Schottky diode

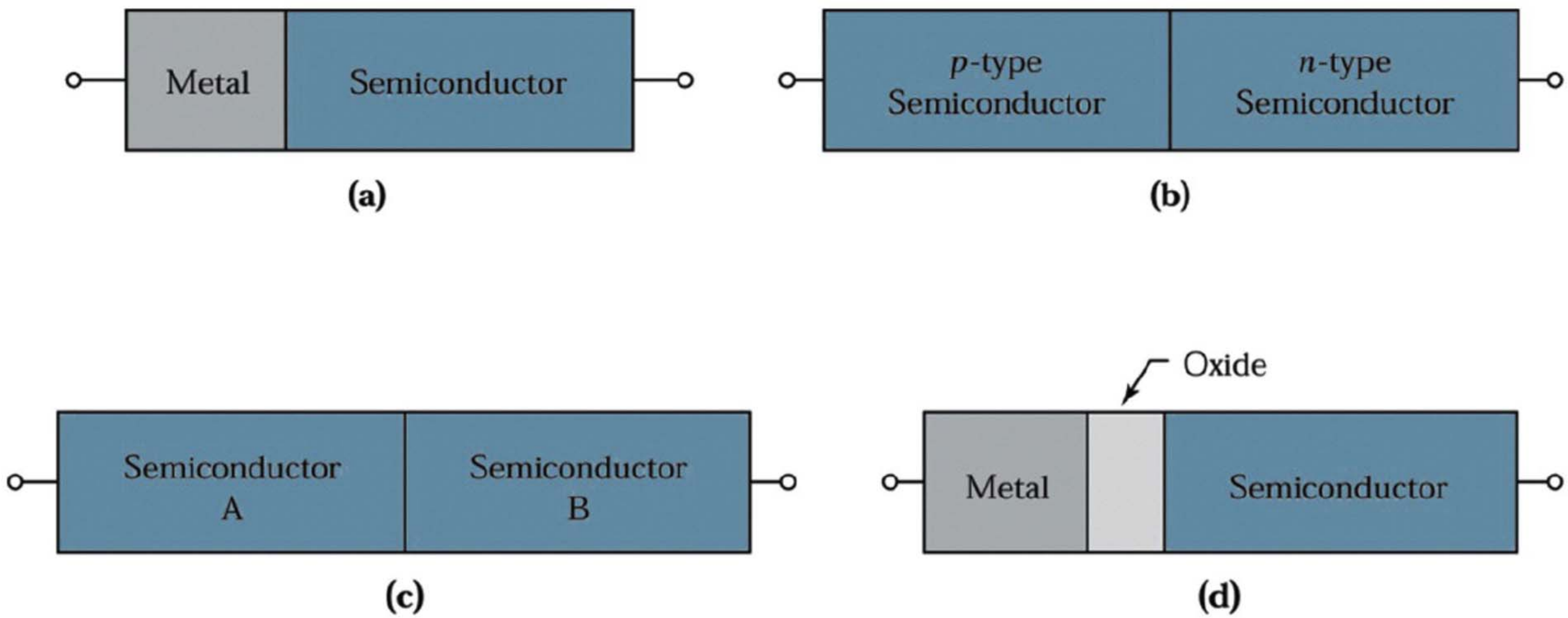


Figure 0.2
© John Wiley & Sons, Inc. All rights reserved.

Basic device building blocks. (*a*) Metal-semiconductor interface; (*b*) *p*-*n* junction; (*c*) heterojunction interface; and (*d*) metal-oxide-semiconductor structure.

Metal-Semiconductor Contacts

There are 2 kinds of metal-semiconductor contacts:

- Rectifying
  “Schottky diode”

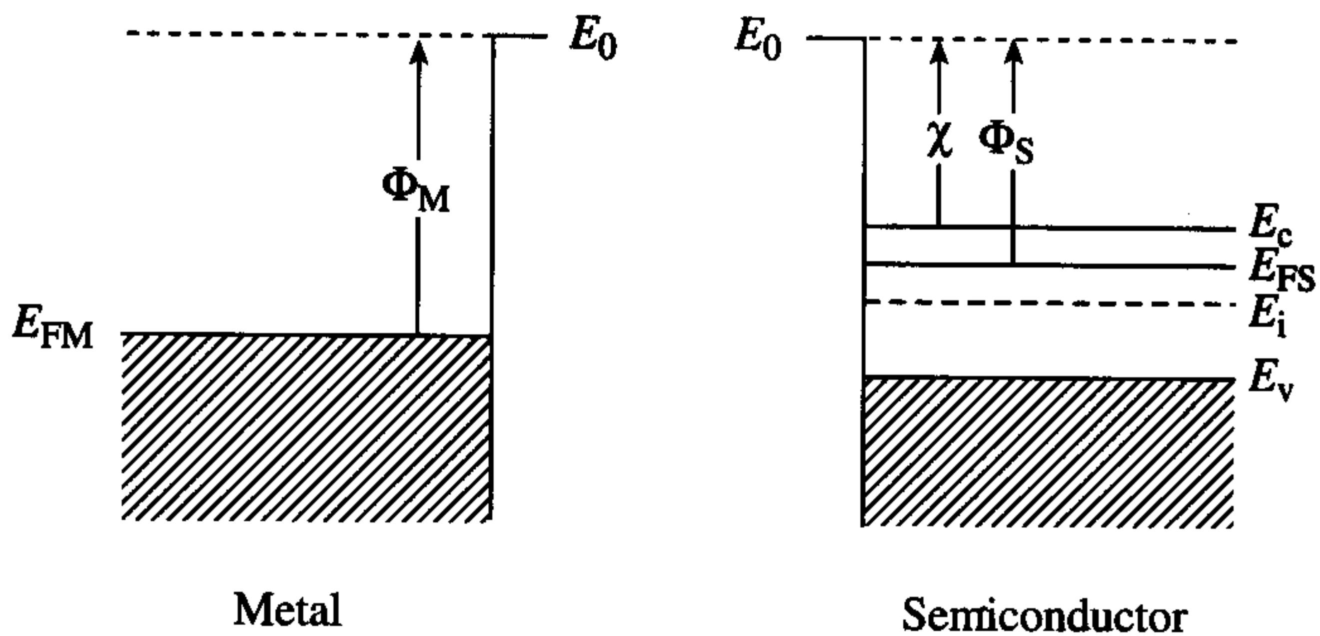
- Non-rectifying
  “Ohmic contact”

Metal-semiconductor (MS) junctions

- Many of the properties of pn junctions can be realized by forming an appropriate metal-semiconductor rectifying contact (Schottky contact)
  - Simple to fabricate
  - Switching speed is much higher than that of p-n junction diodes
- Metal-Semiconductor junctions are also used as ohmic-contact to carry current into and out of the semiconductor device

