HKN ECE 340 Exam II Review Session

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I assume that you have sufficient knowledge of all topics covered on Exam I (even though average was 55%)

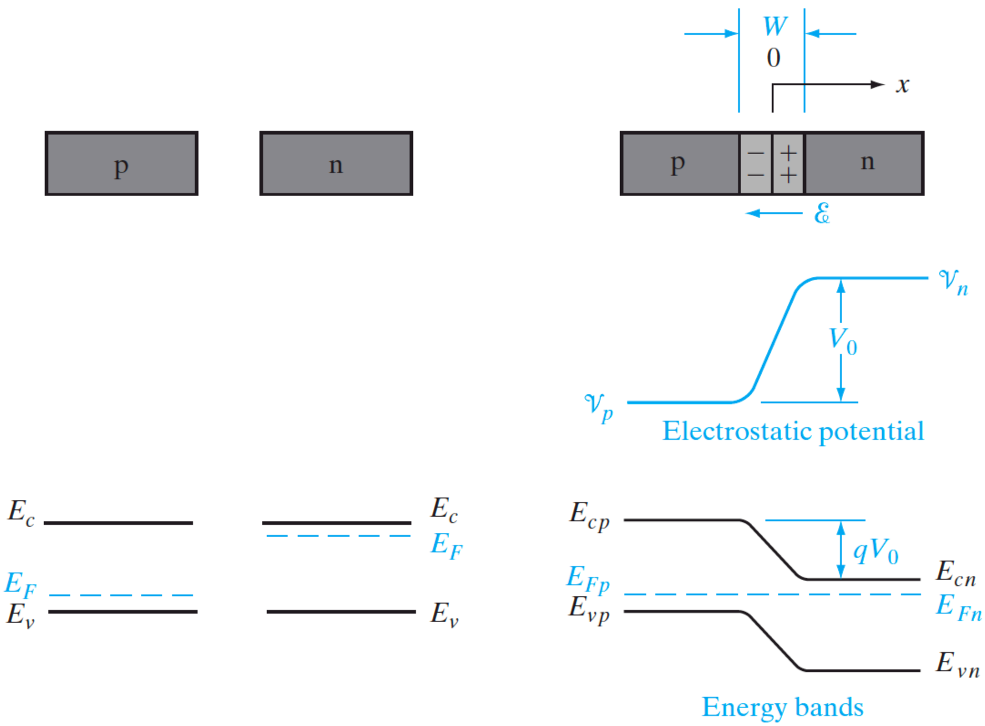
Topics:

1. Fabrication of pn junction (Take ECE 444)
2. PN junction equilibrium condition, contact potential
3. Space charge at a junction
4. Current flow, Carrier injection
5. Diode equation, Minority and Majority carrier current
6. Reverse-bias breakdowns
7. Stored charges, Junction and Diffusion capacitance
8. Optoelectronic Devices
9. Metal Semiconductor Junctions

Tips:

- Just try to write down whatever you know
- The exam is really lengthy so don't spend all your time on one question
- Try draw and explain what you write

pn Equilibrium Condition and the Contact Potential



(a) (b)

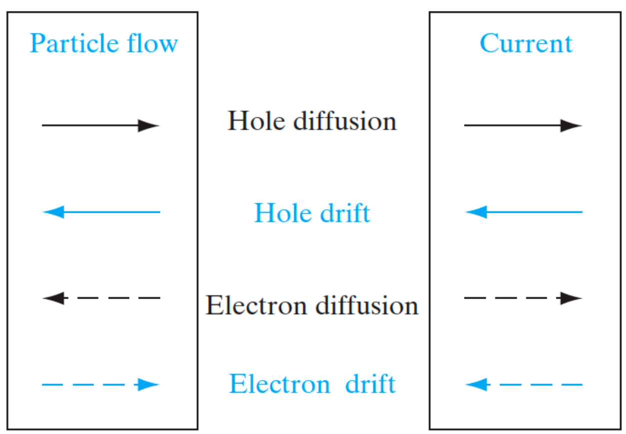
$$J_p(\text{drift}) + J_p(\text{diff.}) = 0$$

$$J_n(\text{drift}) + J_n(\text{diff.}) = 0$$

$$J_p(x) = q\left[\mu_p p(x)\mathscr{E}(x) - D_p \frac{dp(x)}{dx}\right] = 0$$

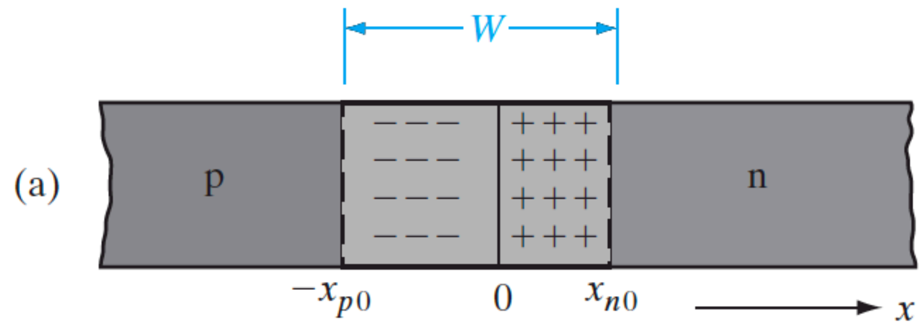
$$\mathscr{E}(x) = -d\mathscr{V}(x)/dx$$

