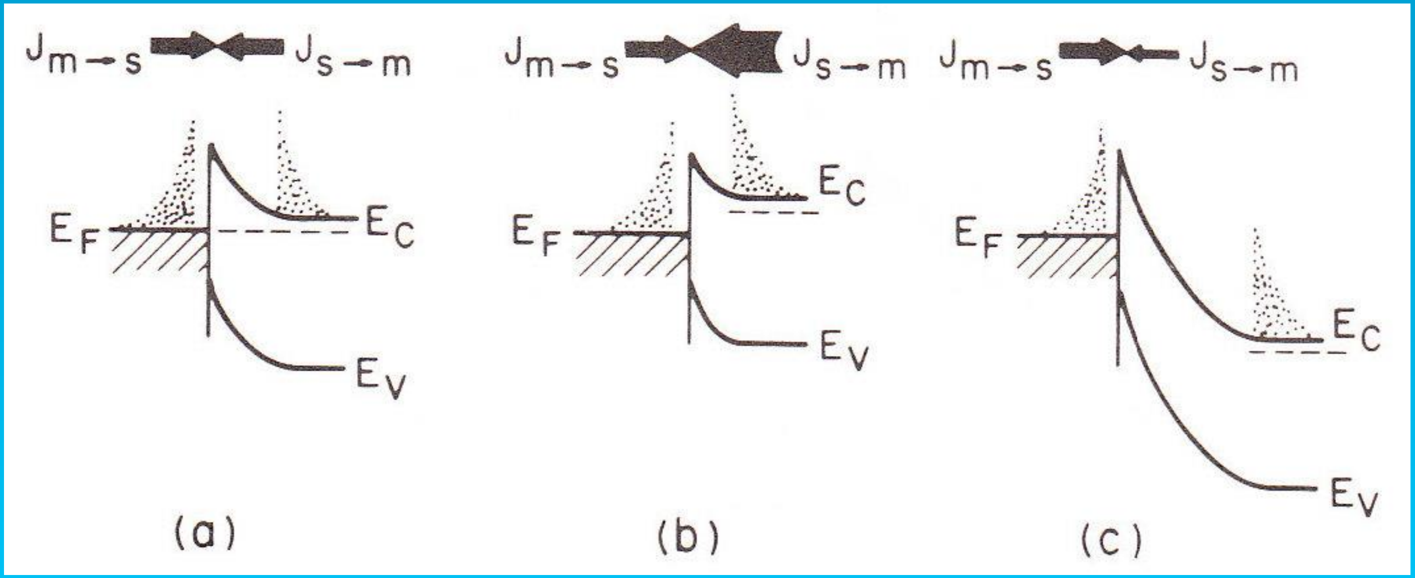
Schottky barrier

– only allows current to flow in one direction, e.g. Al-Si; Ti/Au – GaAs

It is a necessary condition that $\varphi_m > \varphi_s$

Current transport in metal-semiconductor contacts is due mainly to majority carriers, in contrast to p-n junctions, where current transport is mainly due to minority carriers.

For moderately doped semiconductors ($N_D \leq 10^{17}cm^{-3}$) operated at 300K, the dominant current transport mechanism is thermionic emission of majority carriers from the semiconductor over the potential barrier into the metal.



$J_{m \to s}$
$J_{s \to m}$
E_F
E_C
E_V
(a)
(b)
(c)

a) At thermal equilibrium, the current density is balanced by two equal and opposite flows of carriers, thus there is zero net current flow

b) When a forward bias is applied to the contact, the electrostatic potential difference across the barrier is reduced and the electron density at the surface increases: $J_s \rightarrow m \gg J_m \rightarrow s$

c) When a reverse bias is applied, $J_s \rightarrow m \ll J_m \rightarrow s$

Schottky diode equation

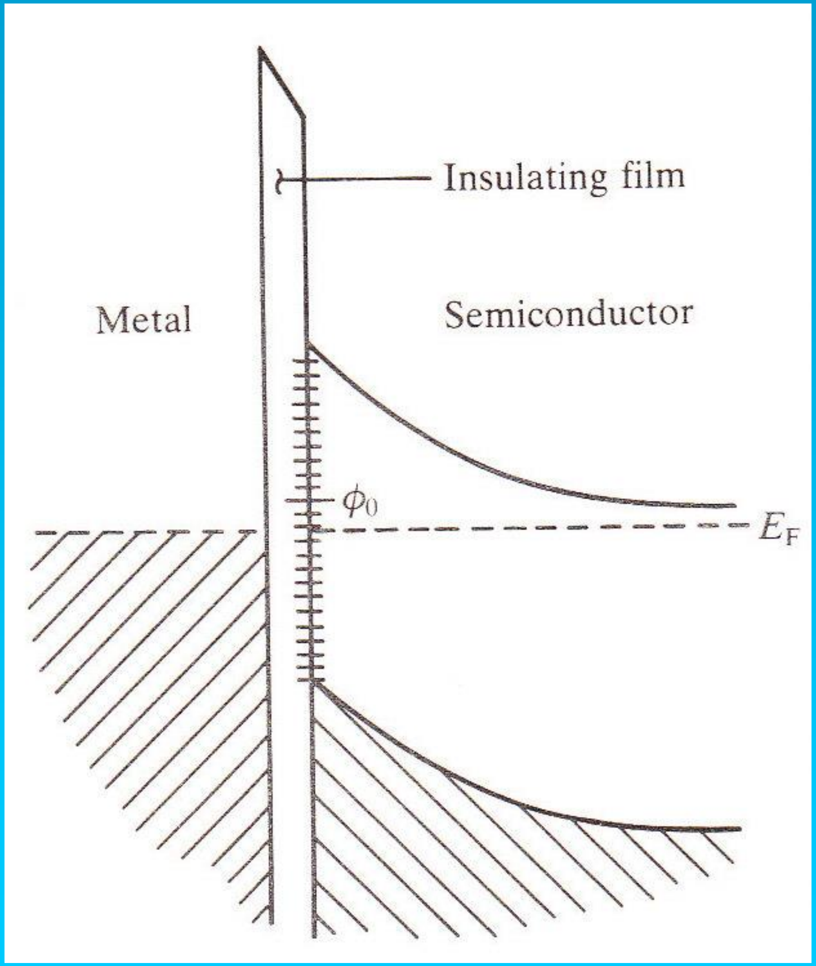
The current-voltage characteristic of a metal-semiconductor contact under thermionic emission condition is:

$$J = A^{*}T^{2}e^{-q\phi_{Bn}/kT}\left(e^{qV/kT} - 1\right)$$

$$A^{*} = \frac{4\pi m^{*}qk^{2}}{h^{3}}$$

φ_{Bn} is the surface pinning potential

With interface states



Band calculation for a Schottky diode

- The relationship between charge and potential in a Schottky diode can be found by solving Poisson's equation :
- $\nabla^2 V(r) = -\rho(r)/\varepsilon$
- where V is the potential, ρ is the charge density, ε is the permittivity and r is the real space vector. The distribution of charge and the electric field in the diode are shown in the diagram. Far away from the junction, both the metal and the semiconductor are in equilibrium, therefore, there is no overall charge.

As a result, both the charge density ρ and the electric field E are zero. At the junction, the semiconductor is depleted of electrons up to a distance w. w is the depletion depth. Since the donors are fixed to the lattice, there is a fixed charge in the depletion layer, which is positive and equal to the donor density N_D.

The total charge is qN_D dA, where A is the diode area on the semiconductor surface. On the metallic side of the barrier there is an accumulation of electrons. This accumulation of electrons must compensate for the electrons removed from the depletion layer of the semiconductor, thus charge is $-qN_D$ dA. However, since the metal is electron rich, the accumulation layer is strongly screened by the electron gas.

This causes the electric field in the metal to drop from its peak value at the interface (x=0) to zero very rapidly since the electrostatic screening length in a metal is very small. As a result, we need only solve Poisson's equation for the semiconductor side of the diode, since the field in the metal has little effect on the behaviour of the diode.

A further simplification arises when we consider a diode that consists of an infinitely large plate of metal. In such a case, we do not need to consider field fringing, thus we need only solve Poisson's equation in one dimension.

Thus,

$$\frac{\partial^2 V(r)}{\partial x^2}+\frac{\partial^2 V(r)}{\partial y^2}+\frac{\partial^2 V(r)}{\partial z^2}=\frac{-\rho(r)}{\varepsilon}$$

becomes a 1D problem, meaning we can disgard the y and z terms, so

$$\frac{\partial^2 V(r)}{\partial x^2}=\frac{-\rho(r)}{\varepsilon}$$

which can be simplified to

$$\frac{\partial^2 V(x)}{\partial x^2} = \frac{-\rho(x)}{\varepsilon}$$

since both potential and charge are invariant in all but the x direction. To solve equation (1), we use the following procedure.

The charge density in the semiconductor is e (N_D – n), where N_D is the donor density and n is the electron density. Inside the depletion layer, we can discard the n term, since there are no free electrons, thus the equation we must solve is

$$d^2V/dx^2 = - eN_D/\varepsilon \qquad (2)$$

Integrating once gives

$$dV/dx = -eN_D\, x/\varepsilon + A \qquad (3)$$

where A is a constant.

To find A, we must match boundary conditions to the solution. From the figure before, we see that the electric field outside the depletion region is zero, therefore at

$x=w$; $dV/dx = 0$, thus

$A = eN_D w/\varepsilon$ and

$$dV(x)/dx = -\,eN_D\,(x-w)/\varepsilon \qquad (4)$$

This tells us what the electric field is. To find out the potential we integrate (4), thus

$$V(x) = - eN_D/\varepsilon \,.\, [x^2/2 - wx] + B$$

Again, we must match the boundary conditions to get the complete solution. At the metal-semiconductor junction, the conduction band is raised to an energy that is qV_{bi} greater than that of the bulk semiconductor, therefore at $x = 0$, $V = -V_{bi}$ (note that the electron energy is positive, but the potential is negative), thus $B = -V_{bi}$, and

$$V(x) = eN_D/\varepsilon \,.\, [wx - x^2/2] - V_{bi}$$

This equation completely describes the shape of the potential barrier formed at a metal semiconductor junction. Typical values for V_{bi} depend upon the doping, but the surface pinning potential φ_{Bn} is relatively invariant for many metals making contact with GaAs. A typical value is 0.7V for metals such as Ti or NiCr. Typical doping densities for Schottky diodes are around 10^{21} m^{-3} (using Si as a donor)

- 4pt probe method – to eliminate contact resistance
- TLM method – to measure contact resistance