Work Function

E_0: vacuum energy level

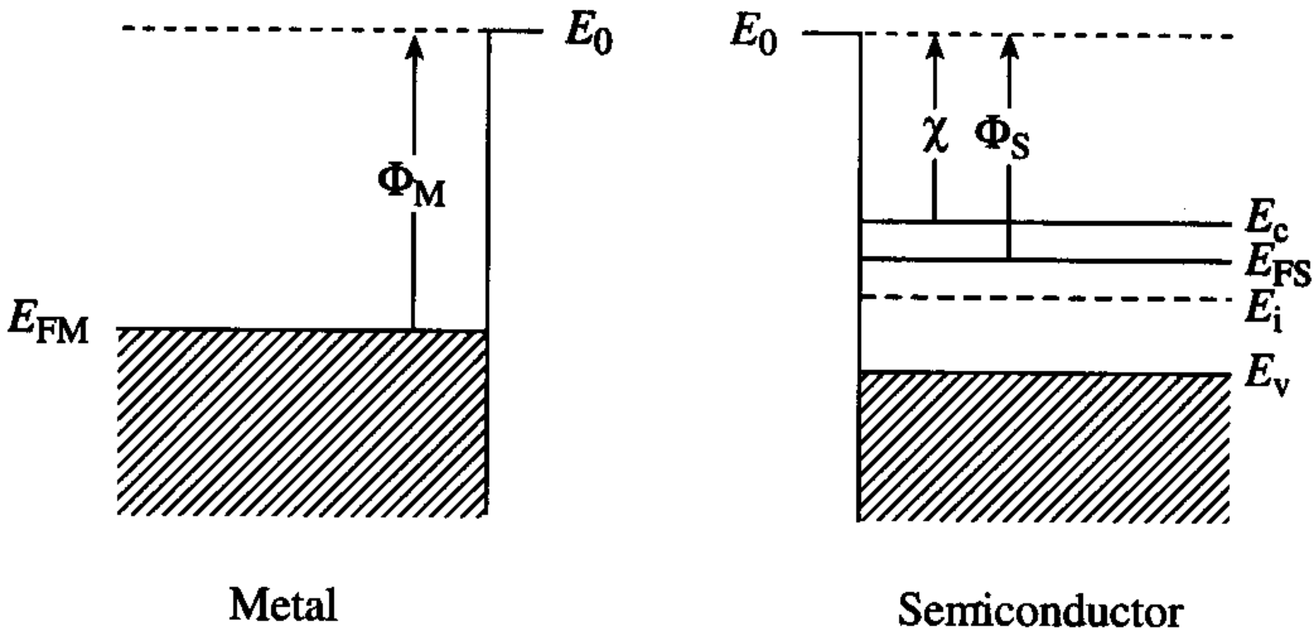


Φ_M: metal work function

Φ_S: semiconductor work function

Work Function

E_0: vacuum energy level



Φ_M: metal work function

Φ_S: semiconductor work function

Assumptions - Ideal MS contacts

- M and S are in intimate contact, on atomic scale
- No oxides or charges at the interface
- No intermixing at the interface

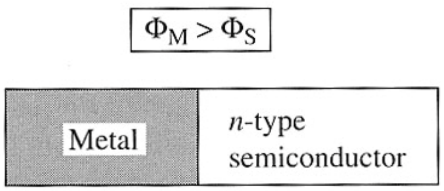
MS contacts

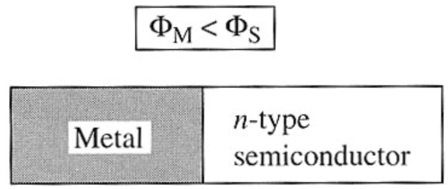
- Vacuum level, E_0 - corresponds to energy of free electrons.
- The difference between vacuum level and Fermi-level is called workfunction, Φ of materials.
  - **Workfunction, Φ_M** is an invariant property of metal. It is the minimum energy required to free up electrons from metal. (3.66 eV for Mg, 5.15eV for Ni etc.)
- The semiconductor **workfunction, Φ_s,** depends on the doping.

$$\Phi_s = \chi + (E_C - E_F)$$

- where $\chi = (E_0 - E_C)|_{SURFACE}$ is a fundamental property of the semiconductor. (Example: χ = 4.0 eV, 4.03 eV and 4.07 eV for Ge, Si and GaAs respectively)

Energy band diagrams for ideal MS

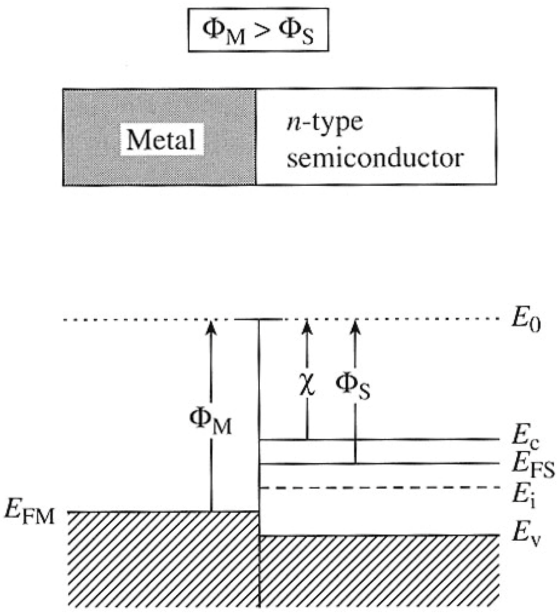




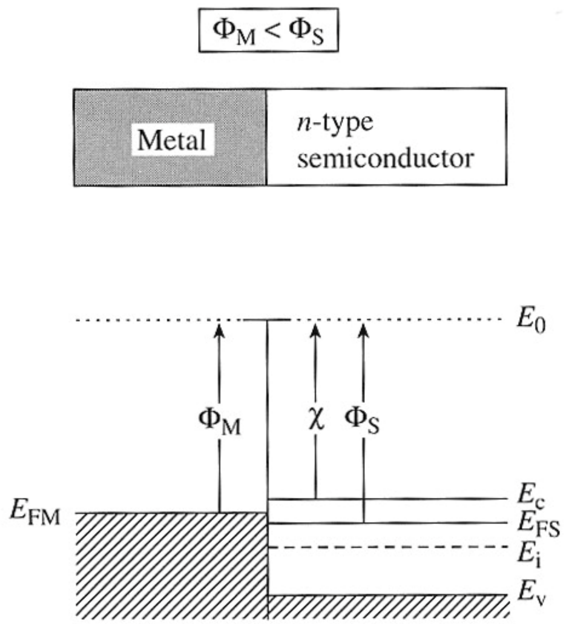
$\Phi_M > \Phi_S$

$\Phi_M < \Phi_S$

Energy band diagrams for ideal MS



(a)



(c)

