Physics of Semiconductor Devices

Lecture 11

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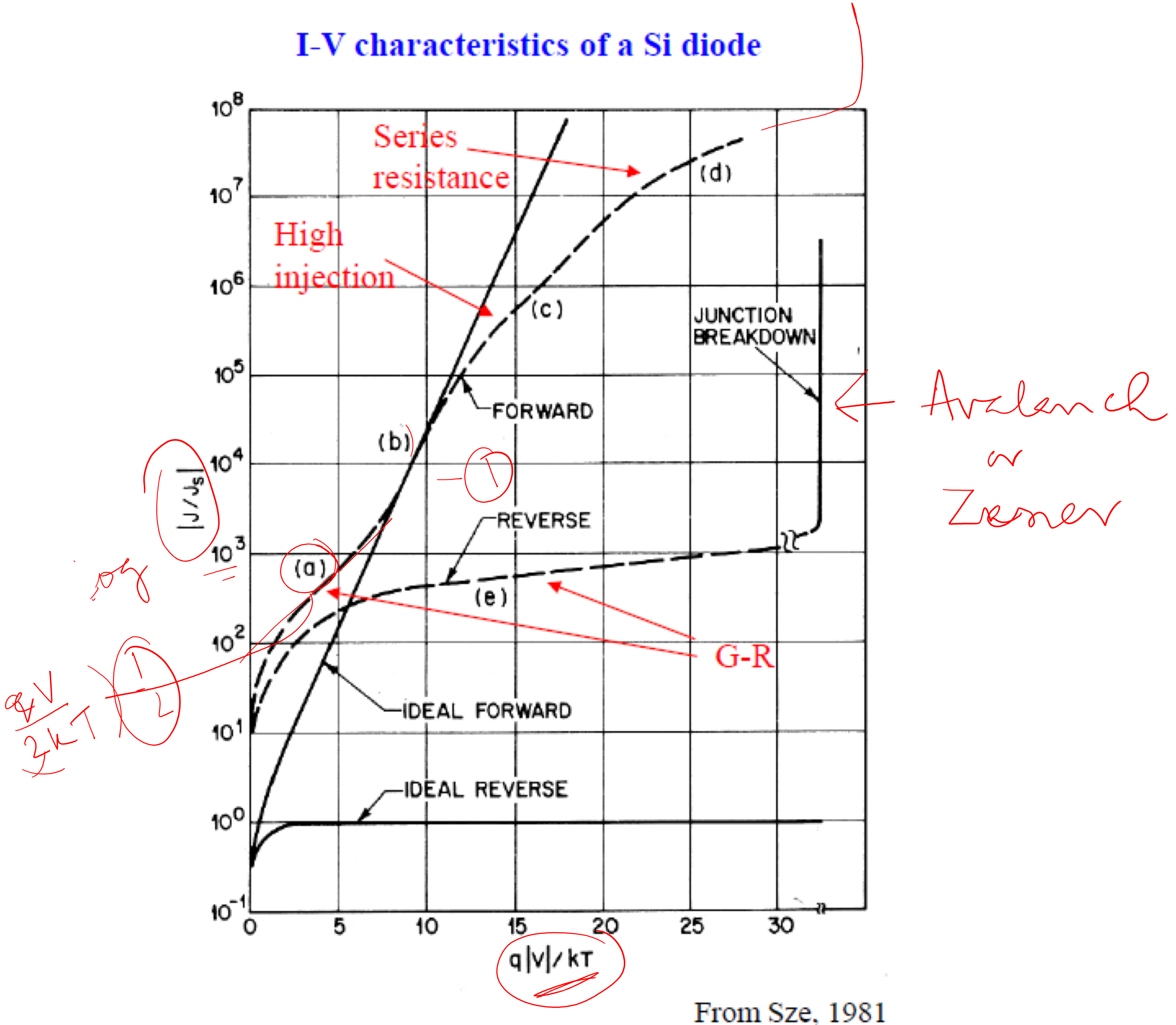
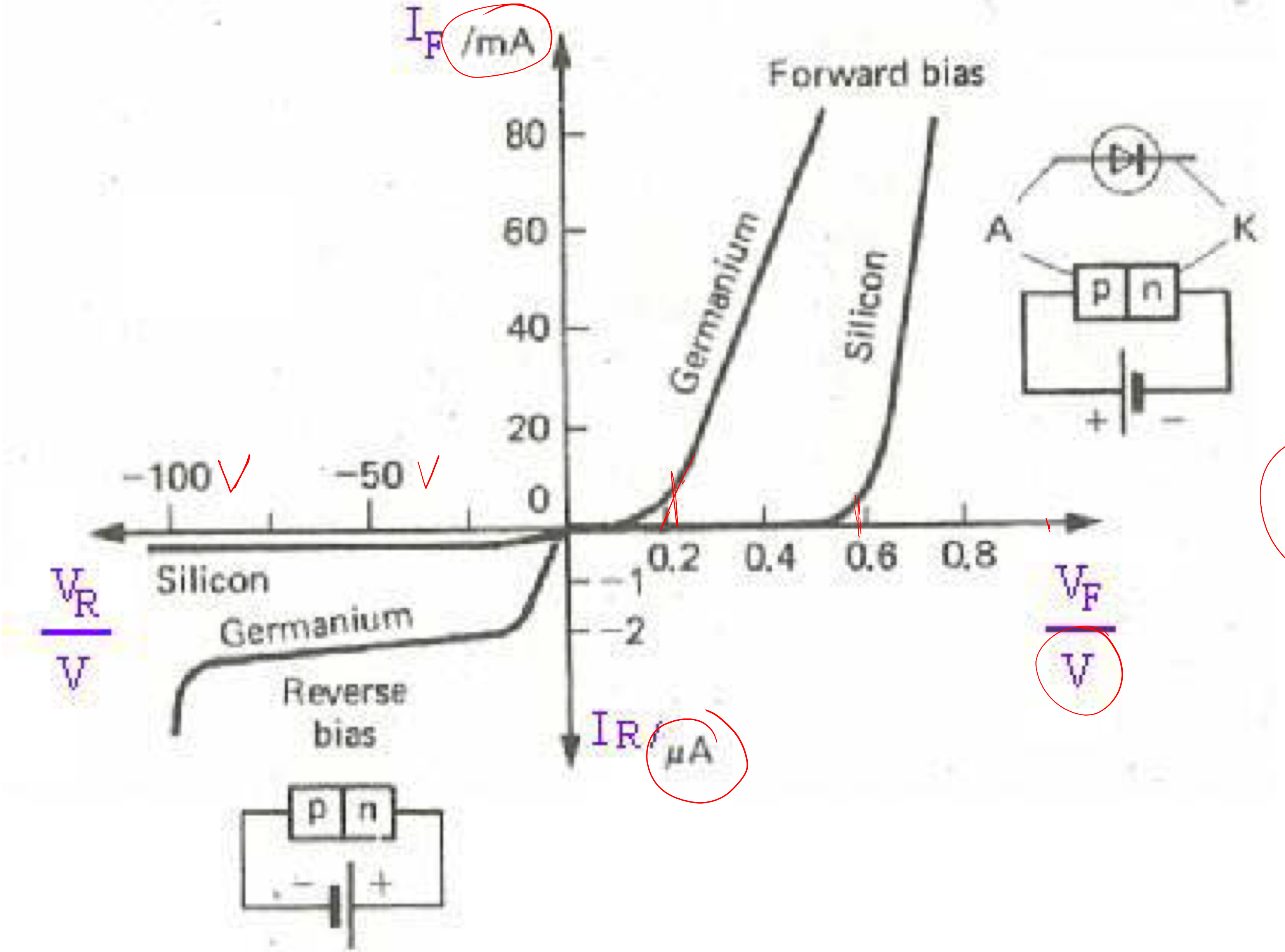
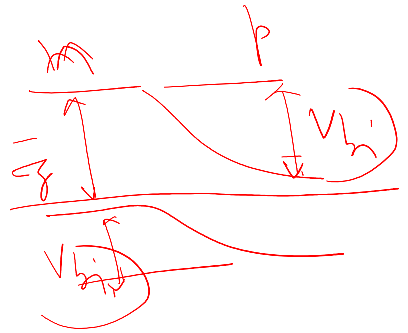
I-V characteristics of a Si diode



From Sze, 1981





$\frac{1}{2}E_g \simeq V_{bi}$

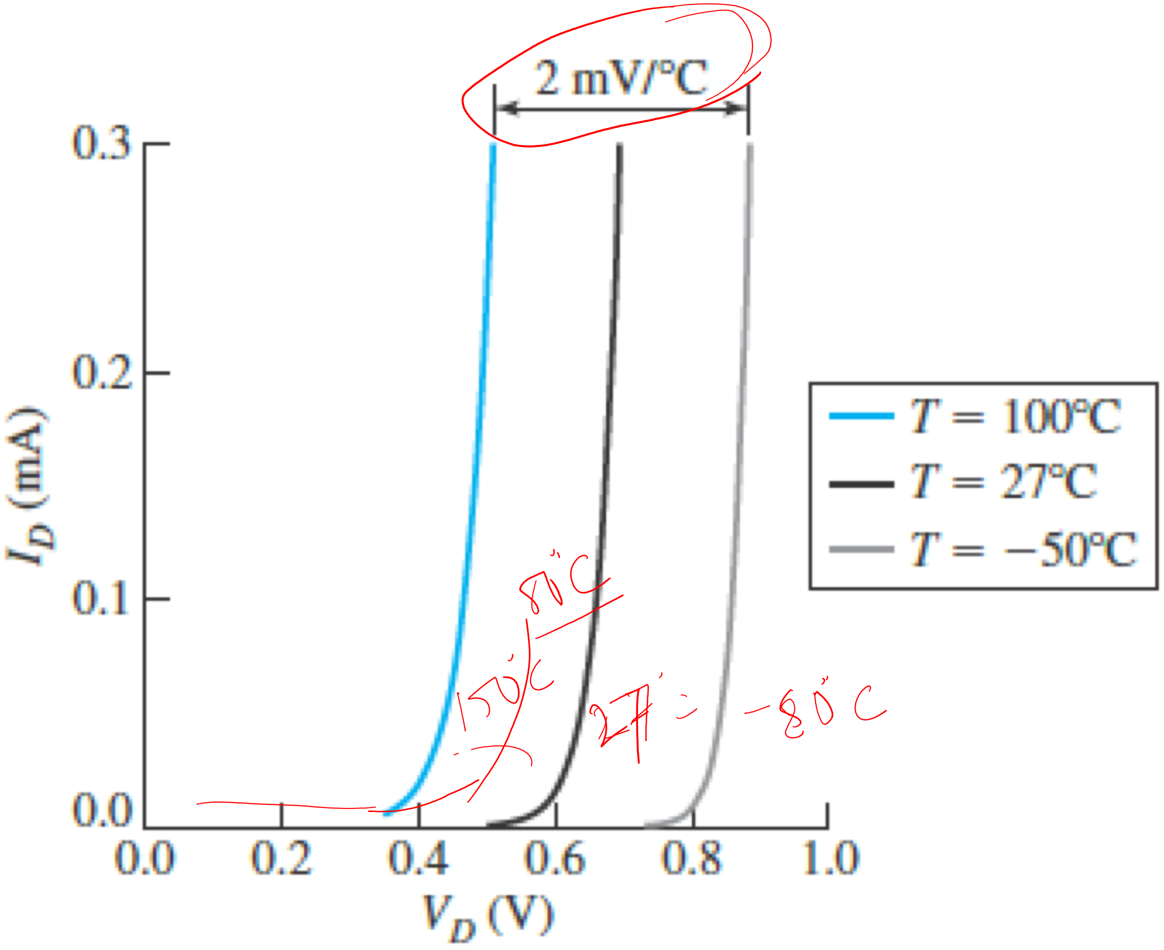
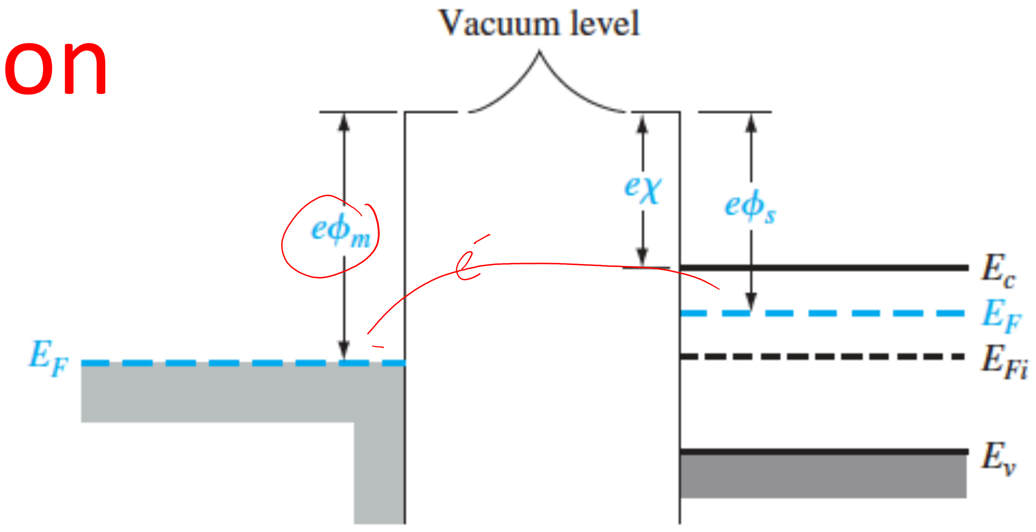


Figure 6.14 Temperature dependence of the diode characteristic.

