SEMICONDUCTOR MATERIALS & DEVICES

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CHAPTER 7: METAL-SEMICONDUCTOR CONTACTS AND SCHOTTKY DIODES

METAL-SEMICONDUCTOR CONTACTS

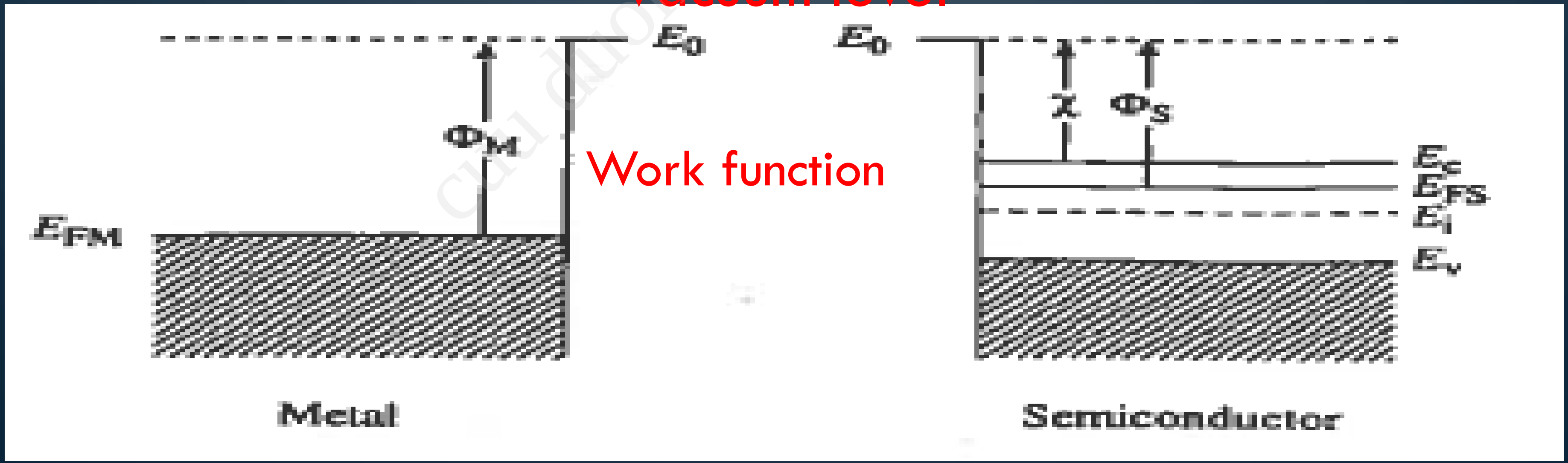
- **Ideal MS contact**

1. Intimate contact on an atomic scale, no layers of any type (oxide…) between component.

2. No interdiffusion or intermixing of metal and semiconductor

3. No adsorbed impurities or surface charges at interface

Vacuum level



METAL-SEMICONDUCTOR CONTACTS

Metal workfunction Φ_M

(energy difference between vacuum level and Fermi energy)