(a) and (c) An instant after contact formation

$\Phi_M > \Phi_S$

$\Phi_M < \Phi_S$

Energy band diagrams for ideal MS

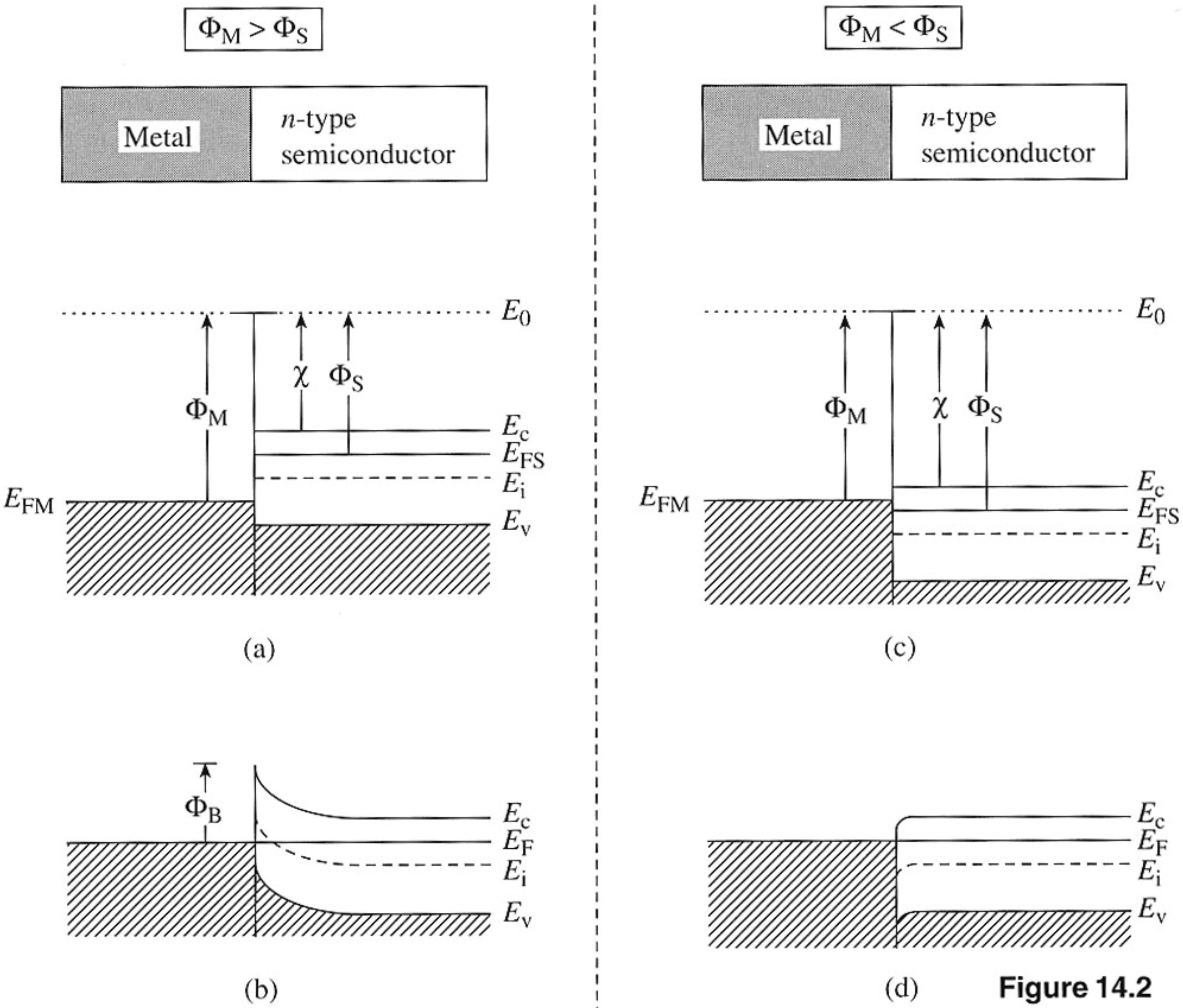


Figure 14.2

(a) and (c) An instant after contact formation

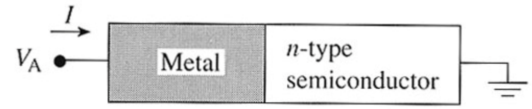
(b) and (d) under equilibrium conditions

$\Phi_M > \Phi_S$ $\Phi_M < \Phi_S$

MS (n-type) contact with $\Phi_M > \Phi_S$

- Soon after the contact formation, electrons will begin to flow from S to M near junction.
- Creates surface depletion layer, and hence a built-in electric field (similar to p^+-n junction).
- Under equilibrium, net flow of carriers will be zero, and Fermi-level will be constant.
- A barrier Φ_B forms for electron flow from M to S.
- $\Phi_B = \Phi_M - \chi$ ... ideal MS (n-type) contact. Φ_B is called "barrier height".
- Electrons in semiconductor will encounter an energy barrier equal to $\Phi_M - \Phi_S$ while flowing from S to M.

MS (n-type) contact with $\Phi_M > \Phi_S$



(a)

Response to applied bias for n-type semiconductor

Note: An applied positive voltage lowers the band since energy bands are drawn with respect to electron energy.

MS (n-type) contact with $\Phi_M > \Phi_S$

Response to applied bias for n-type semiconductor

Note: An applied positive voltage lowers the band since energy bands are drawn with respect to electron energy.

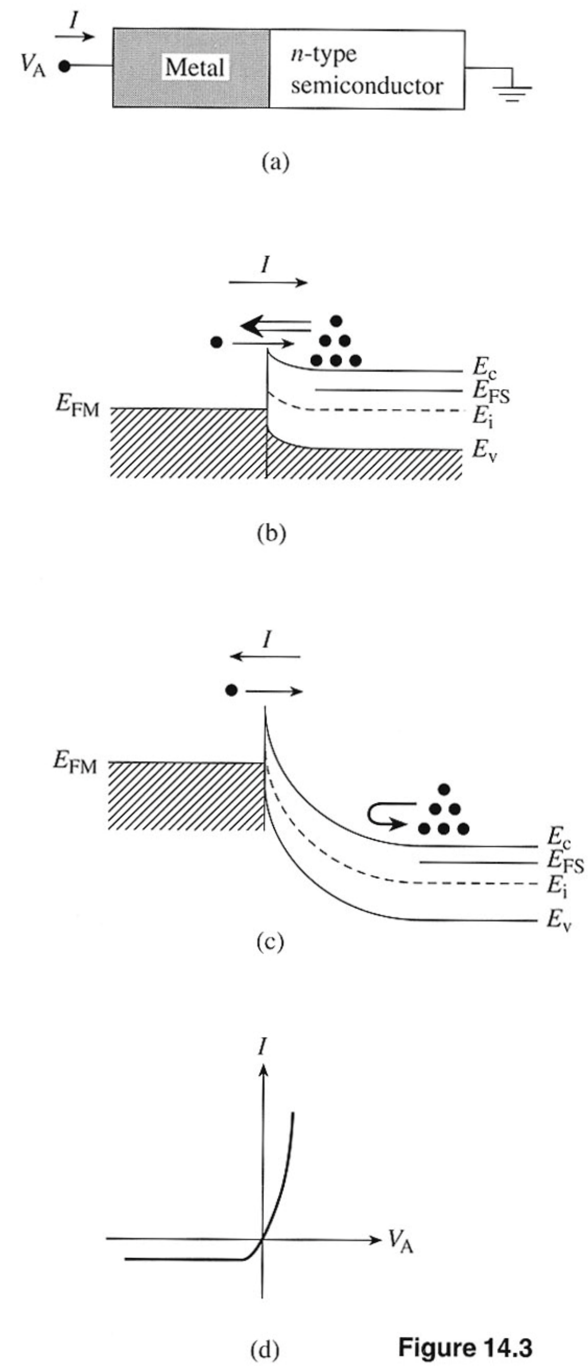
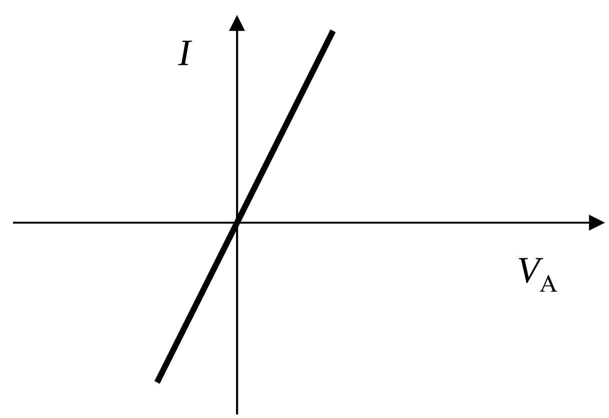