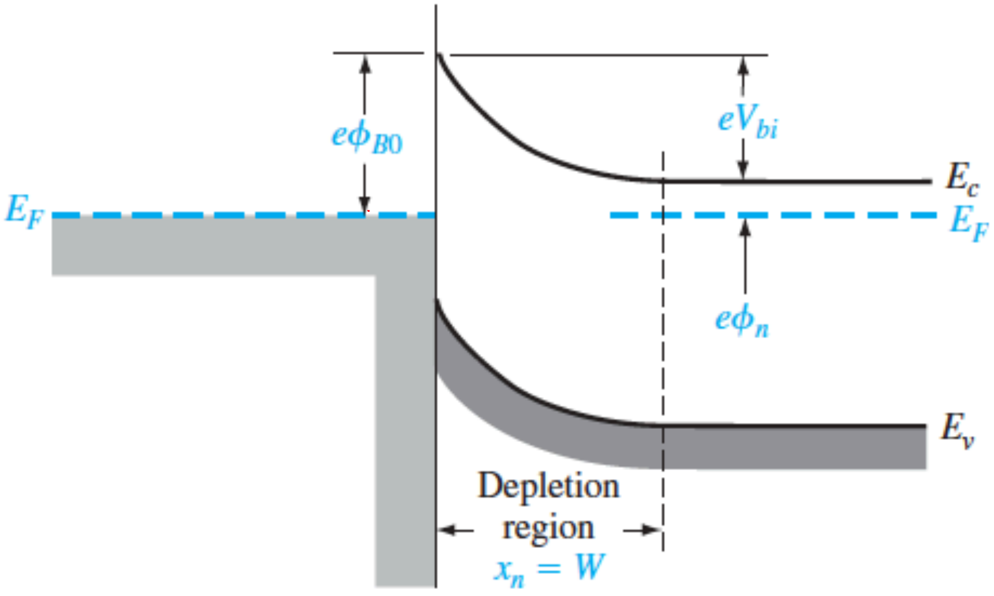
$E_g \neq f(T)$

MS Junction

$\phi_m > \phi_s$



(a)



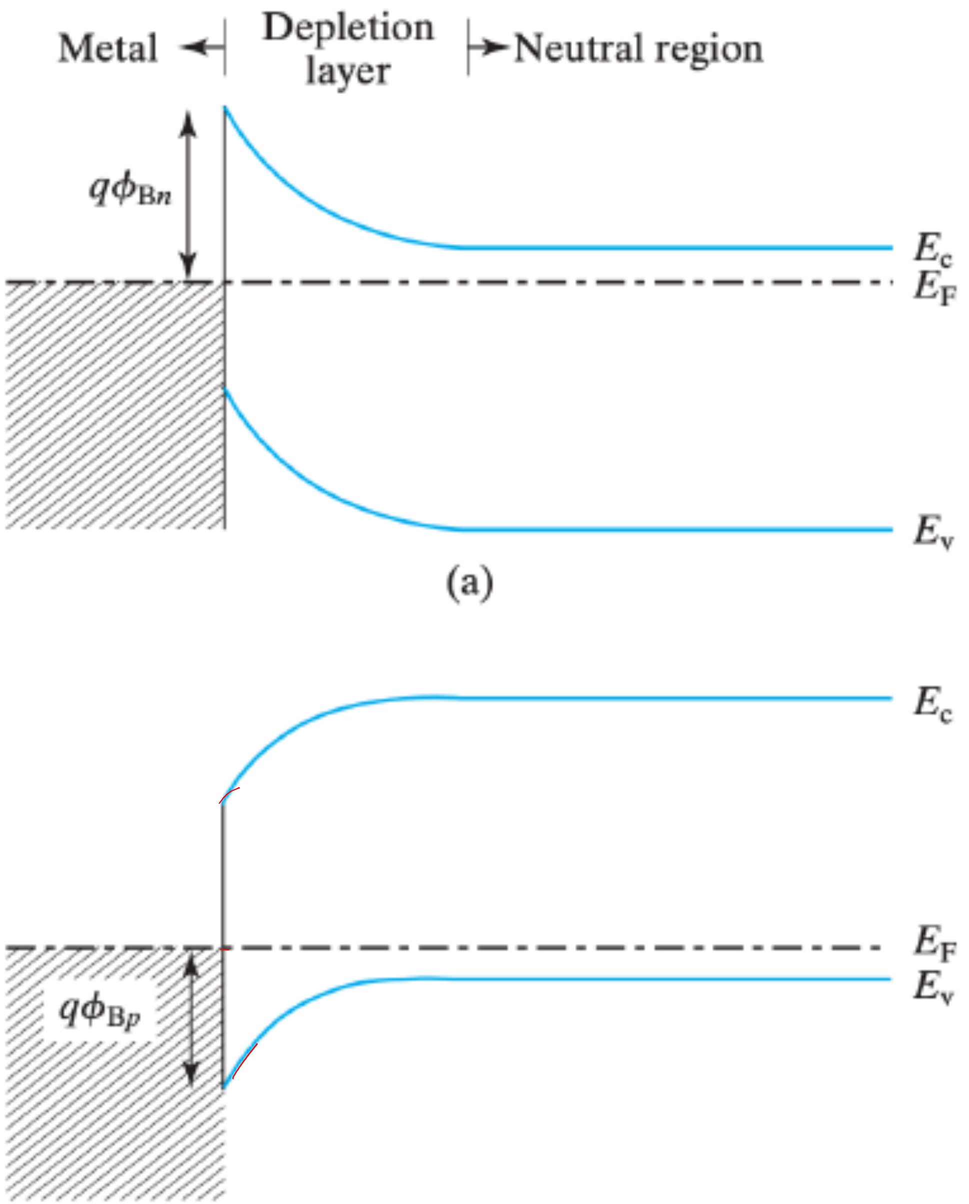
(b)

indep of doping

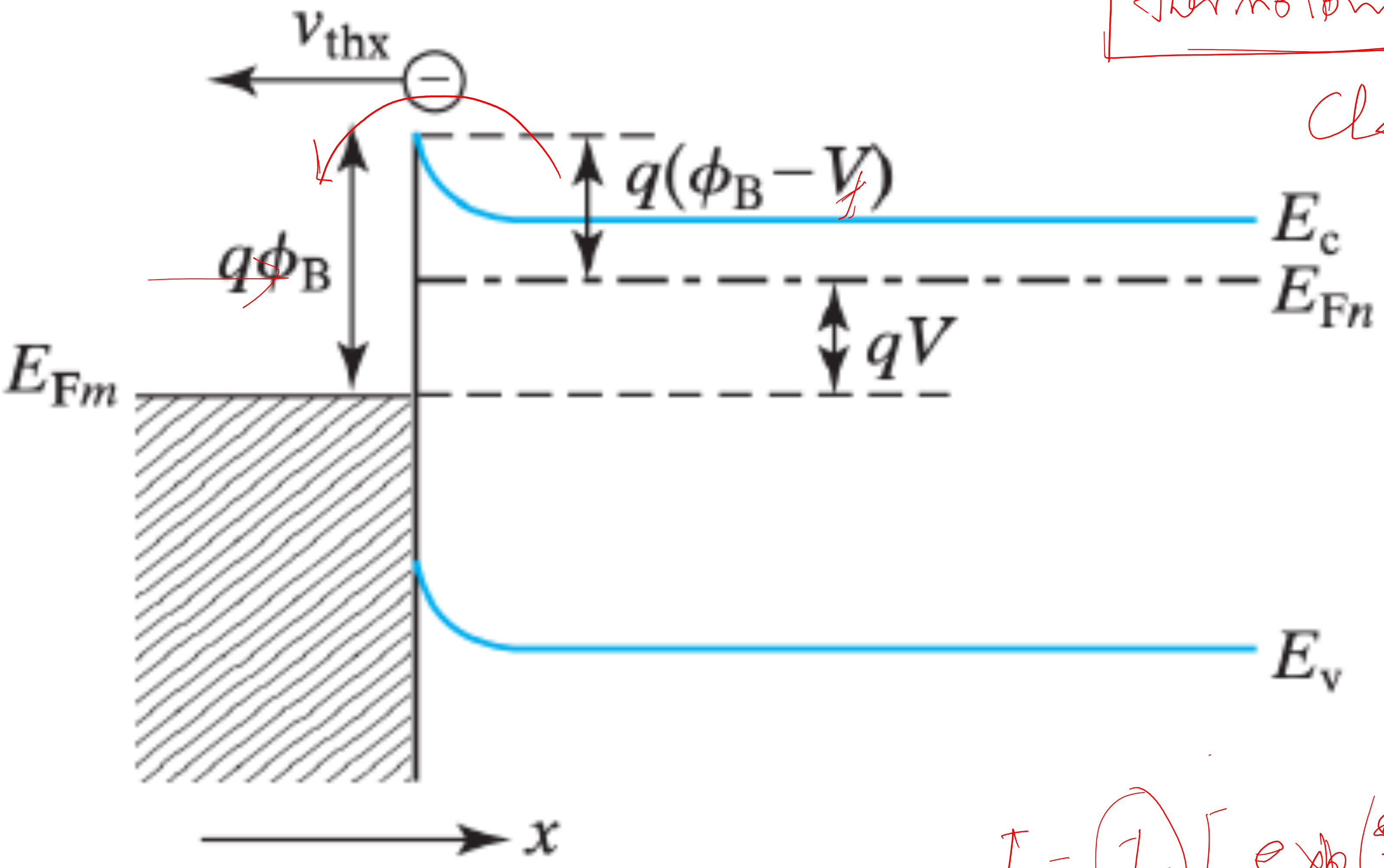
$$\boxed{\phi_{B0} = (\phi_m - \chi)}$$

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

MS Junction



$$\boxed{\phi_{Bn} + \phi_{Bp} = E_g}$$



$\boxed{\text{Thermoionic Emission}}$

Classical effect

$$I = I_s \left[\exp\left(\frac{qV}{kT}\right) - 1 \right]$$

Current flows in an MS junction due to **thermionic emission**, which is a term describing the physics of carriers hopping **over a barrier**. Unlike tunneling, thermionic emission is a classical effect. Being a classical effect, we require that the kinetic energy of charge carriers exceed the potential energy barrier limiting their motion.

$$\frac{1}{2}m_n^* v_x^2 \geq e\left(\phi_{bi} - V_A\right)$$

$\xrightarrow{x}$

Equivalently, this relation can be expressed in terms of a minimum velocity, which is more portable since the velocity directly relates to the current.

$$v_x \geq v_{min}$$

$$\boxed{v_{min} \equiv \sqrt{\frac{2e}{m_n^*}(\phi_{bi} - V_A)}}$$

$$I_{S\rightarrow M} = -eA\int_{-\infty}^{-v_{min}} n(v_x)dv_x$$

It can be shown that the electron concentration as a function of velocity is given by:

$$n(v_x) = \left(\frac{4\pi k_b T m_n^{*2}}{\hbar^3}\right)\exp\left(\frac{E_F - E_C}{k_b T}\right)\exp\left(-\frac{m_n^*}{2k_b T}v_x^2\right)$$ MB stat

Substituting this expression into the expression for the current and performing the integration yields the following:

$$\boxed{I_{S\rightarrow M} = \underbrace{A\mathscr{A}^* T^2 \exp\left(-\frac{\phi_{Bn}}{k_b T}\right)}_{I_s}\exp\left(\frac{eV_A}{k_b T}\right)}$$

...where the constants are defined as follows:

$$\mathscr{A}^* \equiv \left(\frac{m_n^*}{m_e}\right)\mathscr{A}$$

$$\mathscr{A} \equiv \frac{e m_e k_b^2}{2\hbar^3\pi^2} = \text{Richardson's Constant}$$ free $\bar{e}$