Semiconductor workfunction

$$\Phi_S = \chi + (E_c - E_F)_{FB}$$

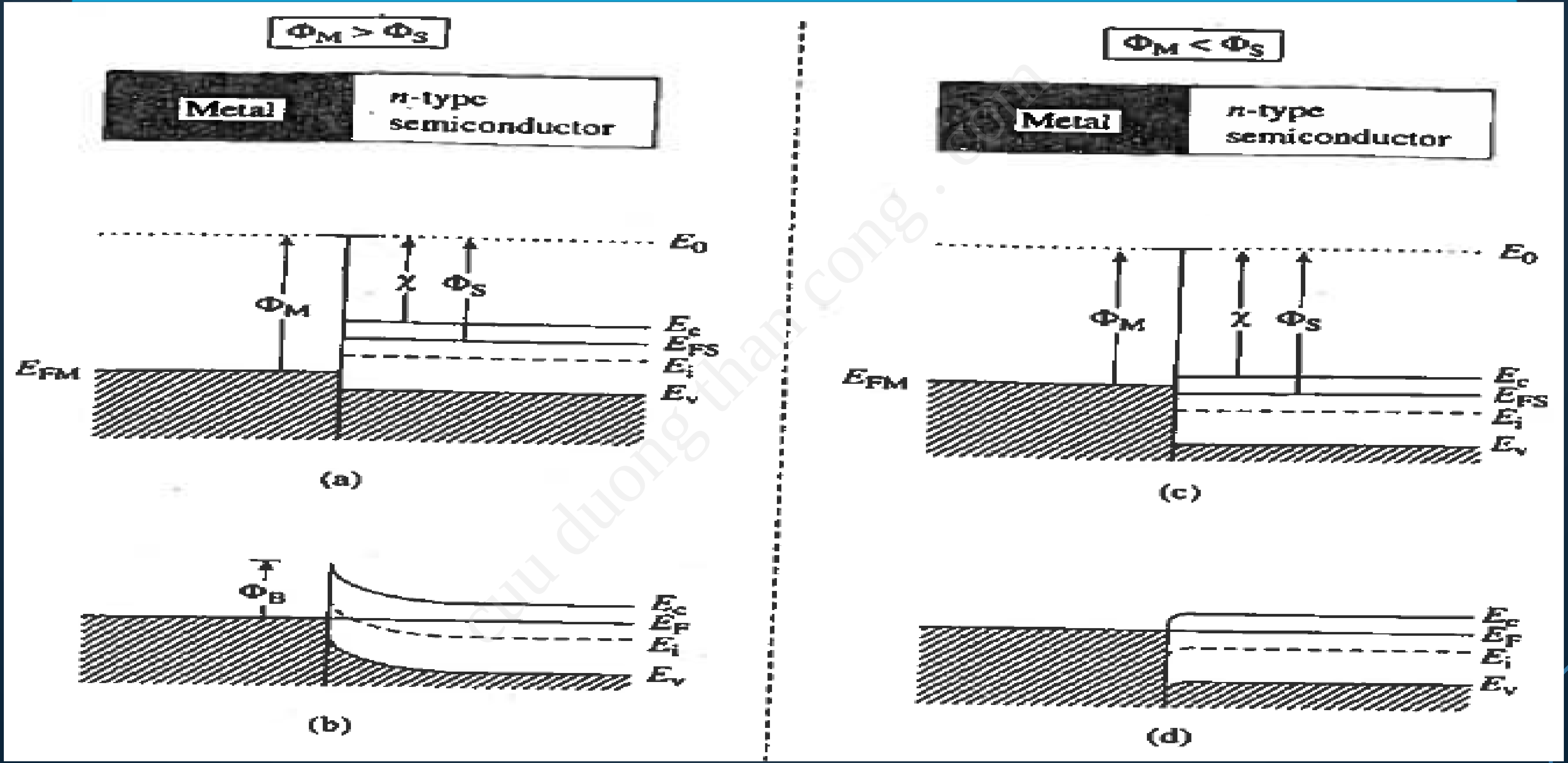
Electron affinity

$$\chi \equiv (E_0 - E_c)|_{surface}$$

(fundamental property)

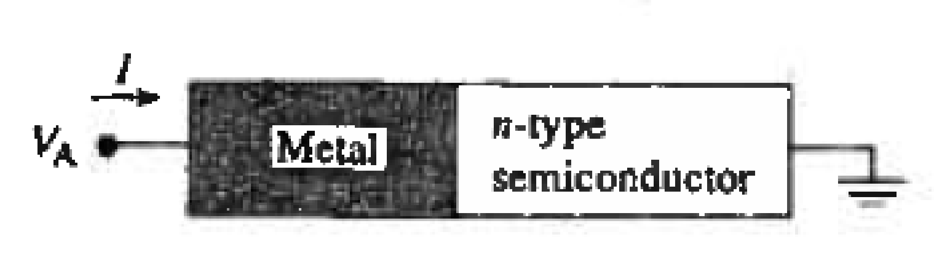
χ = 4.0 eV (Ge); 4.03eV (Si); 4.07 eV (GaAs)