Figure 14.3

MS (n-type) contact with $\Phi_M < \Phi_S$

- No barrier for electron flow from S to M.
- So, even a small $V_A > 0$ results in large current.
- As drawn, small barrier exists for electron flow from M to S, but vanishes when $V_A < 0$ is applied to the metal. Large current flows when $V_A < 0$.
- The MS(n-type) contact when $\Phi_M < \Phi_S$ behaves like an ohmic contact.



Energy band diagrams for ideal MS

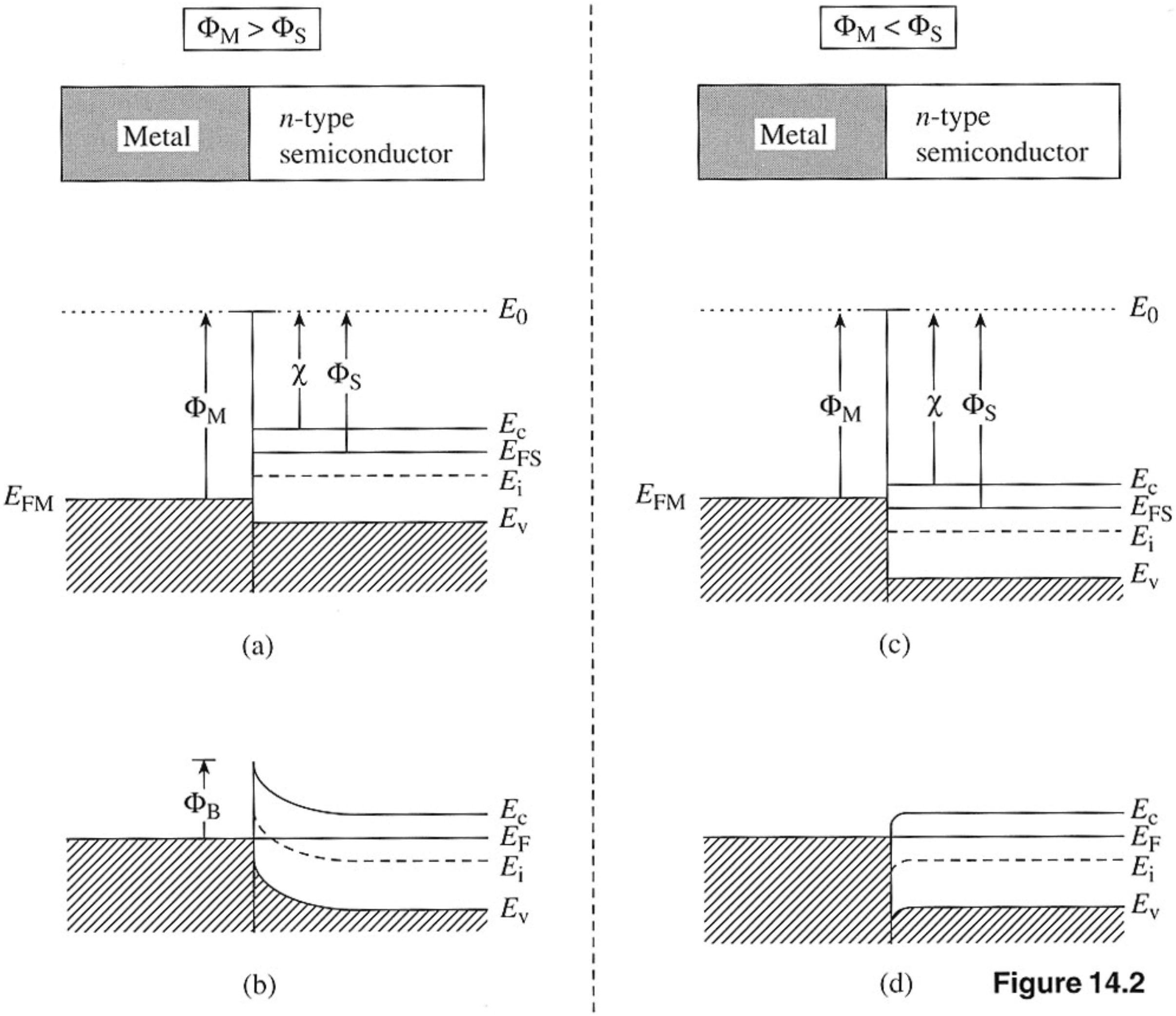


Figure 14.2

(a) and (c) An instant after contact formation

(b) and (d) under equilibrium conditions

$\Phi_M > \Phi_S$ $\Phi_M < \Phi_S$

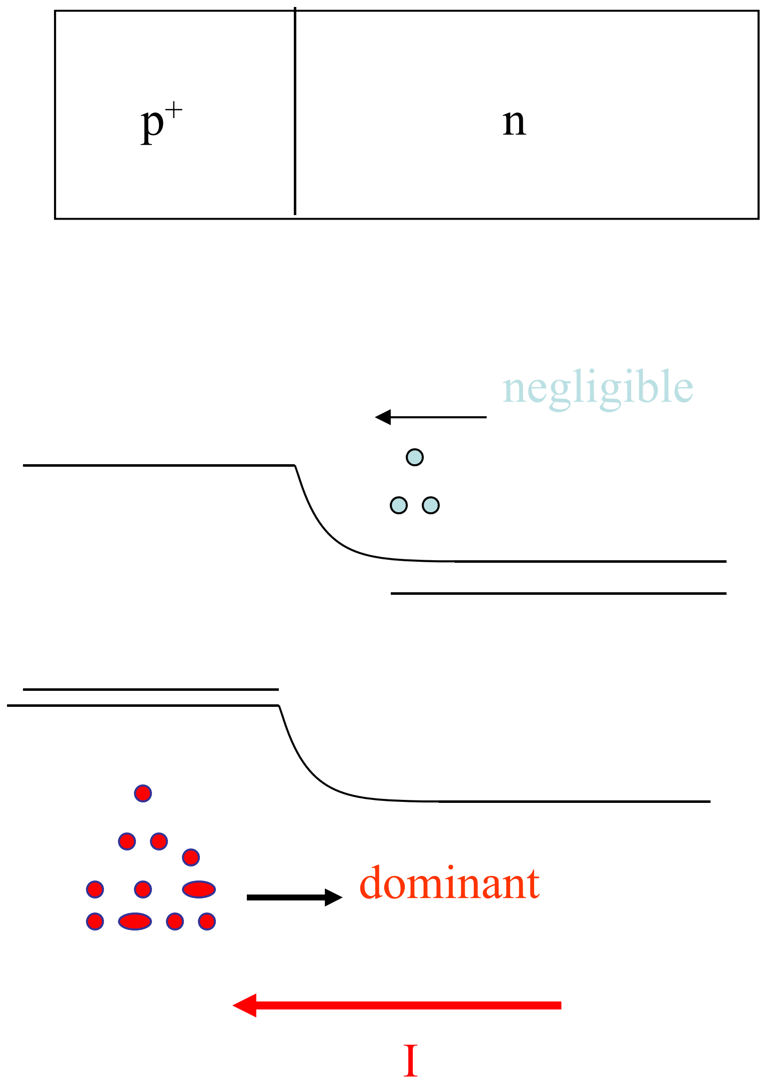
Schottky diode *vs* *pn* diode

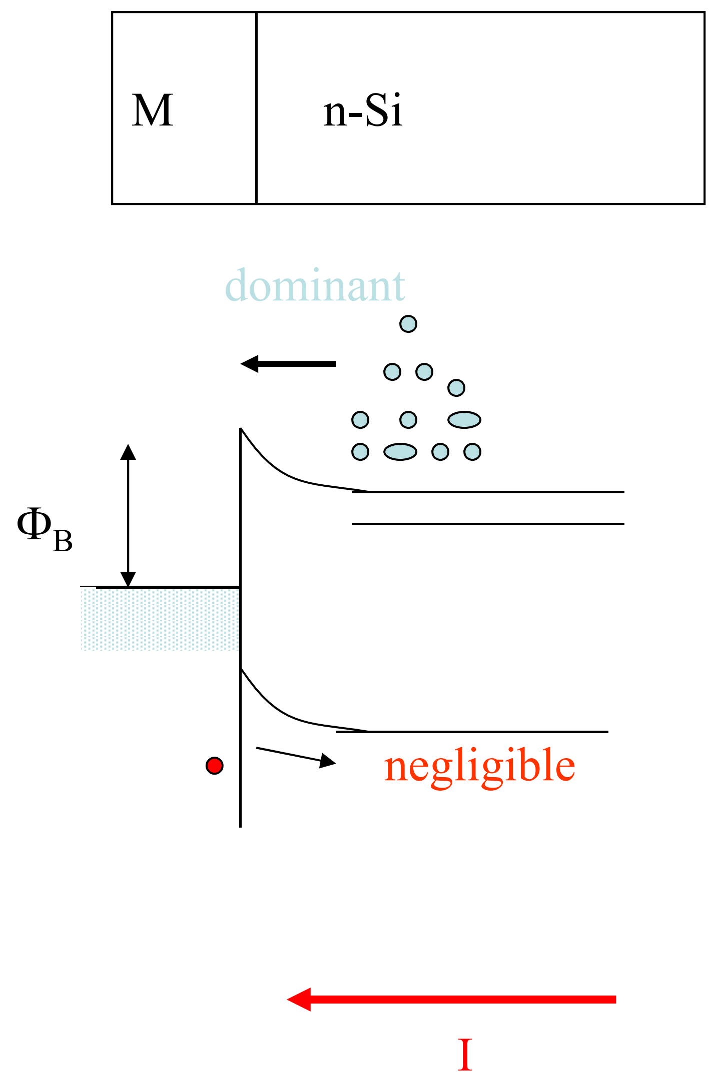
- MS diode electrostatics and the general shape of the MS diode I-V characteristics are similar to p^+n diodes, but the details of current flow are different.