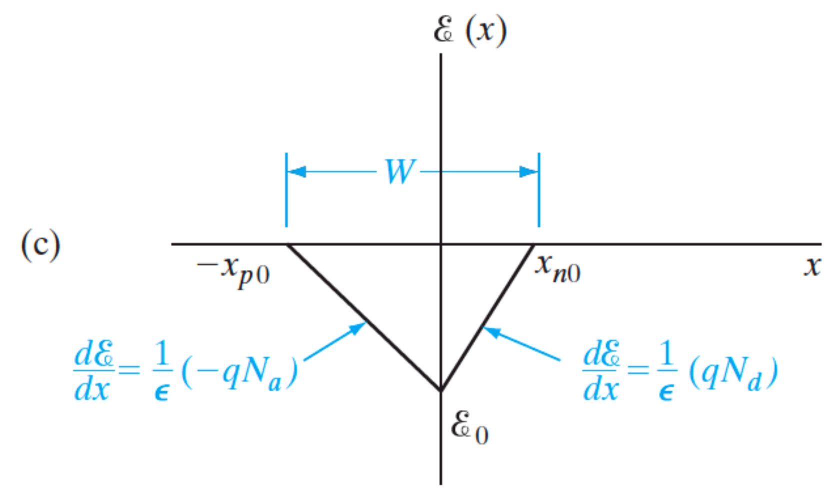
$$\boxed{\frac{p_p}{p_n} = \frac{n_n}{n_p} = e^{qV_0/kT}}$$

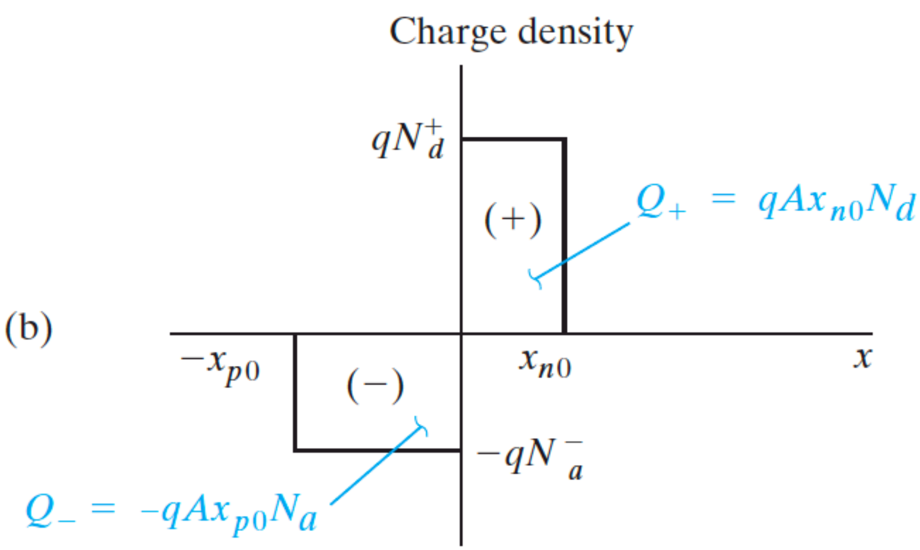


The Depletion Region

Also called the transition region, space charge region, and body region. Called the depletion region because it is "depleted of free charge carriers." The region has bound charges present which come from the ionized donors and acceptors in the doped regions. This is formed near the junction because most recombination occurs at the junction.







Space charge and electric field distribution within the transition region of a p-n junction with $N_D > N_A$:

(a) the transition region, with x = 0 defined at the metallurgical junction

(b) charge density within the transition region, neglecting the free carriers

(c) the electric field distribution, where the reference direction for $\mathscr{E}$ is arbitrarily taken as the +x

$$qAx_{p0}N_a = qAx_{n0}N_d$$

⇨ Due to charge neutrality in the depletion region

⇨ If the charge density of one of the sides is higher due to doping, more volume on the lightly doped region needs to be covered