For the current flowing in the opposite direction, due to electrons injected from the metal to the semiconductor, they always see the same barrier height. Therefore, we can write:

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

At equilibrium, the current components must vanish, such that:

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

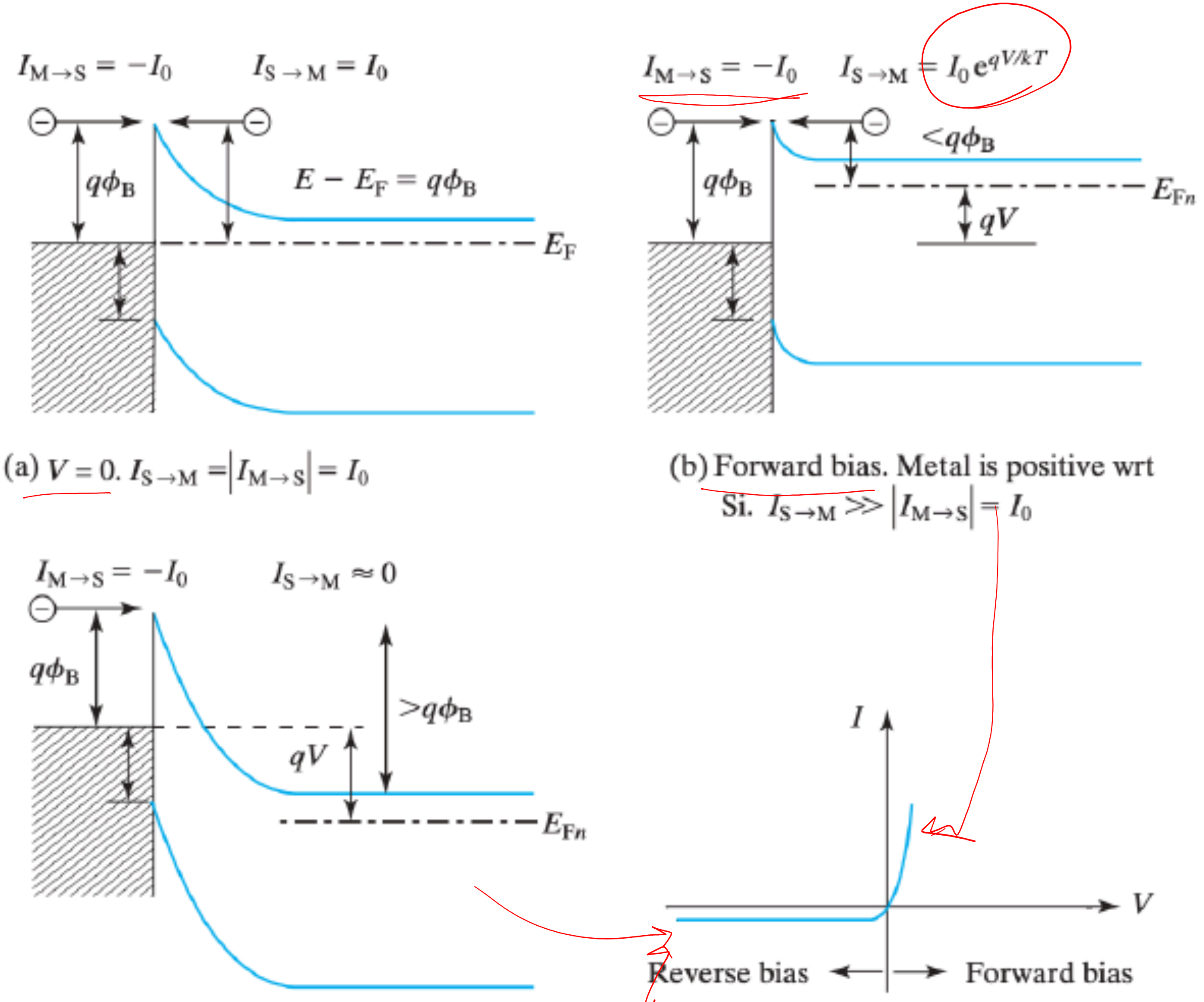
This leads to the following:

$$I_{M\to S} = -I_{S\to M}(V_A = 0) = -A\mathscr{A}^* T^2 \exp\left(-\frac{\phi_{Bn}}{k_b T}\right)$$

Combining the results under non-equilibrium conditions, is then:

$$\boxed{I = I_S\left(\exp\left(\frac{eV_A}{k_b T}\right) - 1\right)}$$

$$I_S \equiv A\mathscr{A}^* T^2 \exp\left(-\frac{\Phi_{Bn}}{k_b T}\right)$$



(a) $V = 0$. $I_{S\to M} = |I_{M\to S}| = I_0$

(b) Forward bias. Metal is positive wrt Si. $I_{S\to M} \gg |I_{M\to S}| = I_0$

(c) Reverse bias. Metal is negative wrt Si. $I_{S\to M} \ll |I_{M\to S}| = I_0$

(d) Schottky diode IV.

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

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

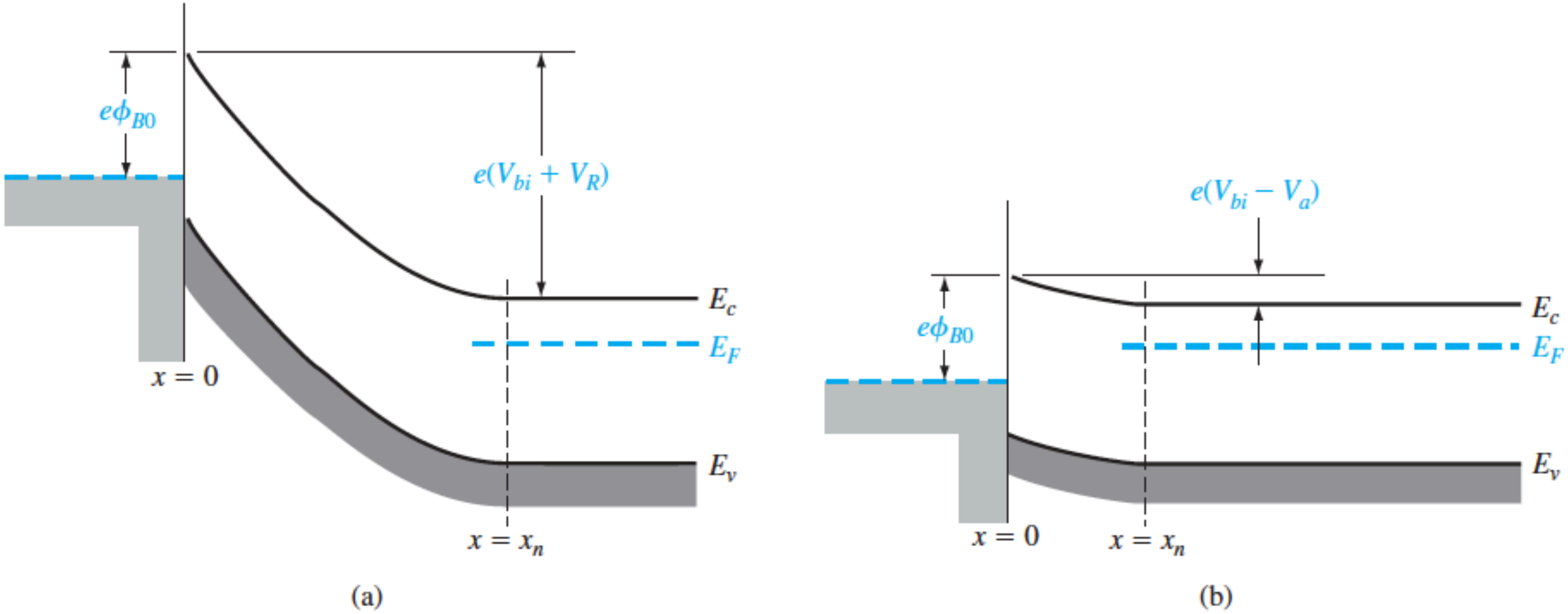


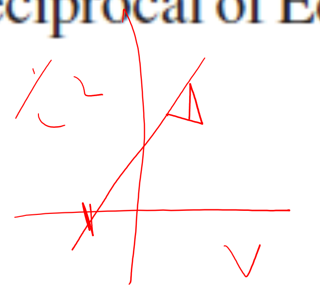
Figure 9.2 | Ideal energy-band diagram of a metal–semiconductor junction (a) under reverse bias and (b) under forward bias.

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

$$C' = eN_d \frac{dx_n}{dV_R} = \left[\frac{e\epsilon_s N_d}{2\,(V_{bi} + V_R)}\right]^{1/2} \tag{9.8}$$

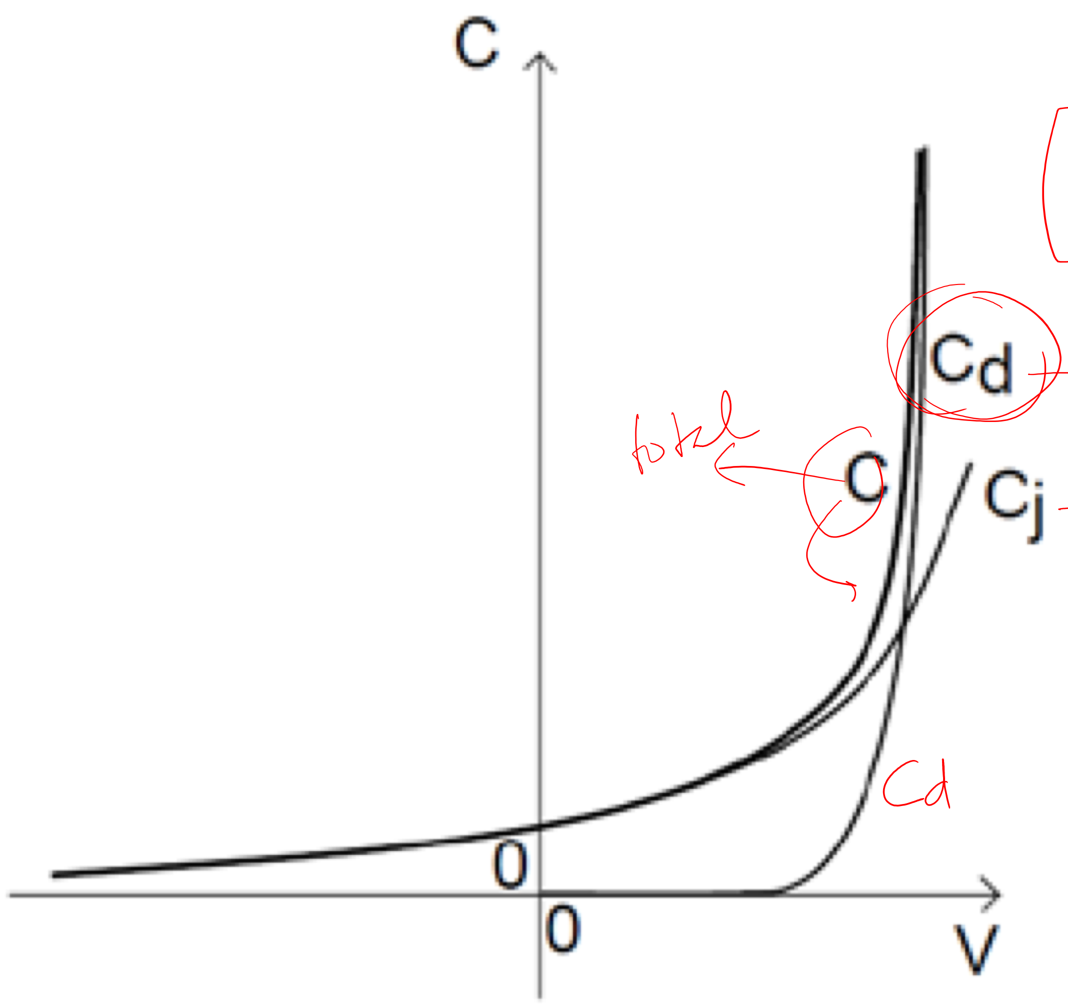
where C' is the capacitance per unit area. If we square the reciprocal of Equation (9.8), we obtain

$$\left(\frac{1}{C'}\right)^2 = \frac{2(V_{bi} + V_R)}{e\epsilon_s N_d} \tag{9.9}$$



We can use Equation (9.9) to obtain, to a first approximation, the built-in potential barrier V_{bi}, and the slope of the curve from Equation (9.9) to yield the semiconductor doping N_d. We can calculate the potential ϕ_n and then determine the Schottky barrier ϕ_{B0} from Equation (9.2).