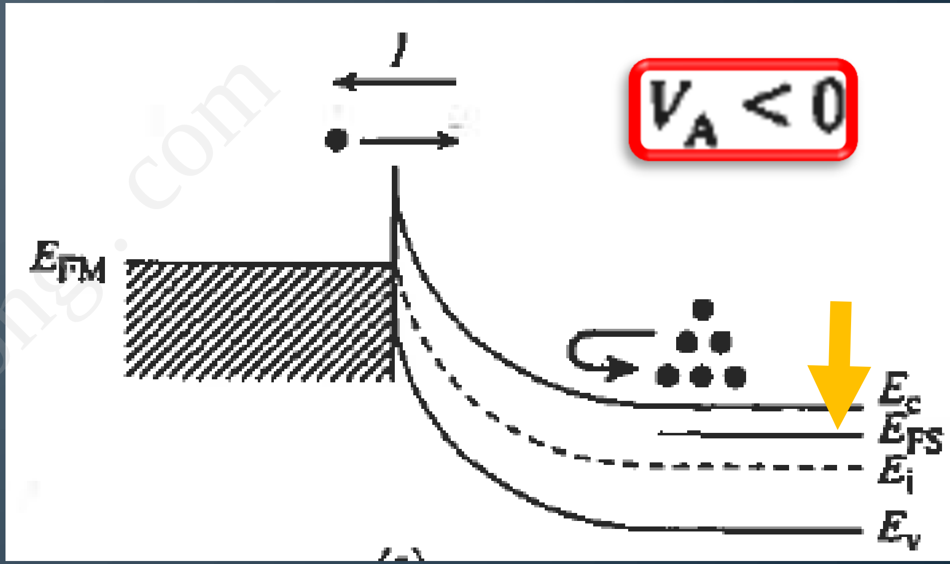
METAL-SEMICONDUCTOR CONTACTS

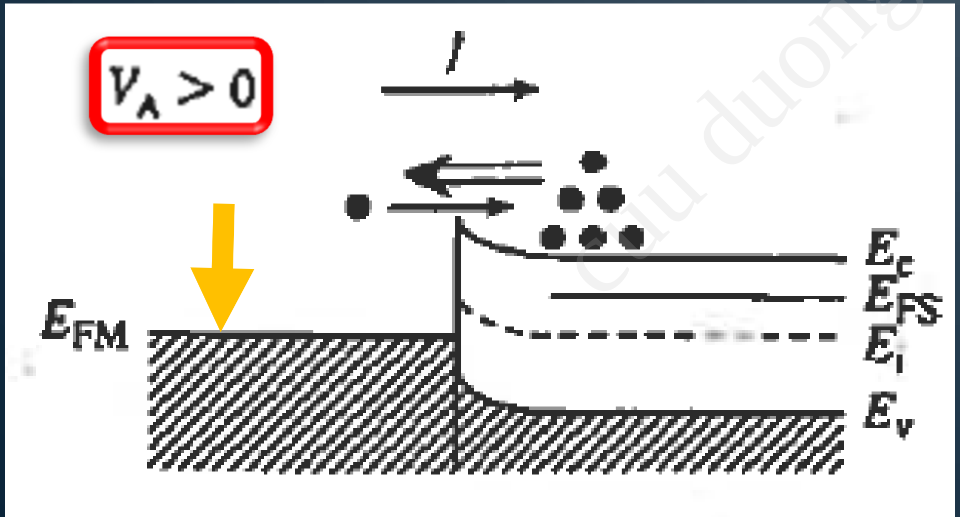


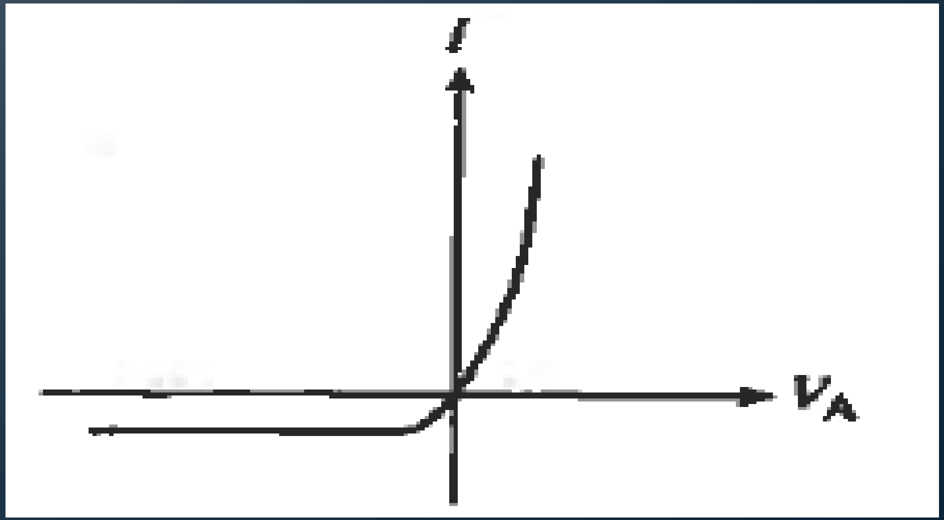
$\Phi_B = \Phi_M - \chi$ . . . ideal MS(*n*-type) contact

METAL-SEMICONDUCTOR CONTACTS









METAL-SEMICONDUCTOR CONTACTS

Table 14.1 Electrical Nature of Ideal MS Contacts.

	n-type Semiconductor	*p-type Semiconductor*
$\Phi_M > \Phi_S$	Rectifying	Ohmic
$\Phi_M < \Phi_S$	Ohmic	Rectifying

METAL-SEMICONDUCTOR CONTACTS

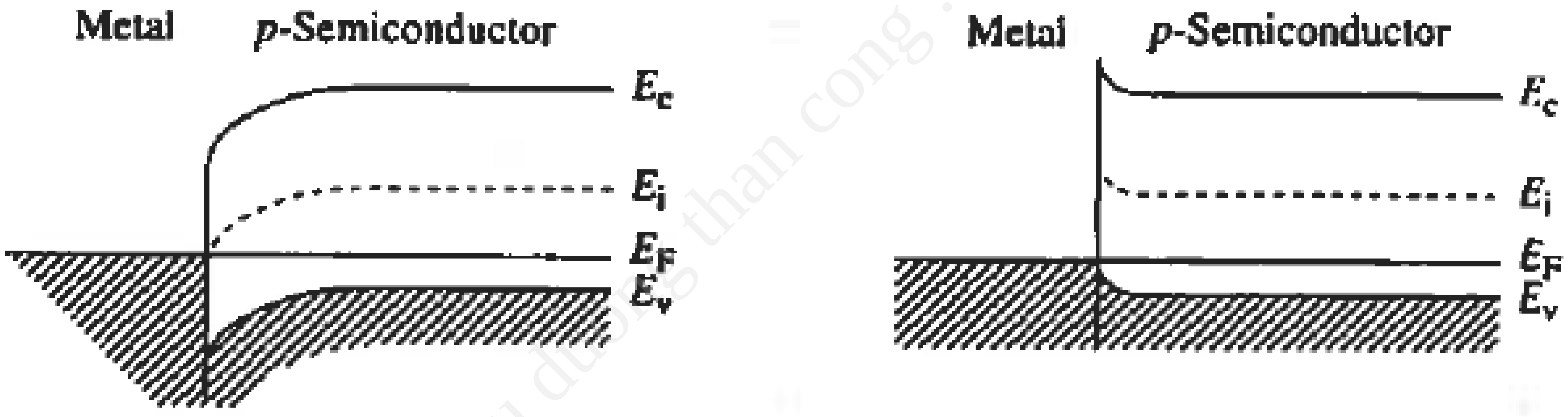
P: (a) Construct the equilibrium energy band diagram appropriate for an ideal *p*-type semiconductor to metal contact where $\Phi_M < \Phi_S$.

(b) Repeat part (a) when $\Phi_M > \Phi_S$.

(c) Verify that an ideal MS contact formed from a metal and a *p*-type semiconductor will be rectifying if $\Phi_M < \Phi_S$ and ohmic-like if $\Phi_M > \Phi_S$.

(d) Establish an expression for the barrier height, $\Phi_B = E_{FM} - E_v|_{interface}$, of the rectifying *p*-type contact.