Schottky diode *vs* *pn* diode

- MS diode electrostatics and the general shape of the MS diode I-V characteristics are similar to p^+n diodes, but the details of current flow are different.
- Dominant currents in a p^+n diode
  - arise from recombination in the depletion layer under small forward bias.
  - arise from hole injection from p^+ side under larger forward bias.
- Dominant currents in a MS Schottky diodes
  - Electron injection from the semiconductor to the metal.

Current components in a p$^+$n and MS Schottky diodes



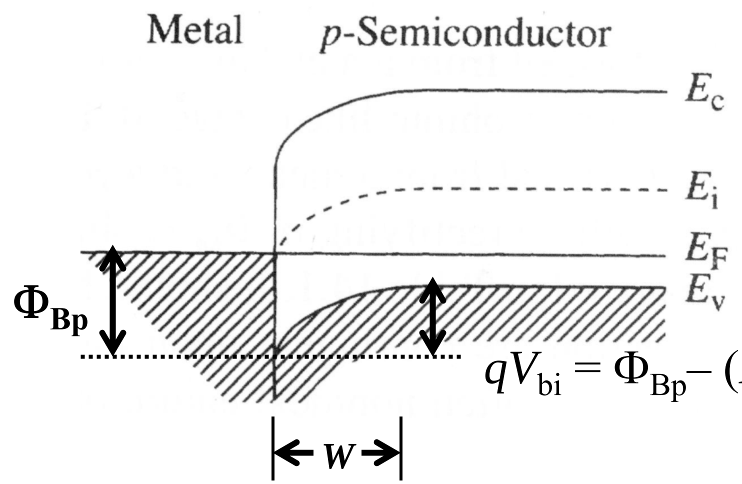


Ideal M-S Contact: $\Phi_M < \Phi_S$, p-type

Equilibrium band diagram:

***Schottky Barrier Height*:**

$$\Phi_{Bp} = \chi + E_G - \Phi_M$$

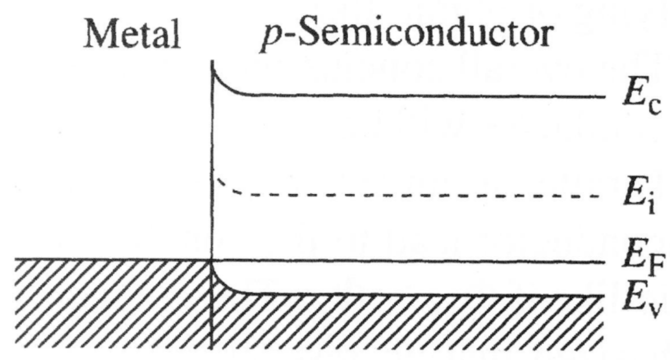


$qV_{bi} = \Phi_{Bp} - (E_F - E_v)$

p-type semiconductor

Ideal M-S Contact: $\Phi_M > \Phi_S$, p-type

Equilibrium band diagram:



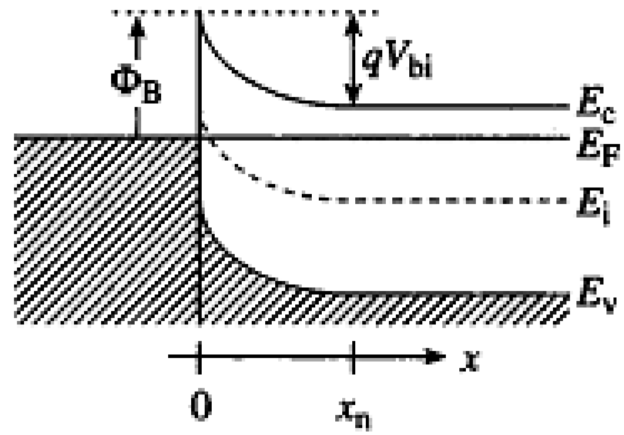
p-type semiconductor

The Depletion Approximation

The semiconductor is depleted of mobile carriers to a depth W

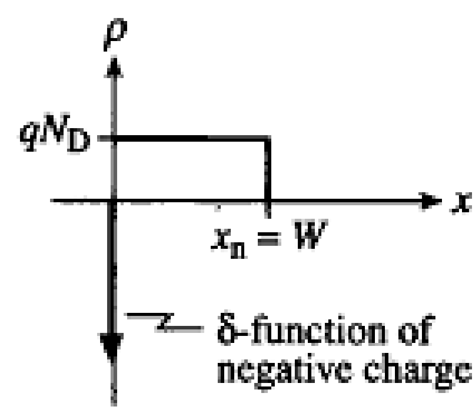
$\Rightarrow$ In the depleted region ($0 \le x \le W$):

$$\rho = q\,(N_D - N_A)$$



Beyond the depleted region ($x > W$):

$$\rho = 0$$

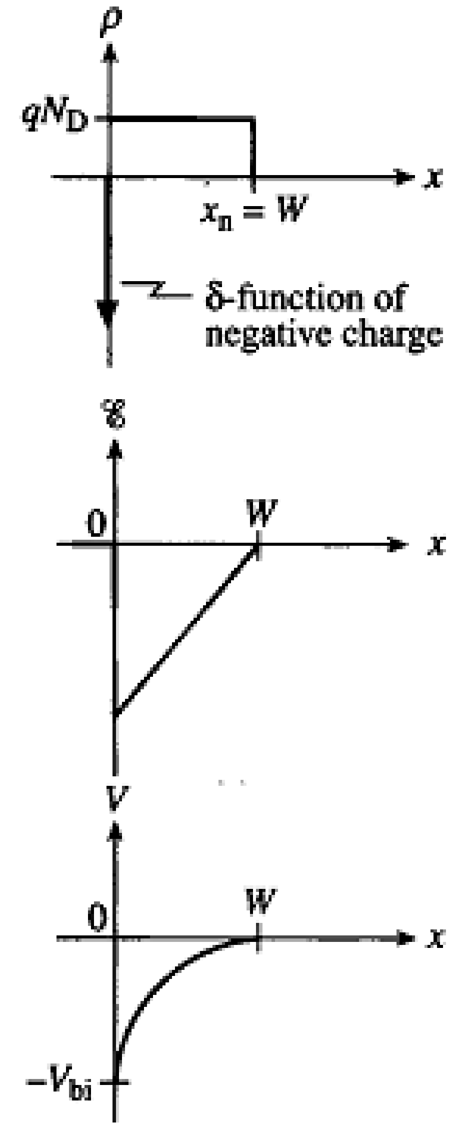


Electrostatics

- Poisson's equation: $\dfrac{\partial \mathcal{E}}{\partial x} = \dfrac{\rho}{\varepsilon_s} \cong \dfrac{qN_D}{\varepsilon_s}$