Bias dependence of C_j and C_d:



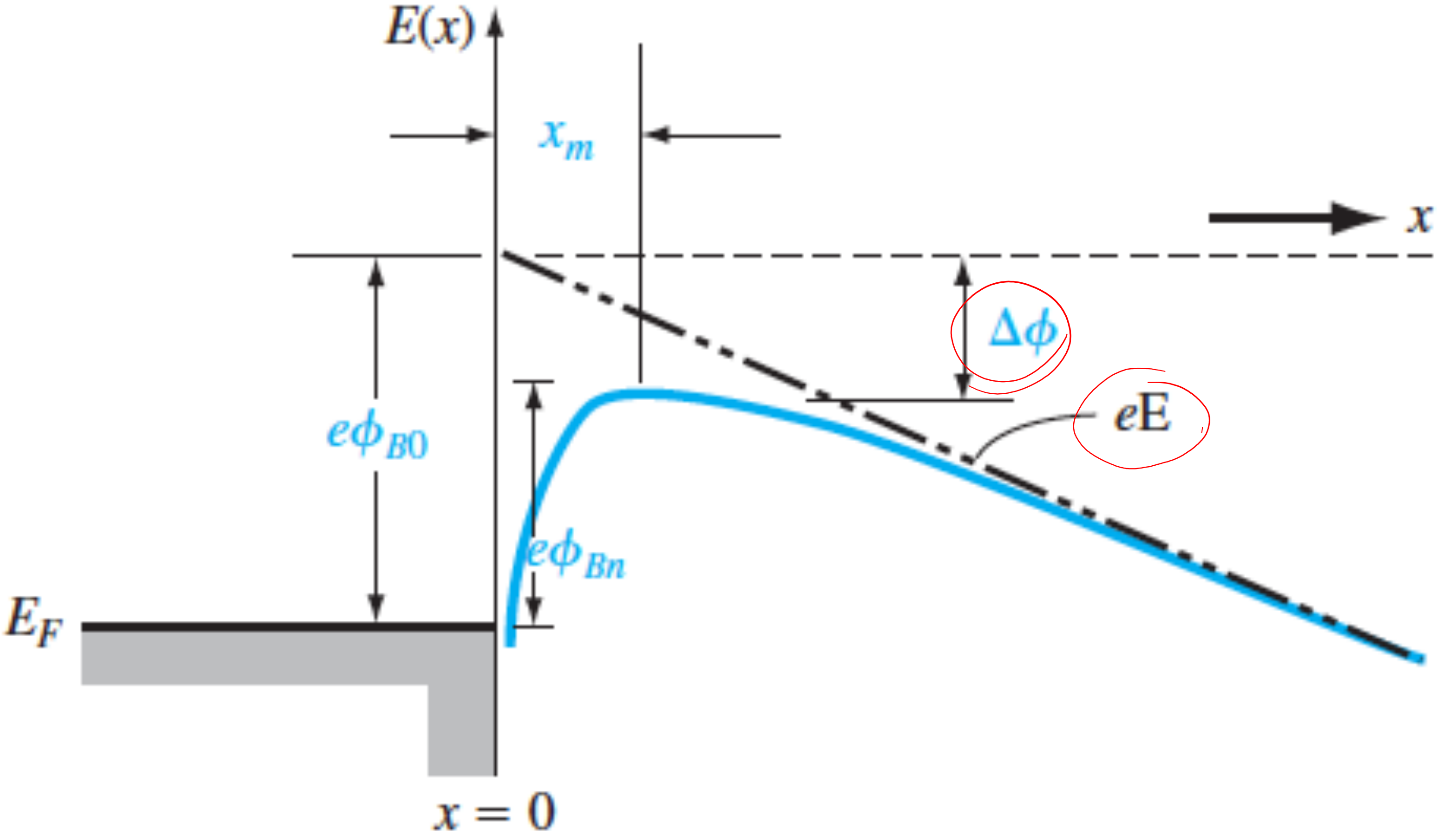
Forward Bias

$\boxed{C_d \gg C_j}$

diffusion

junction (depletion)

Schottky Effect



$$\boxed{\Delta\phi = \sqrt{\frac{eE}{4\pi\epsilon_s}}}$$

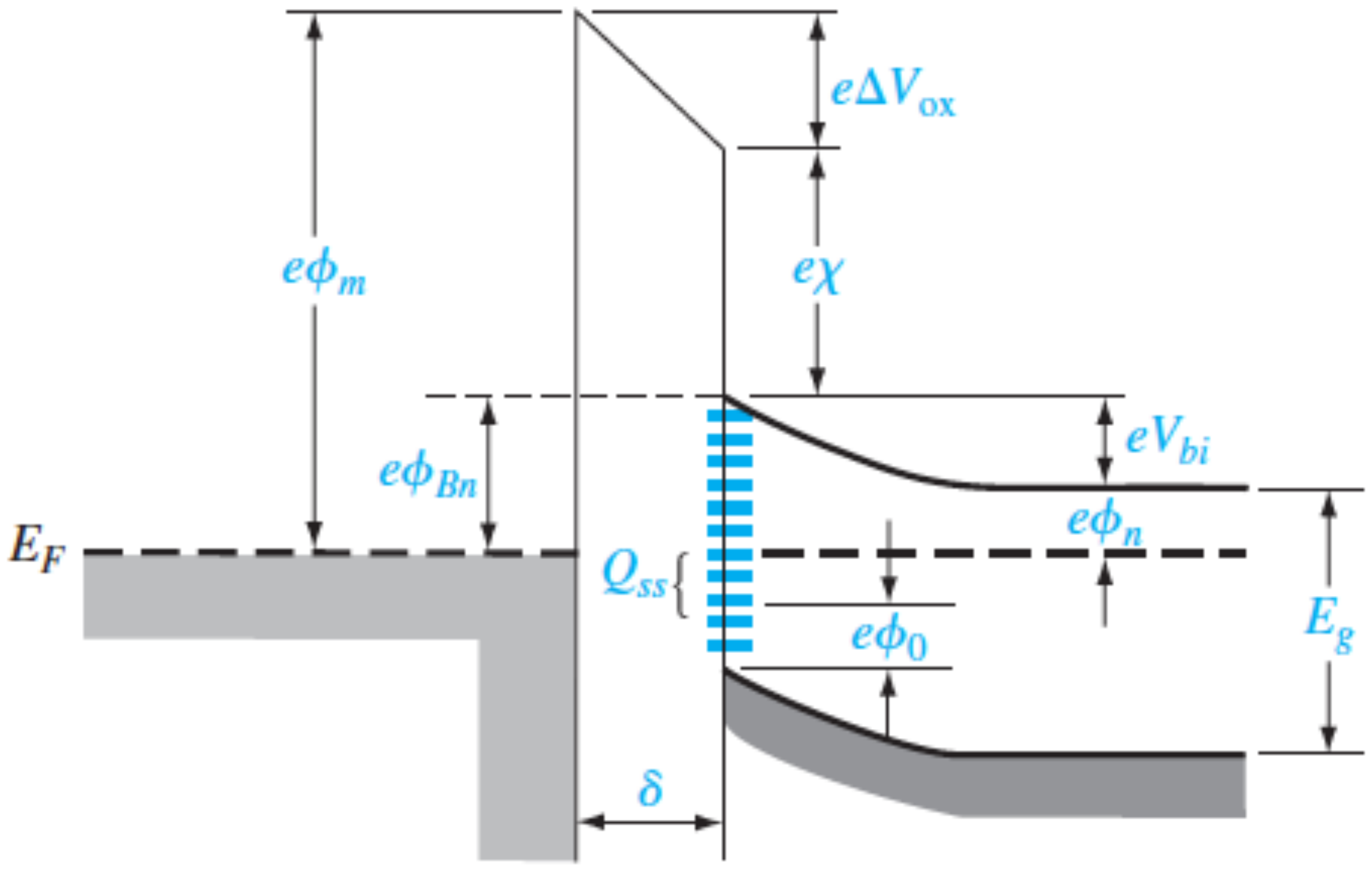
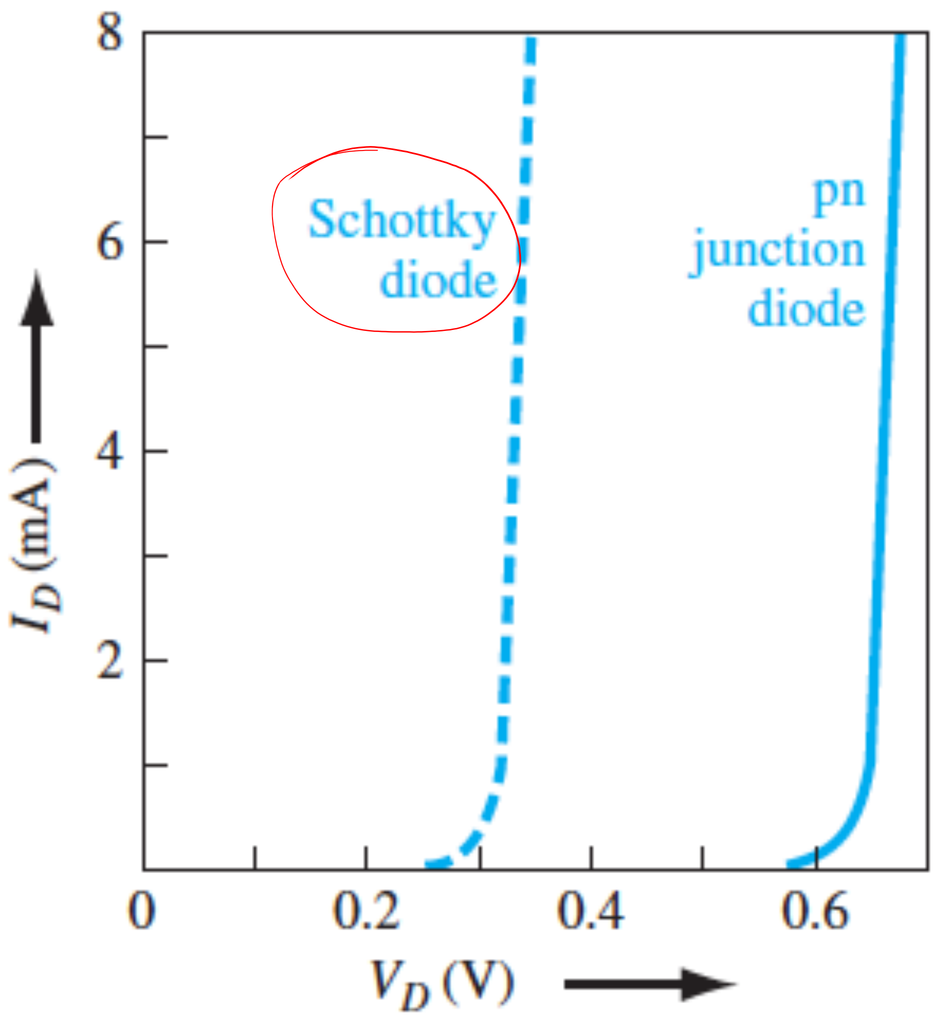
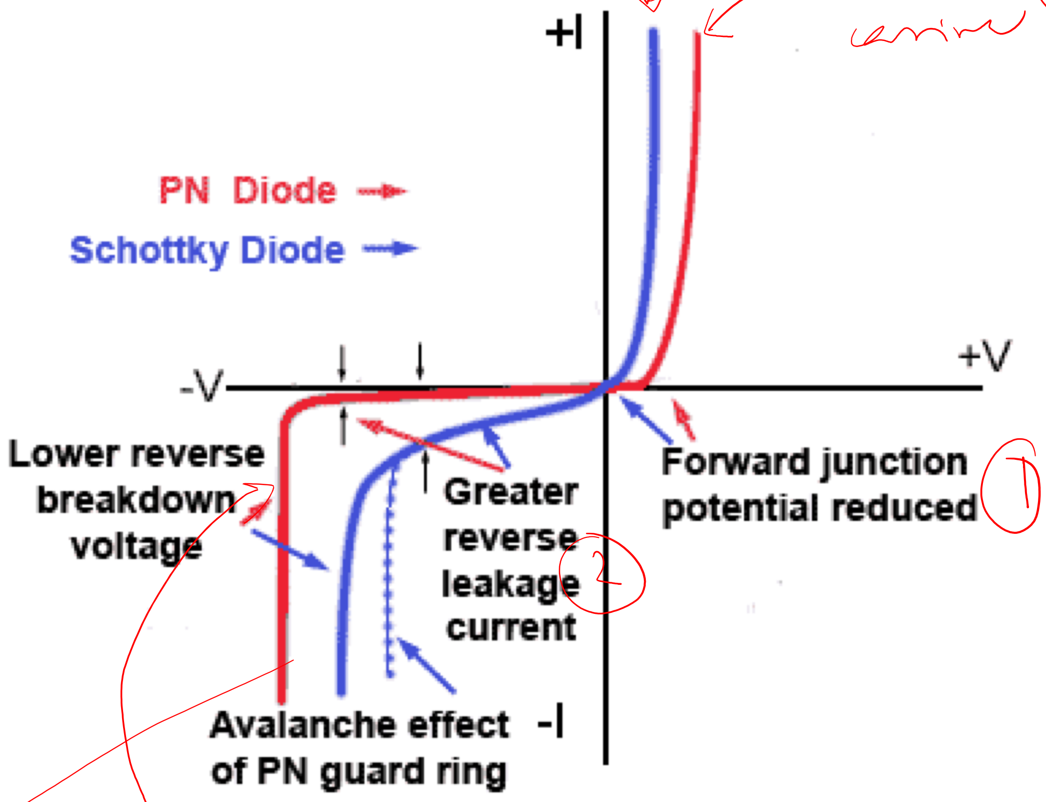