METAL-SEMICONDUCTOR CONTACTS



(a) $\Phi_M < \Phi_S$ (b) $\Phi_M > \Phi_S$

METAL-SEMICONDUCTOR CONTACTS

(c) Hole flow under bias must be examined to determine whether the given MS contacts are rectifying or ohmic. Empty electronic states in the metal, which decrease exponentially with energy below the Fermi level, can be thought of as holes for the purpose of the discussion. For the $\Phi_M < \Phi_S$ contact, there is clearly a barrier to hole flow in both directions under equilibrium conditions. Moving E_{FM} upward relative to E_{FS} reduces the barrier to hole flow from the semiconductor to the metal. The resulting $S \rightarrow M$ hole current is expected to increase exponentially with increased separation between E_{FM} and E_{FS}. Reversing the bias blocks hole flow from the semiconductor to the metal, leaving only a saturating hole current from the metal to the

METAL-SEMICONDUCTOR CONTACTS

semiconductor. The $\Phi_M < \Phi_S$ contact is obviously rectifying. For the $\Phi_M > \Phi_S$ contact, there is no barrier to hole flow from the semiconductor to the metal. Moreover, the small barrier to hole flow from the metal to the semiconductor vanishes if E_{FM} is moved only slightly downward relative to E_{FS}. The $\Phi_M > \Phi_S$ contact is concluded to be ohmic-like, thereby completing the required verification.

(d) Since

$$E_{c|interface} - E_{FM} = \Phi_M - \chi$$

it follows that

$$\Phi_B = E_{FM} - E_{v|interface} = (E_c - E_v) - (E_{c|interface} - E_{FM})$$

or

$$\Phi_B = E_G + \chi - \Phi_M \qquad \text{. . . ideal } MS(p\text{-type}) \text{ contact}$$

SCHOTTKY DIODES

- **Structure**

➢ **Typical metals used are molybdenum, platinum, chromium or tungsten, and certain silicides (e.g., palladium silicide and platinum silicide)**