- The solution is: $\mathcal{E}(x) = -\dfrac{qN_D}{\varepsilon_s}(W - x)$

$$V(x) = -\int \mathcal{E}(x')dx'$$



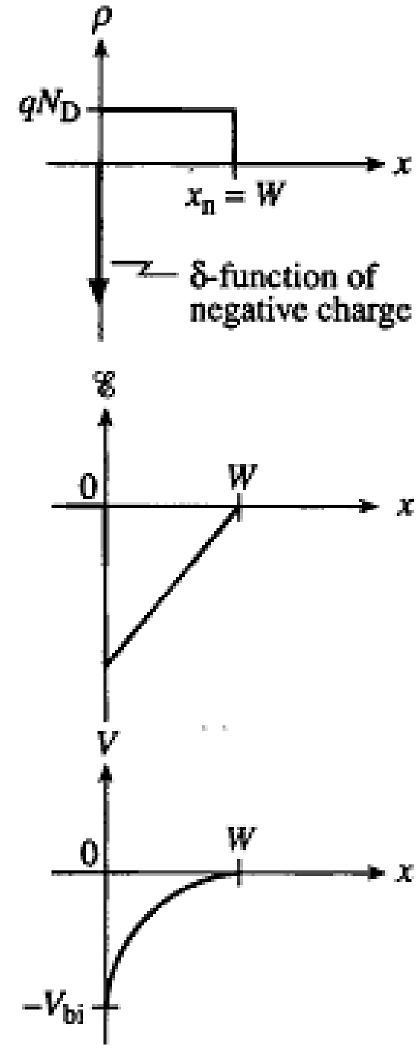
Depletion Width, *W*

$$V(x) = \frac{-qN_D}{2\varepsilon_s}(W-x)^2$$

At $x = 0$, $V = -V_{bi}$

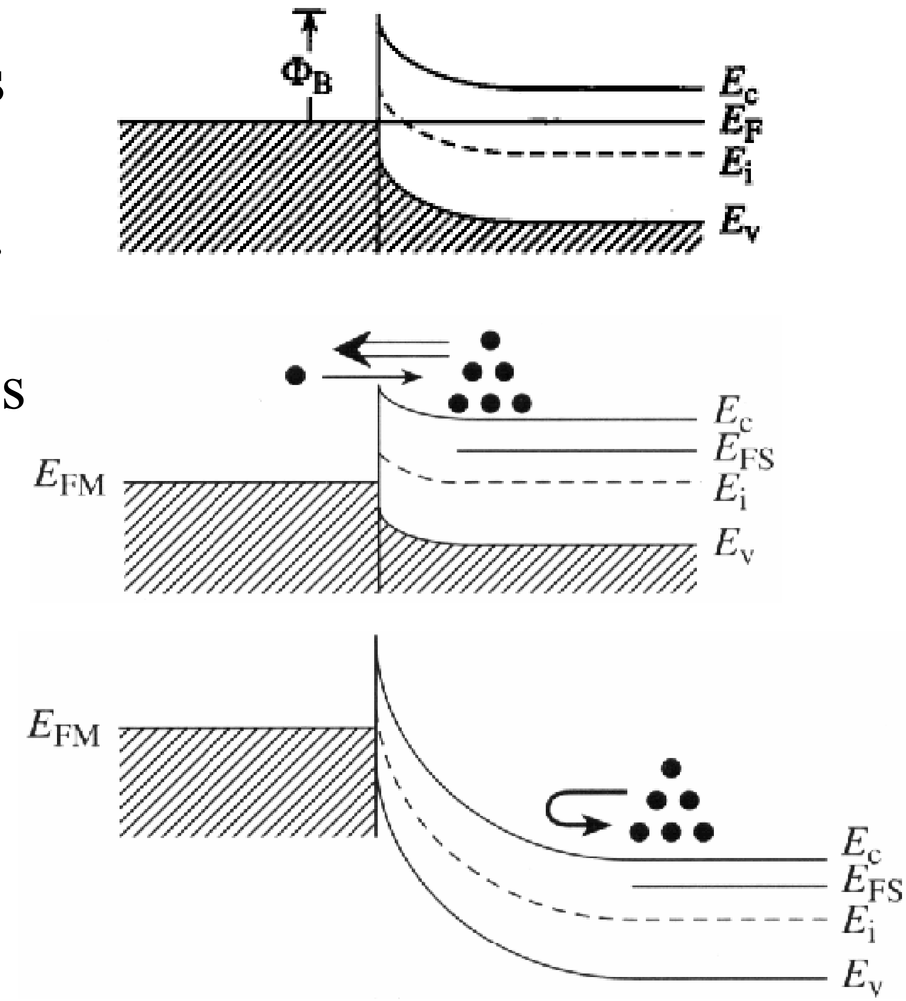
$$\Rightarrow \quad W = \sqrt{\frac{2\varepsilon_s V_{bi}}{qN_D}}$$

- ***W* decreases with increasing N_D**



Voltage Drop across the M-S Contact

- Under equilibrium conditions ($V_A = 0$), the voltage drop across the semiconductor depletion region is the built-in voltage V_{bi}.
- If $V_A \neq 0$, the voltage drop across the semiconductor depletion region is $V_{bi} - V_A$.



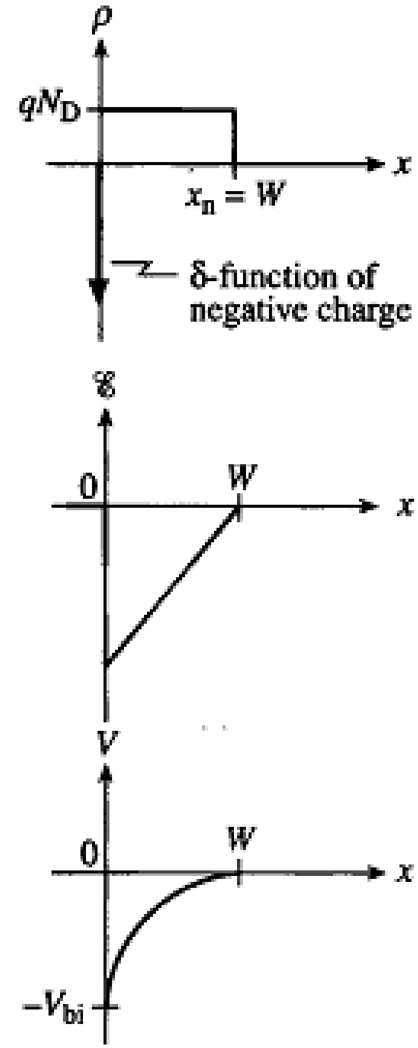
Depletion Width, W, for $V_A \neq 0$

$$V(x) = \frac{-qN_D}{2K_S\varepsilon_0}(W-x)^2$$

At $x = 0$, $V = -(V_{bi} - V_A)$

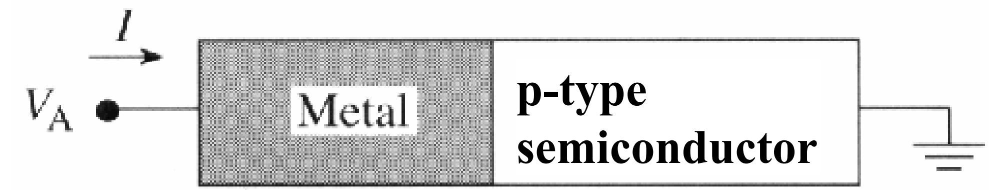
$$\Rightarrow \quad W = \sqrt{\frac{2\varepsilon_s(V_{bi} - V_A)}{qN_D}}$$

- ***W* increases with increasing $-V_A$**
- ***W* decreases with increasing N_D**



W for p-type Semiconductor

$$V(x) = \frac{qN_A}{2K_S\varepsilon_0}(W - x)^2$$



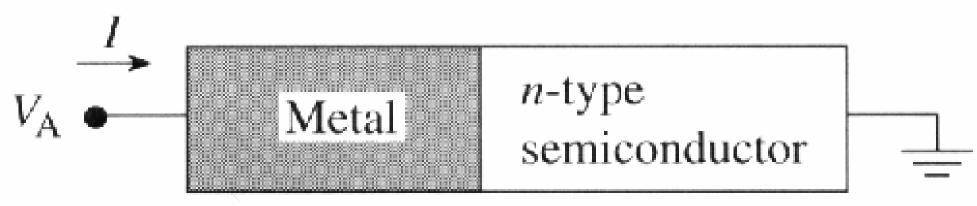
At $x = 0$, $V = V_{bi} + V_A$

$$\Rightarrow \quad W = \sqrt{\frac{2\varepsilon_s(V_A + V_{bi})}{qN_A}}$$

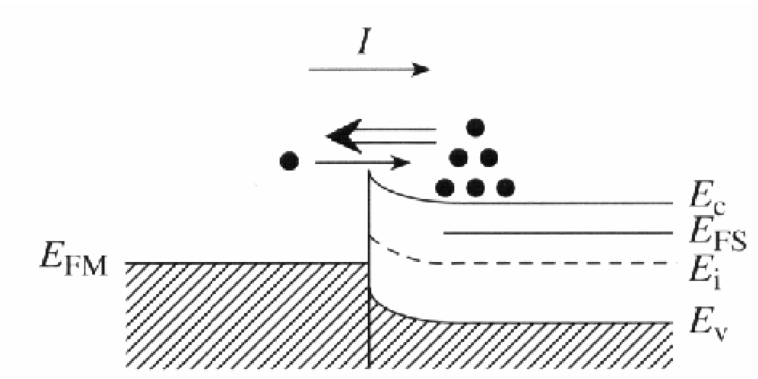
- ***W* increases with increasing V_A**
- ***W* decreases with increasing N_A**