Figure 9.6 | Energy-band diagram of a metal–semiconductor junction with an interfacial layer and interface states.

majority carrier

minority carrier 3





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

$$\boxed{J_s = \frac{eD_n n_{po}}{L_n} + \frac{eD_p p_{no}}{L_p}}$$

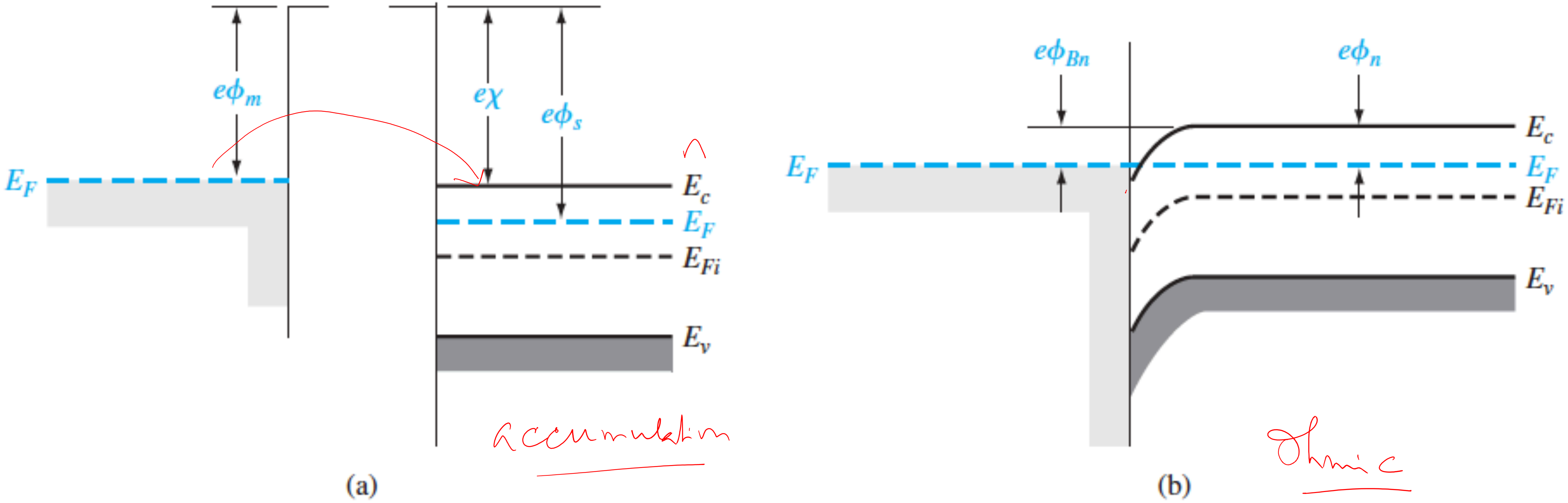


Figure 9.11 | Ideal energy-band diagram (a) before contact and (b) after contact for a metal-n-type semiconductor junction for $\phi_m < \phi_s$.

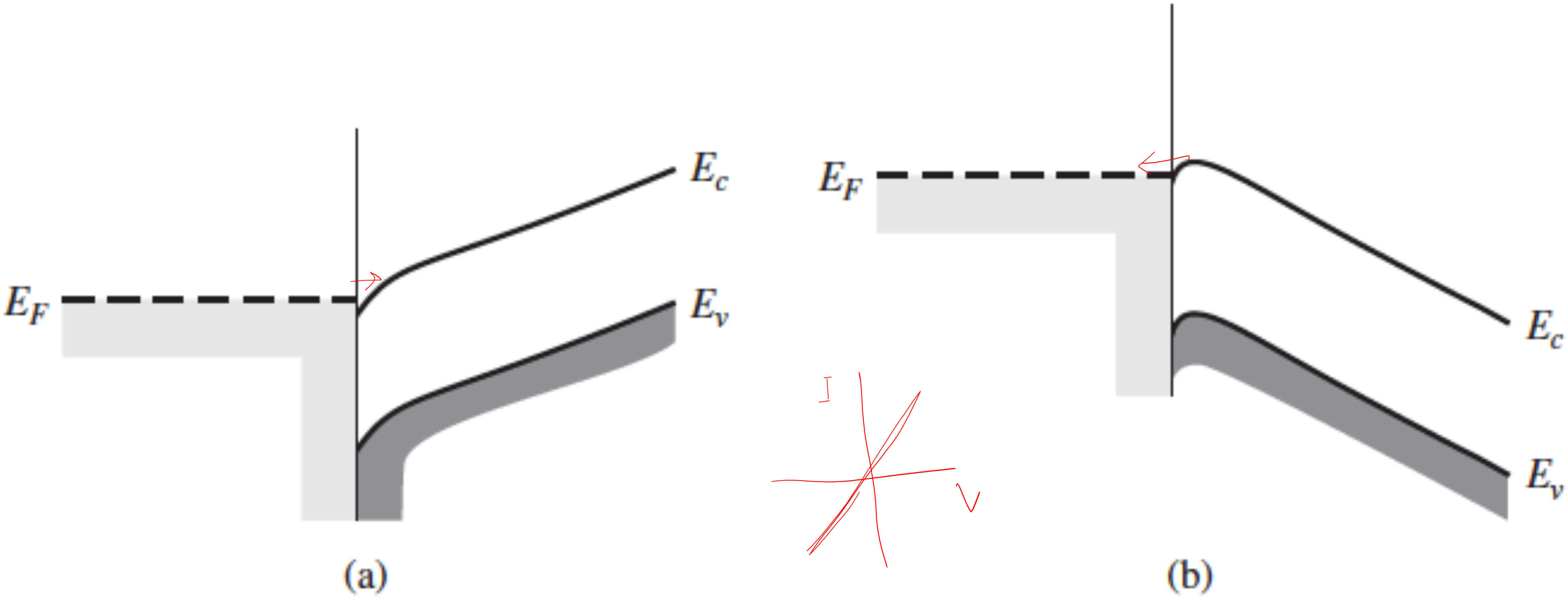


Figure 9.12 | Ideal energy-band diagram of a metal-n-type semiconductor ohmic contact (a) with a positive voltage applied to the metal and (b) with a positive voltage applied to the semiconductor.

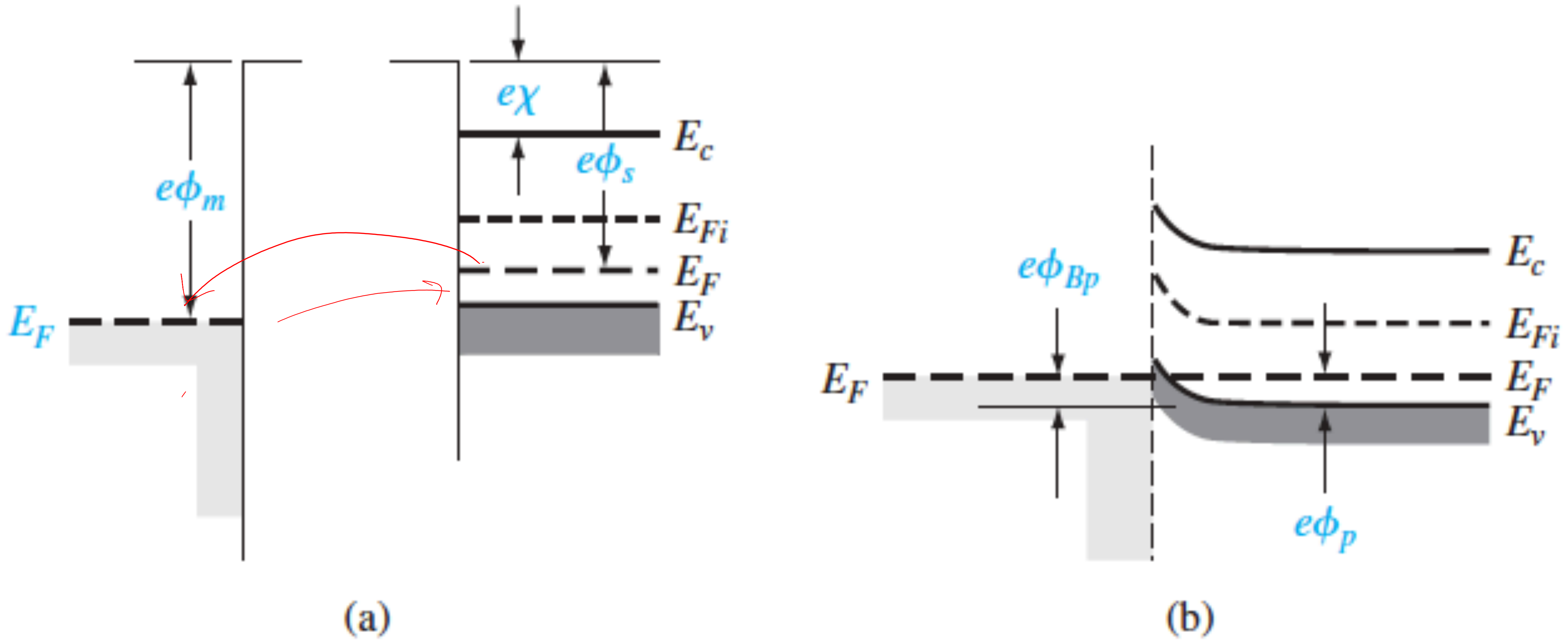


Figure 9.13 | Ideal energy-band diagram (a) before contact and (b) after contact for a metal–p-type semiconductor junction for $\phi_m < \phi_s$.

Ohmic Contact
(practical case)