➢ **The semiconductor would typically be n-type silicon**

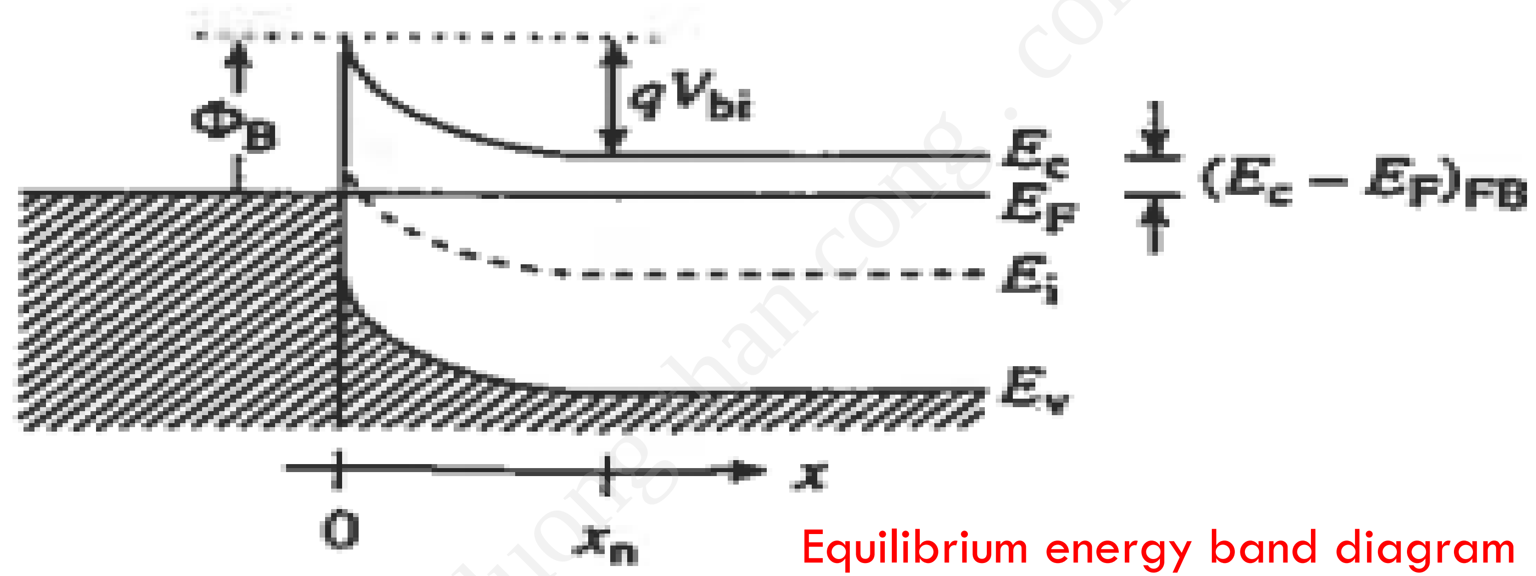
- **Built-in potential**

$$V_{bi} = \frac{1}{q}\left[\Phi_B - (E_c - E_F)_{FB}\right]$$

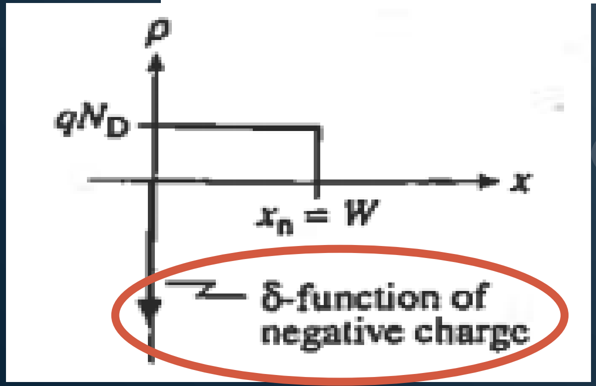
$$\Phi_B = \Phi_M - \chi$$

SCHOTTKY DIODES

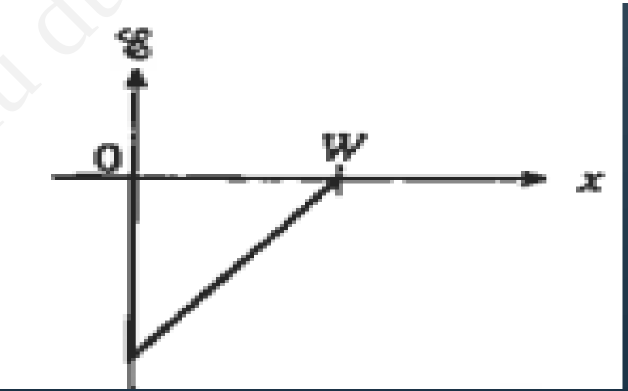
Electrostatic variables in an MS (n-type) diode under equilibrium conditions



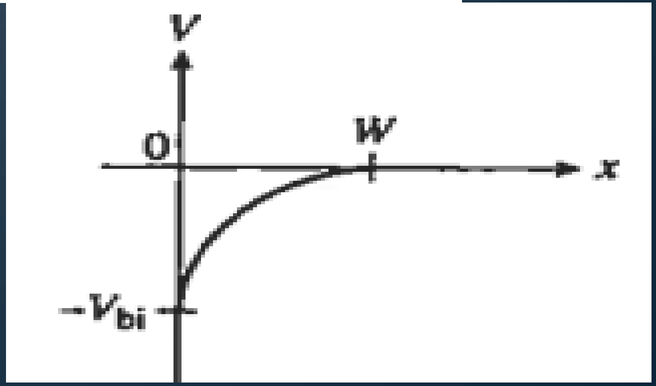
Equilibrium energy band diagram



Charge density



Electric field



Electrostatic potential

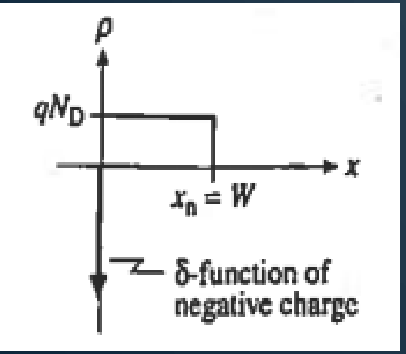
SCHOTTKY DIODES

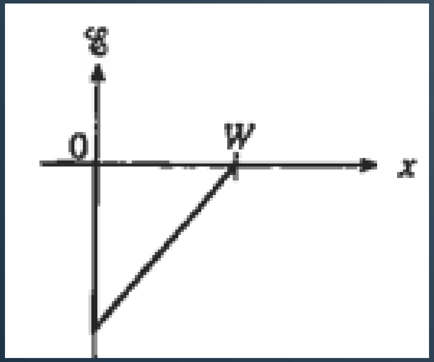
- **Note:**

In metal: Electric field and potential = zero → no need for consideration

In semiconductor (n-type):

$$\rho \cong \begin{cases} qN_D & \ldots 0 \le x \le W \\ 0 & \ldots x > W \end{cases}$$





$$\frac{d\mathcal{E}}{dx} = \frac{\rho}{K_S\varepsilon_0} \cong \frac{qN_D}{K_S\varepsilon_0} \qquad \ldots 0 \le x \le W$$

Poisson's equation

Separating variables and integrating from an arbitrary point x in depletion region to x = W, where ε = 0

$$\int_{\mathcal{E}(x)}^{0} d\mathcal{E}' = \int_x^W \frac{qN_D}{K_S\varepsilon_0}\, dx'$$

$$\mathcal{E}(x) = -\frac{qN_D}{K_S\varepsilon_0}(W - x) \qquad \ldots 0 \le x \le W$$

Similar to ε field on n side in p^+-n junction if $x_n = W$

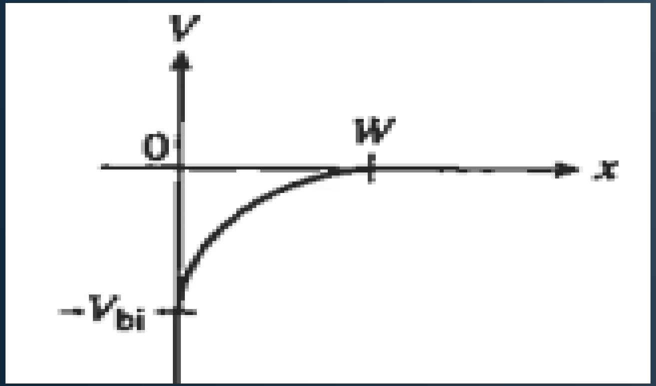
SCHOTTKY DIODES

- **Electric potential**

$$\frac{dV}{dx} = -\mathscr{E} = \frac{qN_D}{K_S\varepsilon_0}(W - x) \qquad \ldots 0 \le x \le W$$

$$\int_{V(x)}^{0} dV' = \int_{x}^{W} \frac{qN_D}{K_S\varepsilon_0}(W - x')dx'$$

$$V(x) = -\frac{qN_D}{2K_S\varepsilon_0}(W - x)^2 \qquad \ldots 0 \le x \le W$$



Electrostatic potential

SCHOTTKY DIODES

- Depletion width

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

$$V(x) = -\frac{qN_D}{2K_S\varepsilon_0}(W - x)^2 \quad \ldots 0 \le x \le W$$

$$-(V_{bi} - V_A) = -\frac{qN_D}{2K_S\varepsilon_0}W^2$$

$$W = \left[\frac{2K_S\varepsilon_0}{qN_D}(V_{bi} - V_A)\right]^{1/2}$$

SCHOTTKY DIODES

P: Copper is deposited on a carefully prepared n-type silicon substrate to form an ideal Schottky diode. $\Phi_M \cong 4.65$ eV, $\chi = 4.03$ eV, $N_D = 10^{16}/\text{cm}^3$, and $T = 300$ K. Determine