I-V curve

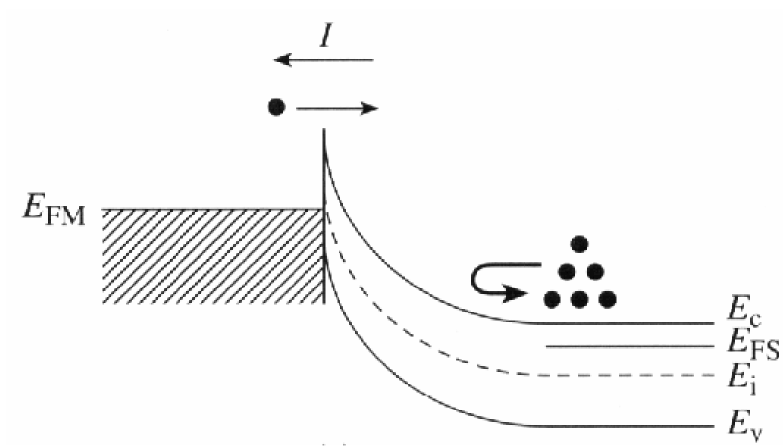
Current Flow



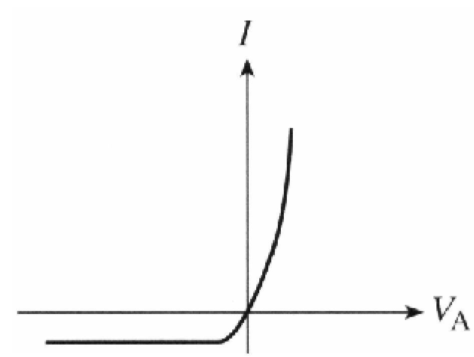
FORWARD BIAS



REVERSE BIAS



- Current is determined by <u>majority-carrier</u> flow across the M-S junction:
  - Under forward bias, majority-carrier drift from the semiconductor into the metal dominates
  - Under reverse bias, majority-carrier drift from the metal into the semiconductor dominates

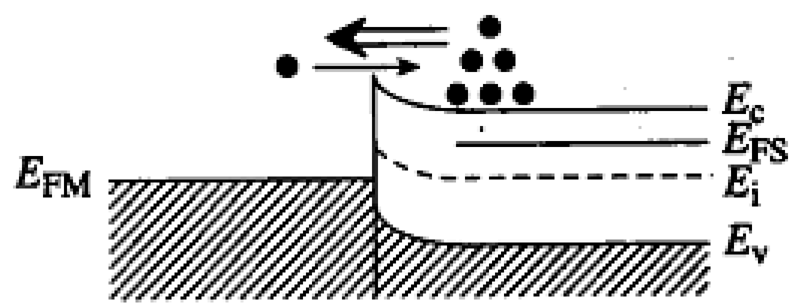


Thermionic Emission Theory

- Electrons can cross the junction int

$$K.E._x = \frac{1}{2} m v_x^{\ 2} \geq q\left(V_{bi} - V_A\right)$$

$$|v_x| \geq v_{\min} \equiv \sqrt{\frac{2q}{m_n^*}\left(V_{bi} - V_A\right)}$$



- Thus the current for electrons at a given velocity is:

$$I_{s\bullet\to M, v_x} = -qAv_x n(v_x)$$

- So, the total current over the barrier is:

$$I_{s\bullet\to M} = -qA \int_{-\infty}^{-v_{\min}} v_x n(v_x) dv_x$$

Schottky Diode *I* - *V*

For a nondegenerate semiconductor, it can be shown that

$$n(v_x) = \left[\frac{4\pi k T m_n^{*2}}{h^3}\right] e^{(E_F - E_c)/kT} e^{-(m_n^*/2kT)v_x^2}$$

We can then obtain

$$I_{S \bullet \to M} = \frac{4\pi q m_n^* k^2}{h^3} A T^2 e^{-\Phi_B/kT} e^{qV_A/kT}$$

$$= A J_S e^{qV_A/kT}, \text{ where } J_S \equiv 120 \frac{m_n^*}{m_0} T^2 e^{-\Phi_B/kT} \text{ A/cm}^2$$

In the reverse direction, the electrons always see the same barrier Φ_B, so

$$I_{M \bullet \to S} = -I_{S \bullet \to M}(V_A = 0)$$

Therefore $I = I_S(e^{qV_A/kT} - 1)$ where $I_S = AJ_S$

Practical Ohmic Contact

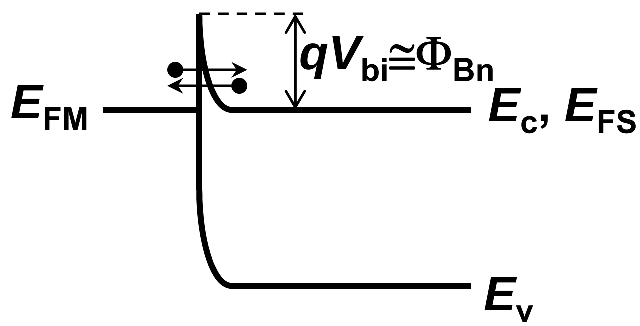
- In practice, most M-S contacts are rectifying

- To achieve a contact which conducts easily in both directions, we dope the semiconductor very heavily
  - → *W* is so narrow that carriers can "tunnel" directly through the barrier

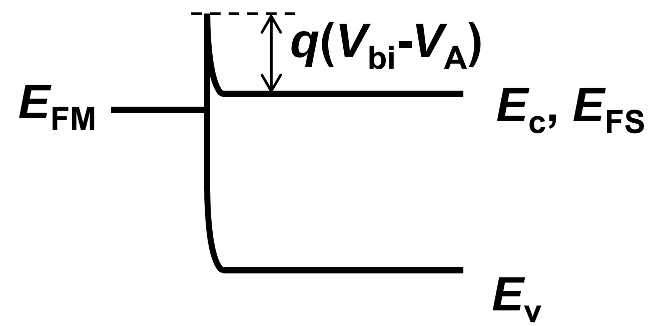
Tunneling Current Density

$$W \cong \sqrt{\frac{2\varepsilon_s \Phi_{Bn}}{qN_D}}$$

Equilibrium Band Diagram



Band Diagram for $V_A \neq 0$



tunneling probability $P = e^{-H(\Phi_{Bn} - V_A)/\sqrt{N_D}}$

where $H = 4\pi\sqrt{\varepsilon_s m_n^*}/h = 5.4 \times 10^9 \sqrt{m_n^*/m_o}\ \mathrm{cm}^{-3/2}\mathrm{V}^{-1}$

$$J_{S \to M} \approx qPN_D v_{thx} = qN_D \sqrt{kT/2\pi m_n^*}\, e^{-H(\Phi_{Bn} - V_A)/\sqrt{N_D}}$$

~The end~