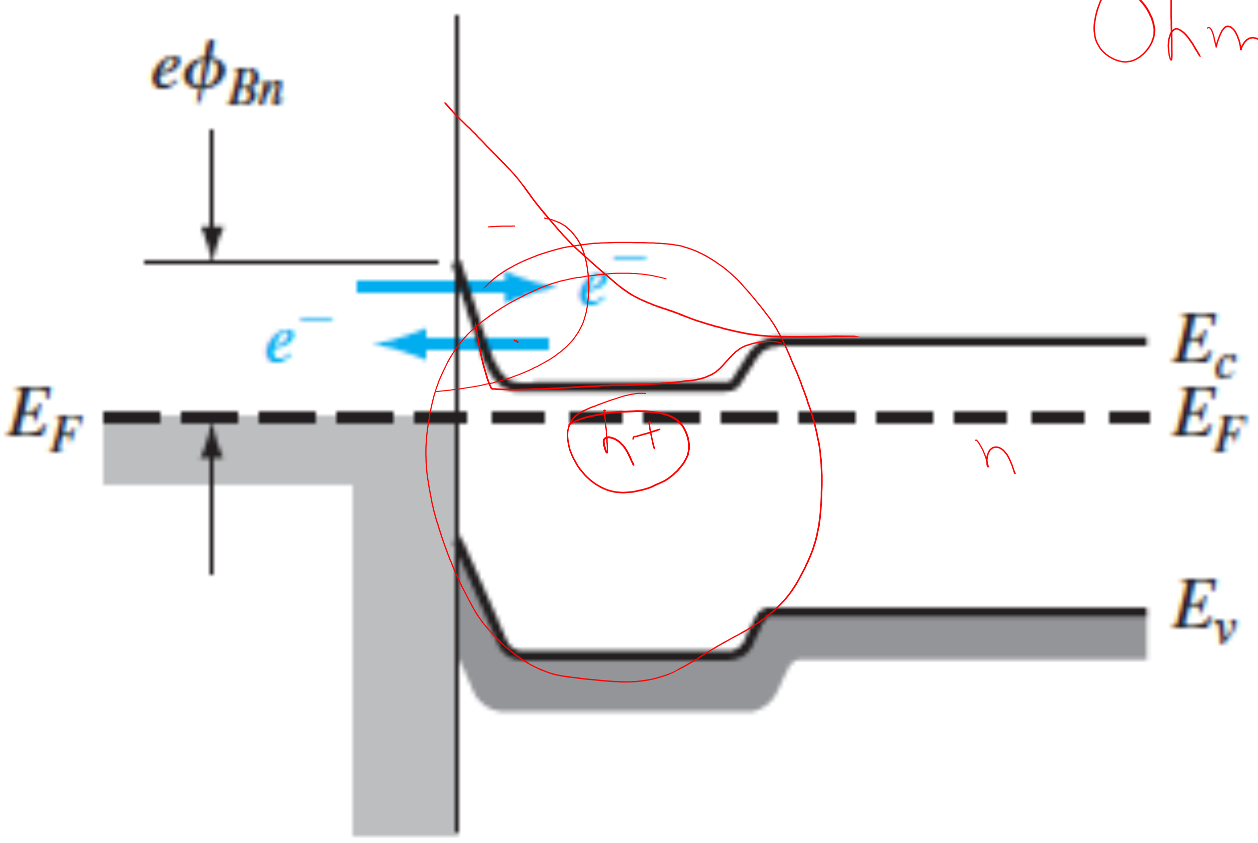


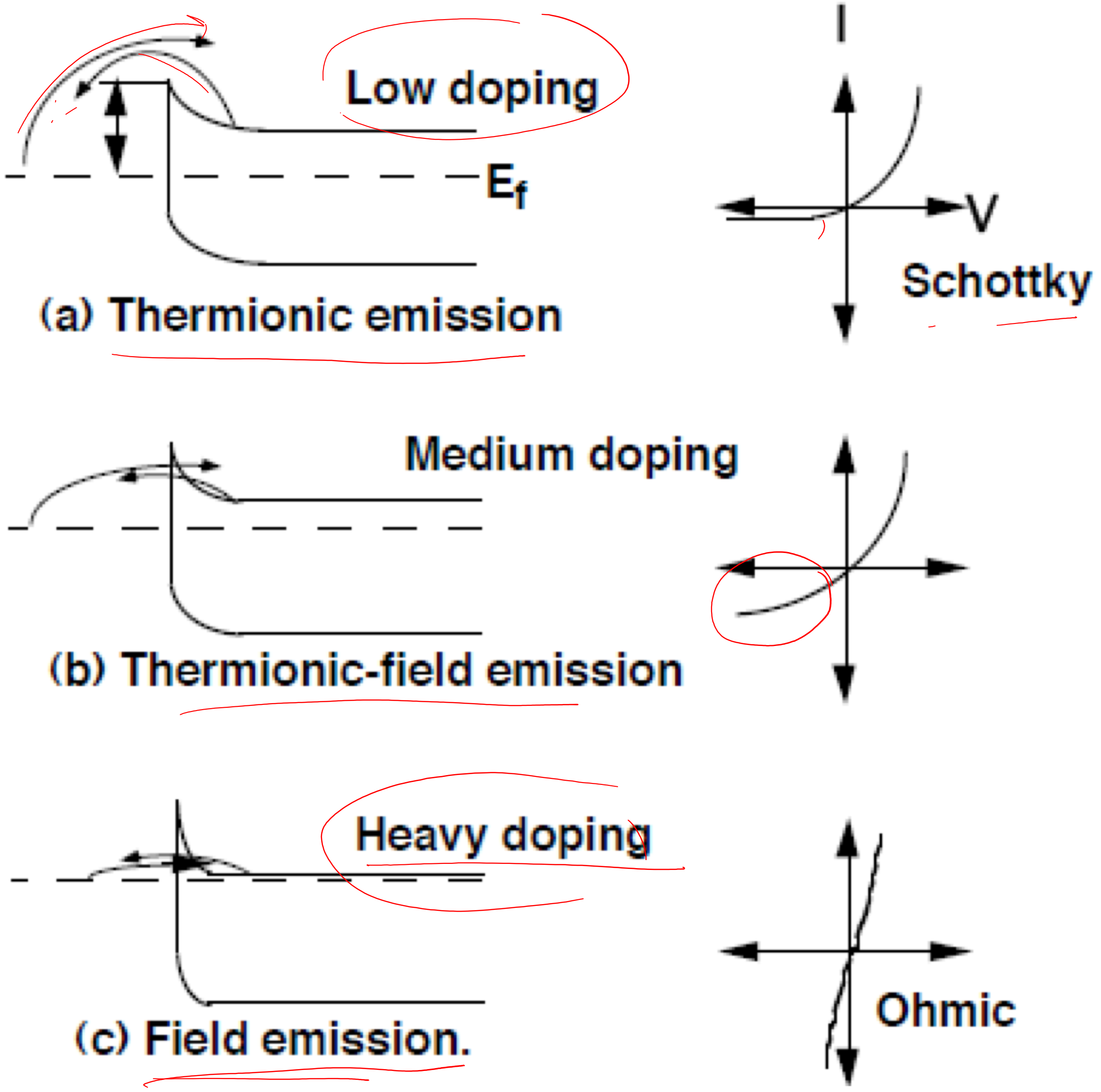
Figure 9.14 | Energy-band diagram of a heavily doped n-semiconductor-to-metal junction.

Al / Si (n or p)

Si p p^{++}

n n^{++}

Conduction Mechanisms for Metal/Semiconductor Contacts



$\phi_m > \phi_s$ n Semicon,

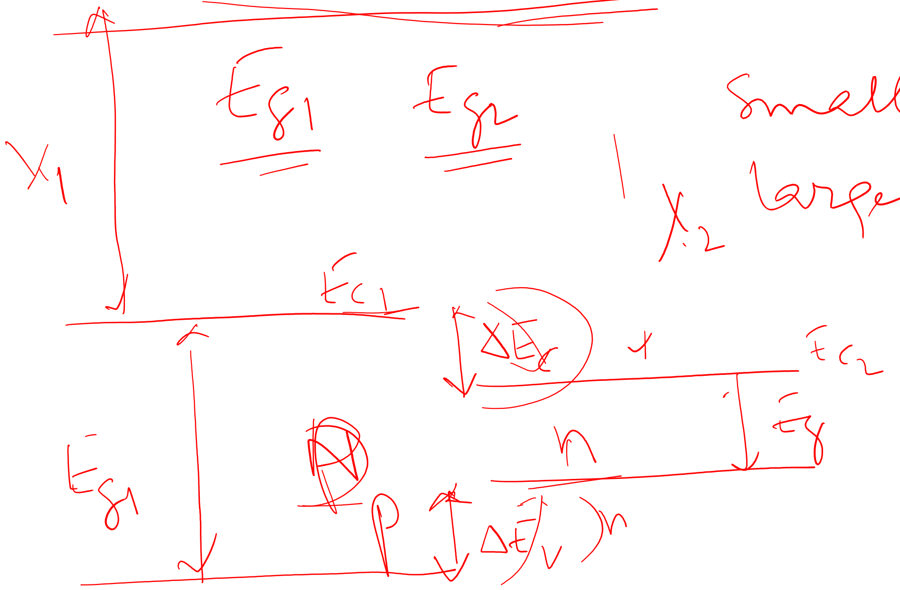
HETEROJUNCTIONS

Two different Band gap material in contact with each other

E_{g1} E_{g2}

Smaller Band gap n p

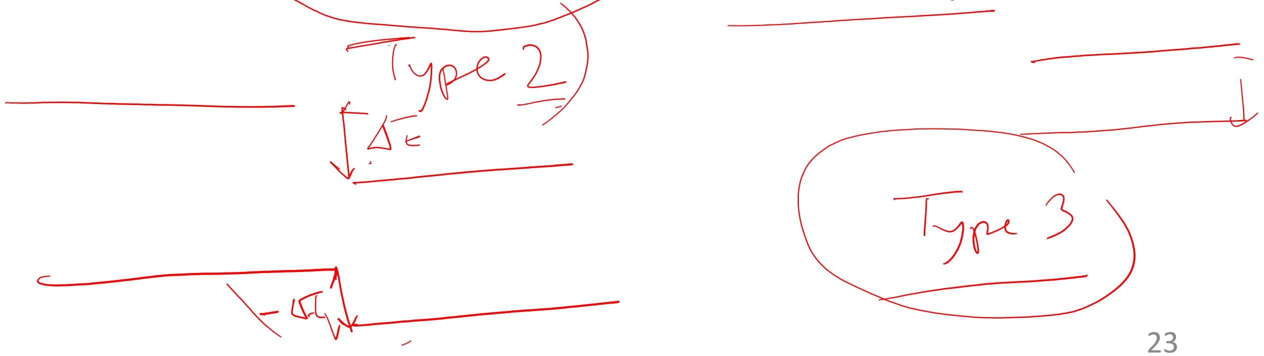
χ_2 larger Band gap N P



$$\Delta E_c + \Delta E_v = \Delta E_g$$

Nn Np

Pn Pp



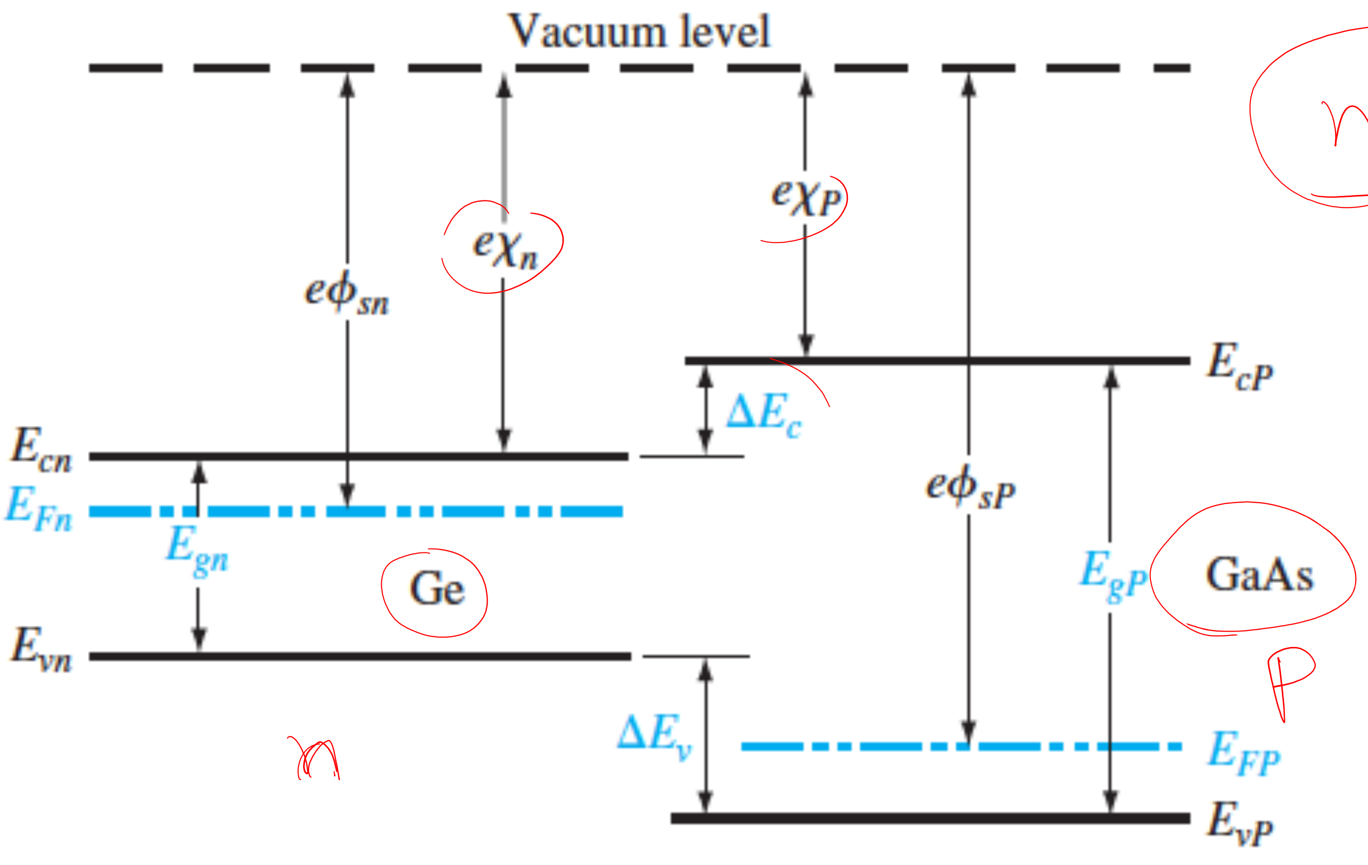


Figure 9.17 | Energy-band diagrams of a narrow-bandgap and a wide-bandgap material before contact.