(a) Φ_B,

(b) V_{bi},

(c) W if $V_A = 0$, and

(d) $|\mathscr{E}|_{max}$ if $V_A = 0$.

S: (a) $\Phi_B = \Phi_M - \chi = 0.62$ eV

(b) $$(E_c - E_F)_{FB} \cong \frac{E_G}{2} - kT \ln\left(\frac{N_D}{n_i}\right) = 0.56 - (0.0259)\ln\left(\frac{10^{16}}{10^{10}}\right) \cong 0.20 \text{ eV}$$

$$V_{bi} = \frac{1}{q}[\Phi_B - (E_c - E_F)_{FB}] = 0.42 \text{ V}$$

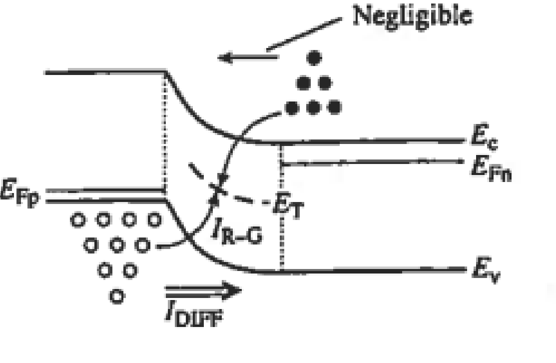
(c) $$W = \left[\frac{2K_S\varepsilon_0}{qN_D}(V_{bi} - V_A)\right]^{1/2} = \left[\frac{(2)(11.8)(8.85 \times 10^{-14})}{(1.6 \times 10^{-19})(10^{16})}(0.42)\right]^{1/2}$$

$$= 0.234\ \mu\text{m}$$

(d) $$|\mathscr{E}|_{max} = |\mathscr{E}_{|x=0}| = \frac{qN_D}{K_S\varepsilon_0}W = \frac{(1.6 \times 10^{-19})(10^{16})(2.34 \times 10^{-5})}{(11.8)(8.85 \times 10^{-14})}$$

$$= 3.59 \times 10^4 \text{ V/cm}$$

SCHOTTKY DIODES

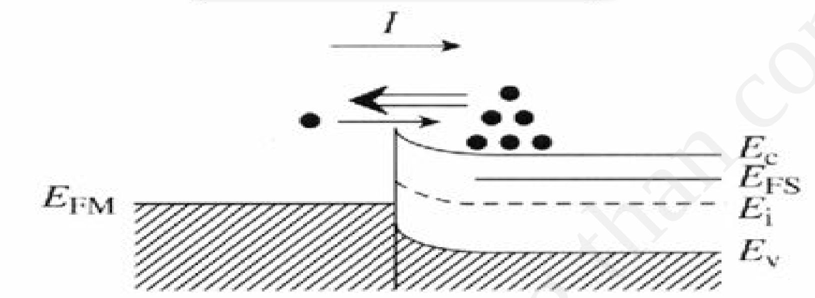


(a) p^+–n junction diode

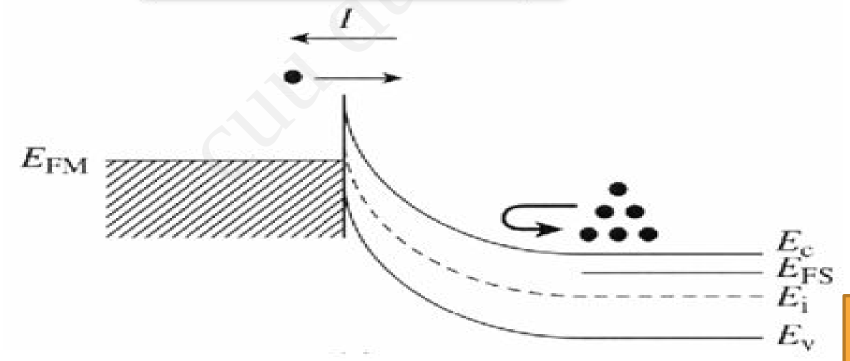
p^+-n junction diode

Current Flow in a Schottky Diode

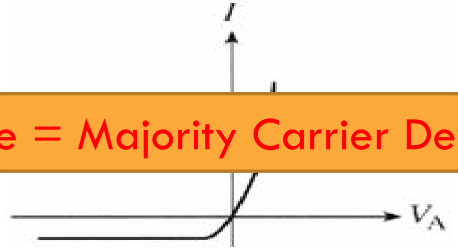
Forward Bias



Reverse Bias

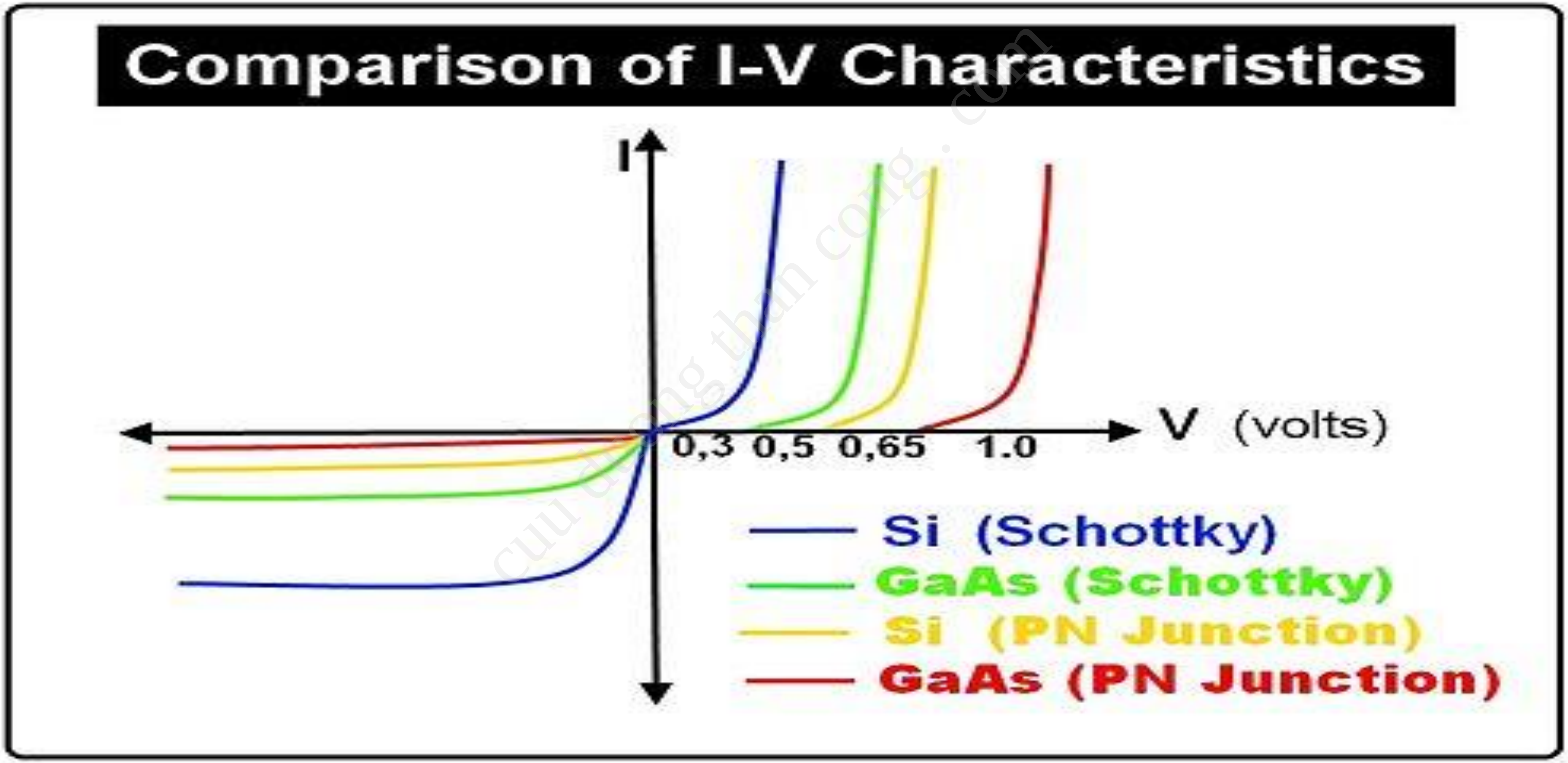


- Current is determined by majority-carrier flow across the MS junction:
  - Under forward bias, majority-carrier diffusion from the semiconductor into the metal dominates
  - Under reverse bias, majority-carrier diffusion from the metal into the semiconductor dominates