nP Type I HJ

nP HJ

HBT

HEMT

$$\Delta E_c = e(\chi_n - \chi_P)$$

$$\Delta E_c + \Delta E_v = E_{gP} - E_{gn} = \Delta E_g$$

$$\Delta E_v = \Delta E_g - \Delta E_c$$

$$V_{bi} = \phi_{sP} - \phi_{sn}$$

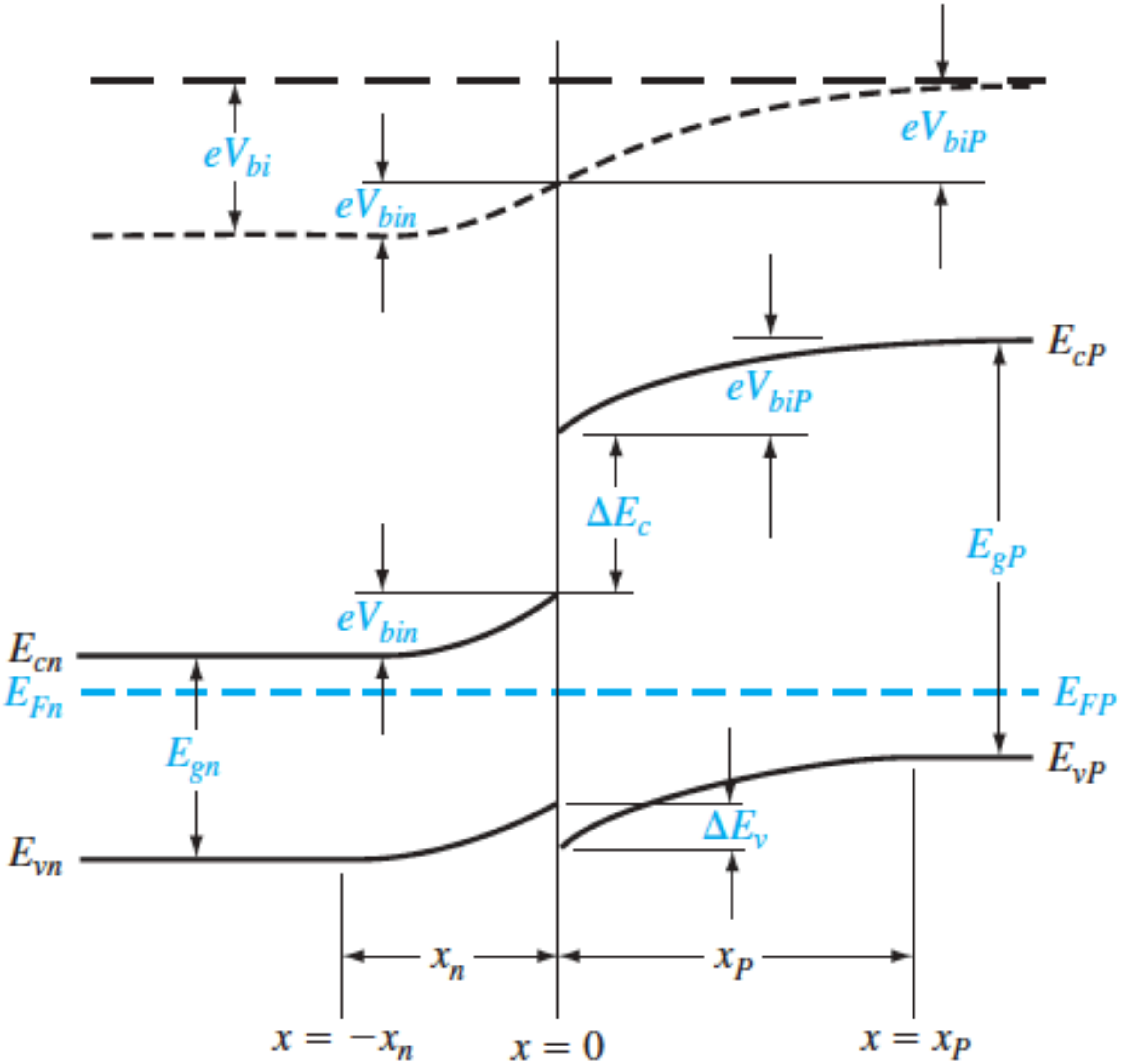


Figure 9.18 | Ideal energy-band diagram of an nP heterojunction in thermal equilibrium.

Equation (9.36), from Figure 9.17, can be written as

$$eV_{bi} = [e\chi_P + E_{gP} - (E_{FP} - E_{vP})] - [e\chi_n + E_{gn} - (E_{Fn} - E_{vn})] \tag{9.37a}$$

or

$$eV_{bi} = e(\chi_P - \chi_n) + (E_{gP} - E_{gn}) + (E_{Fn} - E_{vn}) - (E_{FP} - E_{vP}) \tag{9.37b}$$

which can be expressed as

$$eV_{bi} = -\Delta E_c + \Delta E_g + kT \ln\left(\frac{N_{vn}}{p_{no}}\right) - kT \ln\left(\frac{N_{vP}}{p_{po}}\right) \tag{9.38}$$

Finally, we can write Equation (9.38) as

$$eV_{bi} = \Delta E_v + kT \ln\left(\frac{p_{po}}{p_{no}} \cdot \frac{N_{vn}}{N_{vP}}\right) \tag{9.39}$$

where p_{po} and p_{no} are the hole concentrations in the P and n materials, respectively, and N_{vn} and N_{vP} are the effective density of states functions in the n and P materials, respectively. We can also obtain an expression for the built-in potential barrier in terms of the conduction band shift as

$$\boxed{eV_{bi} = -\Delta E_c + kT \ln\left(\frac{n_{no}}{n_{po}} \cdot \frac{N_{cP}}{N_{cn}}\right)} \tag{9.40}$$

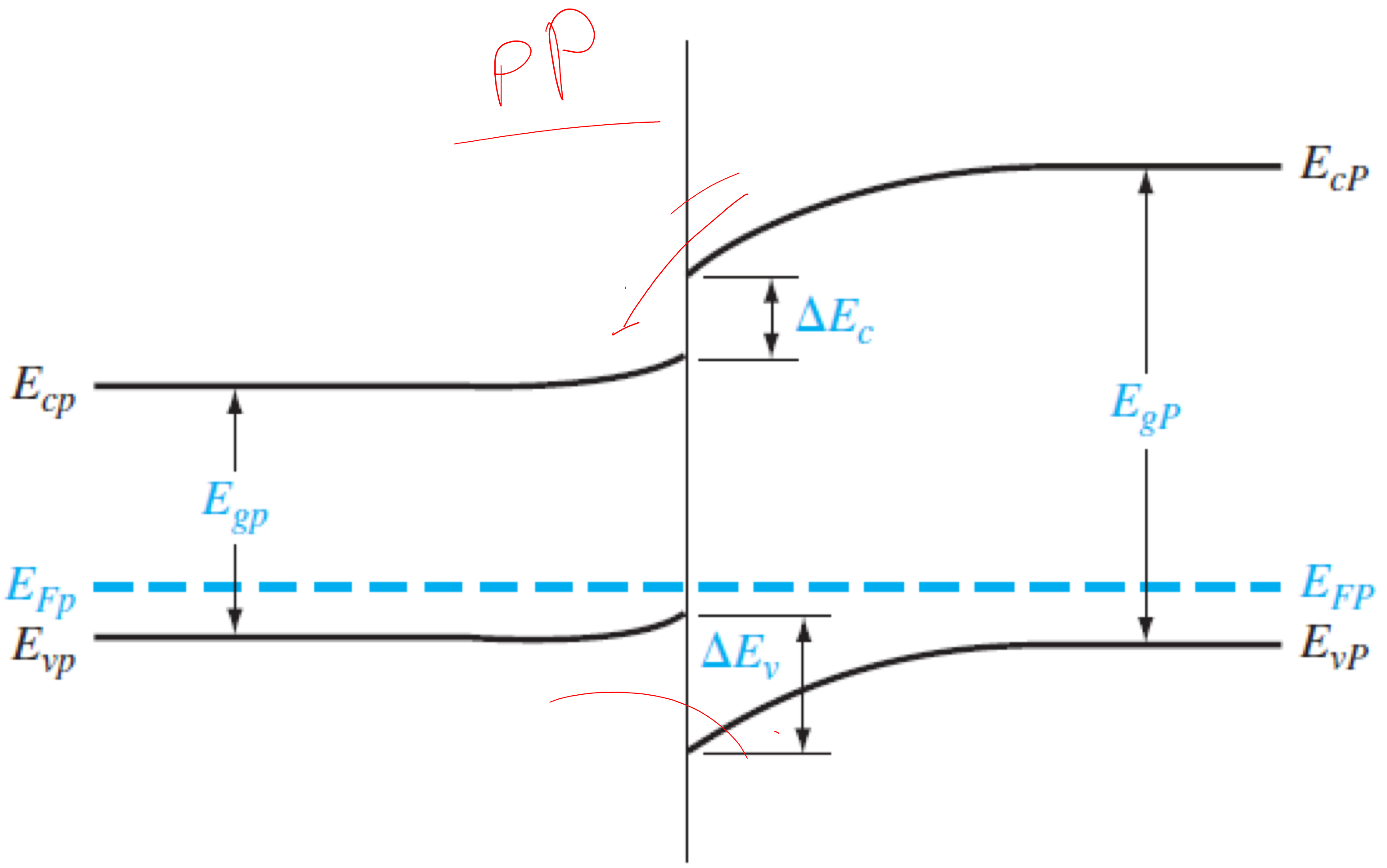


Figure 9.24 | Ideal energy-band diagram of a pP heterojunction in thermal equilibrium.

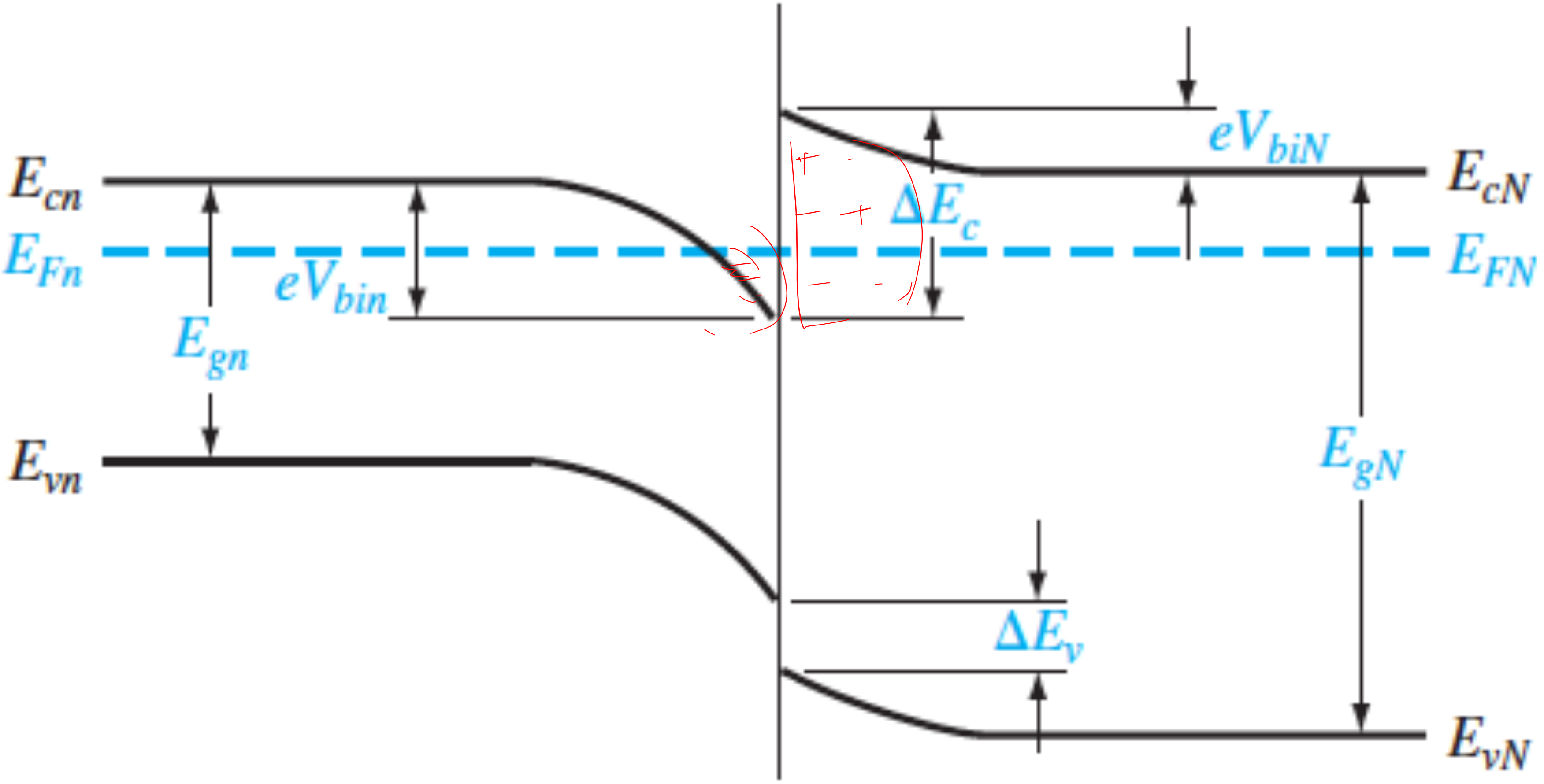


Figure 9.19 | Ideal energy-band diagram of an nN heterojunction in thermal equilibrium.