Schottky Diode = Majority Carrier Device

SCHOTTKY DIODES



SCHOTTKY DIODES

Schottky Diode Electrostatics

- Built-in Voltage

$$V_b = [\Phi_B - (E_c - E_{FS})_{FB}]/q$$

- Charge distribution

$$\rho = \begin{cases} qN_D & 0 \le x \le W \\ 0 & x \le W \end{cases}$$

- Electric field

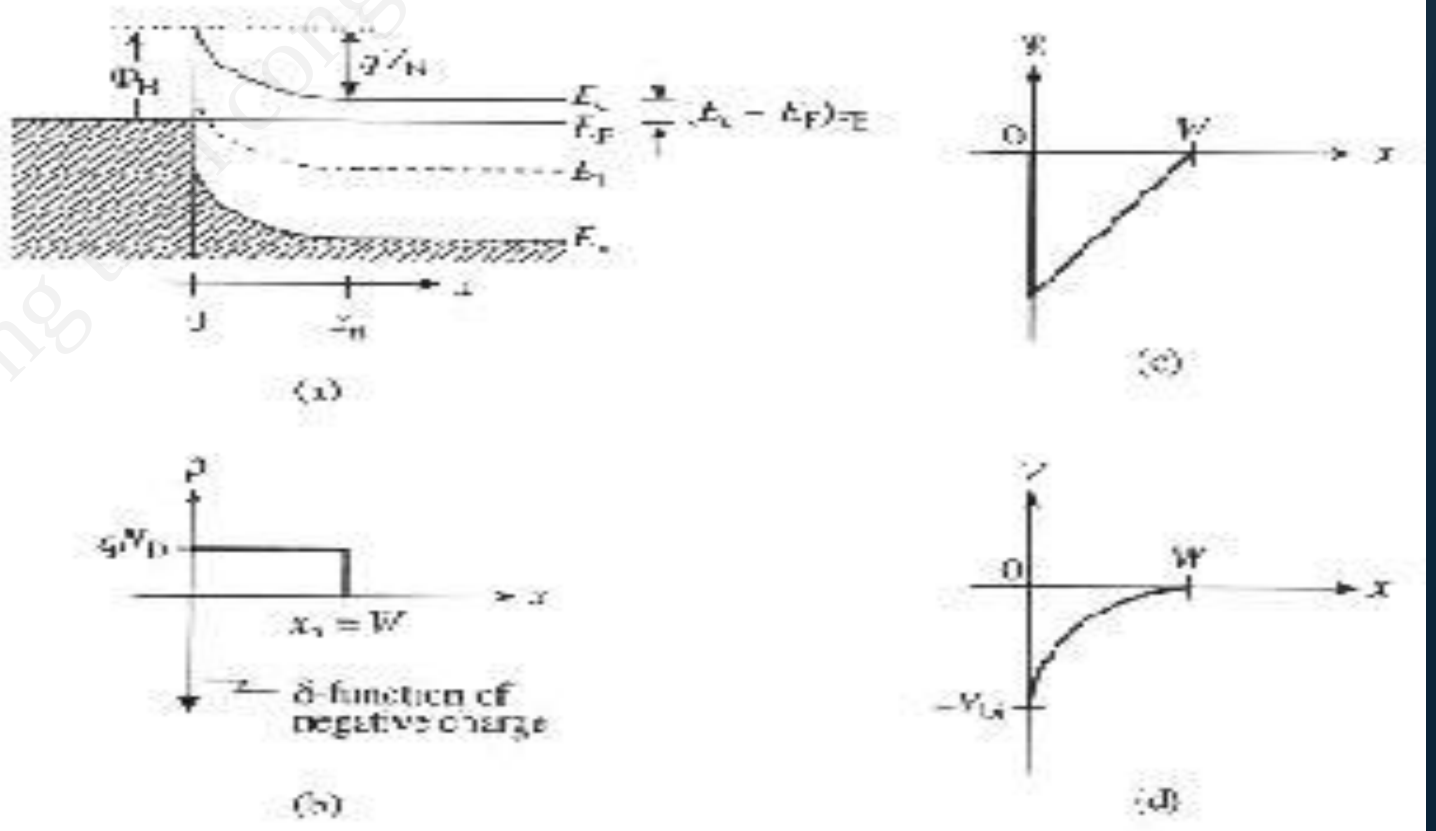
$$E(x) = -\frac{qN_D}{\varepsilon_s}(W - x)$$

- Potential

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

- Depletion width

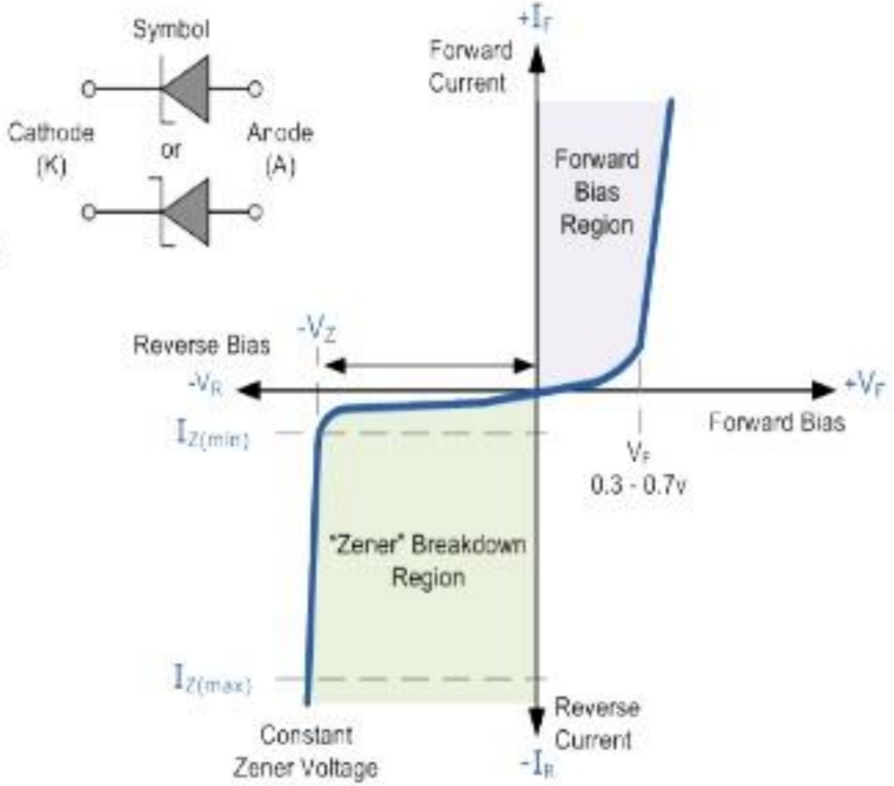
$$W = \left[\frac{2\varepsilon_s}{qN_D}(V_b - V_a)\right]^{1/2}$$



ZENER DIODES

Characteristics . . .

- A Zener diode is always reverse connected
- When forward biased, its characteristics are just like of ordinary diode
- It has sharp breakdown voltage, called Zener voltage



ZENER DIODES