HEMT

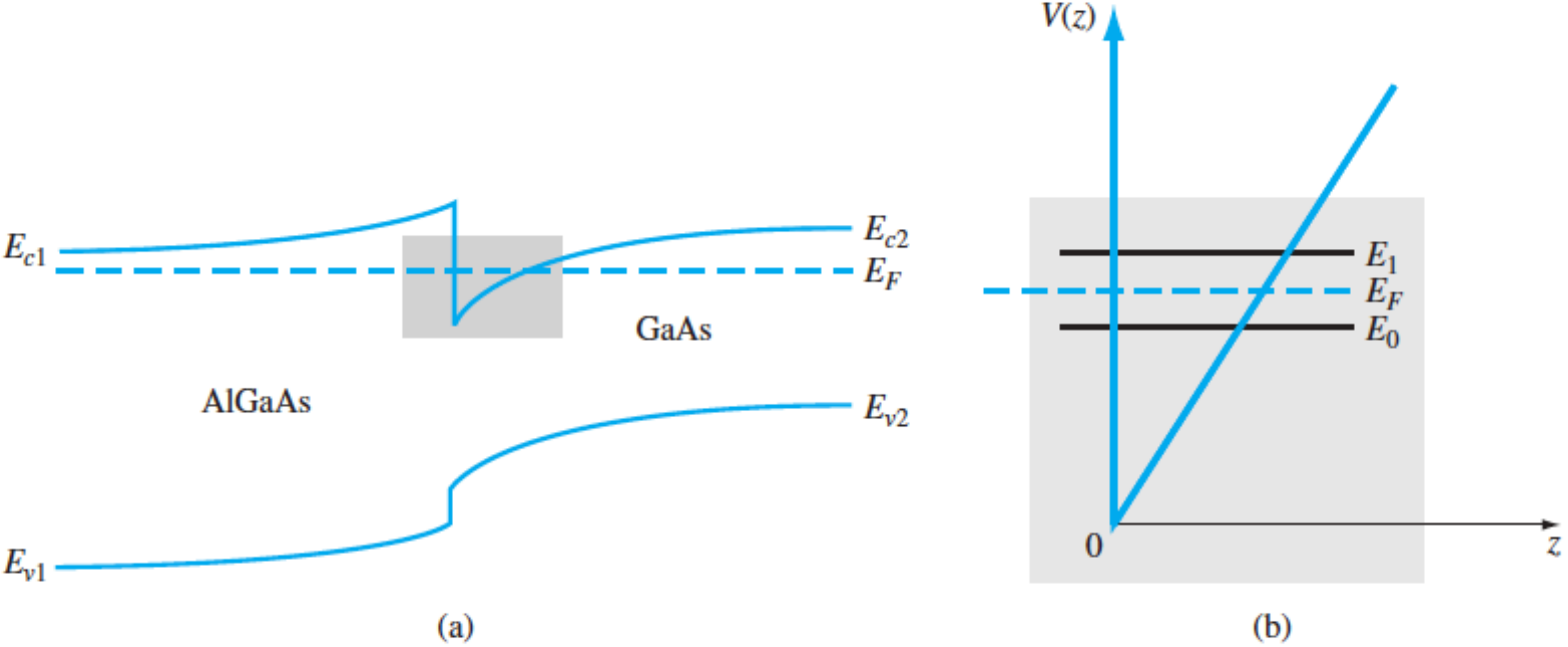


Figure 9.20 | (a) Conduction-band edge at N-AlGaAs, n-GaAs heterojunction; (b) triangular well approximation with discrete electron energies.

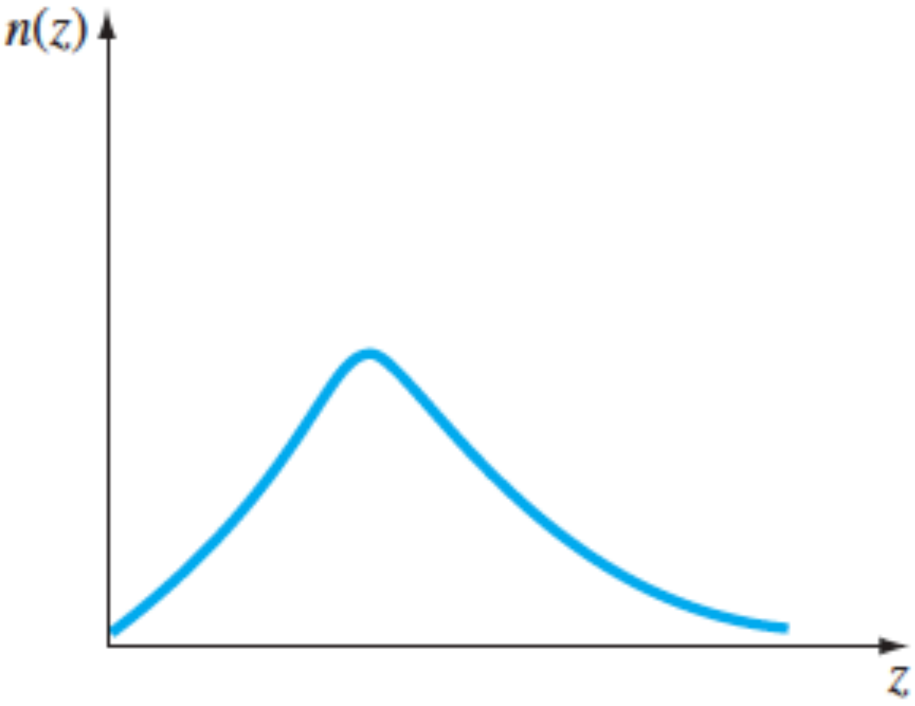


Figure 9.21 | Electron density in triangular potential well.

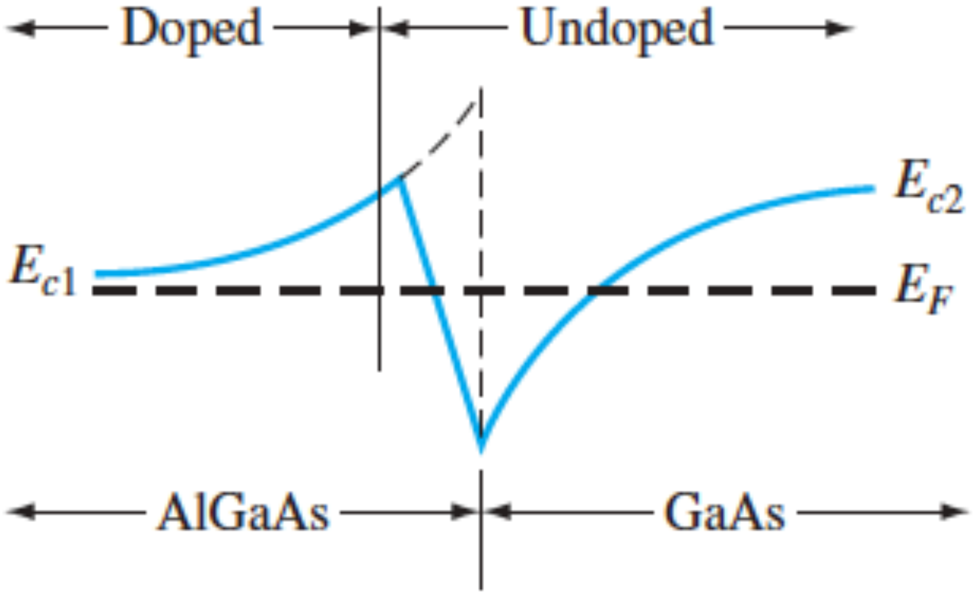


Figure 9.22 | Conduction-band edge at a graded heterojunction.

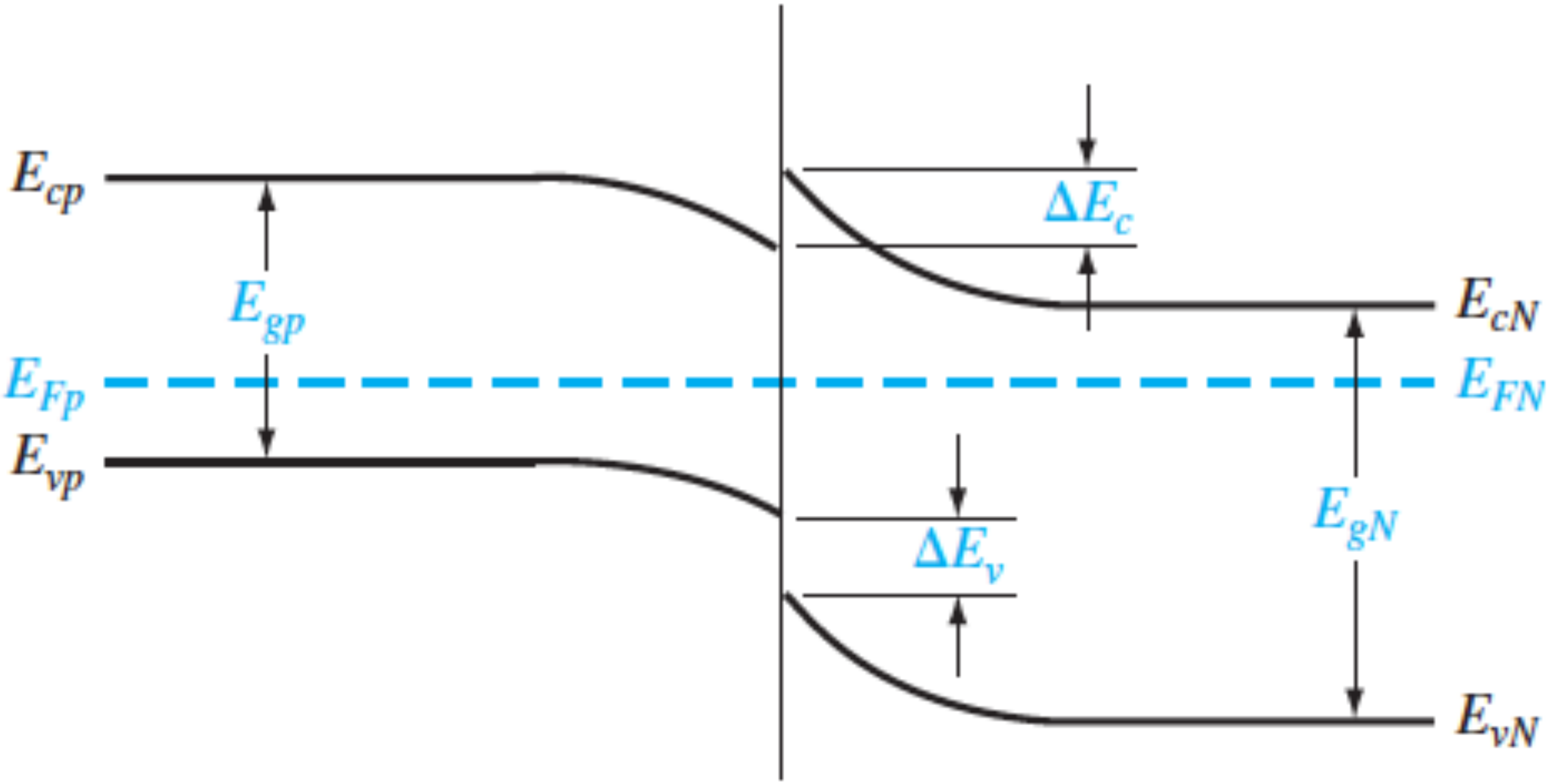


Figure 9.23 | Ideal energy-band diagram of an Np heterojunction in thermal equilibrium.