According to Poisson's Equation

$$\frac{d\mathscr{E}}{dx} = \frac{q}{\epsilon}N_d, \qquad 0 < x < x_{n0}$$

$$\frac{d\mathscr{E}}{dx} = -\frac{q}{\epsilon}N_a, \qquad -x_{p0} < x < 0$$

Maximum Value of EF

$$\mathscr{E}_0 = -\frac{q}{\epsilon}N_d x_{n0} = -\frac{q}{\epsilon}N_a x_{p0}$$

$$\mathscr{E}(x) = -\frac{d\mathscr{V}(x)}{dx} \quad \text{or} \quad -V_0 = \int_{-x_{p0}}^{x_{n0}} \mathscr{E}(x)dx$$

$$V_0 = -\frac{1}{2}\mathscr{E}_0 W = \frac{1}{2}\frac{q}{\epsilon}N_d x_{n0} W \longrightarrow V_0 = \frac{1}{2}\frac{q}{\epsilon}\frac{N_a N_d}{N_a + N_d}W^2$$

$$\boxed{W = \left[\frac{2\epsilon V_0}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2} = \left[\frac{2\epsilon V_0}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)\right]^{1/2}}$$

$$x_{p0} = \frac{WN_d}{N_a + N_d} = \frac{W}{1 + N_a/N_d} = \left\{\frac{2\epsilon V_0}{q}\left[\frac{N_d}{N_a(N_a + N_d)}\right]\right\}^{1/2}$$

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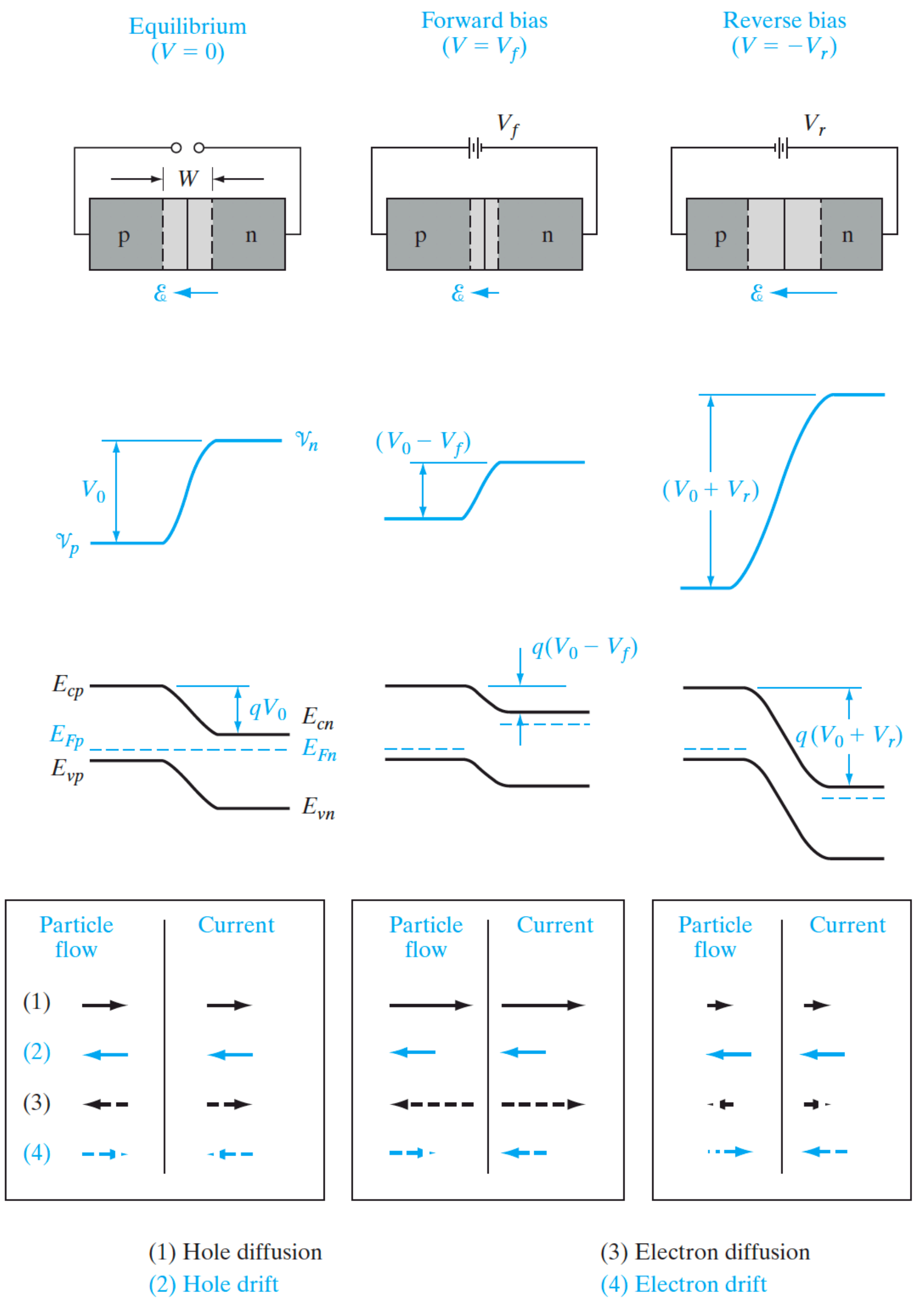
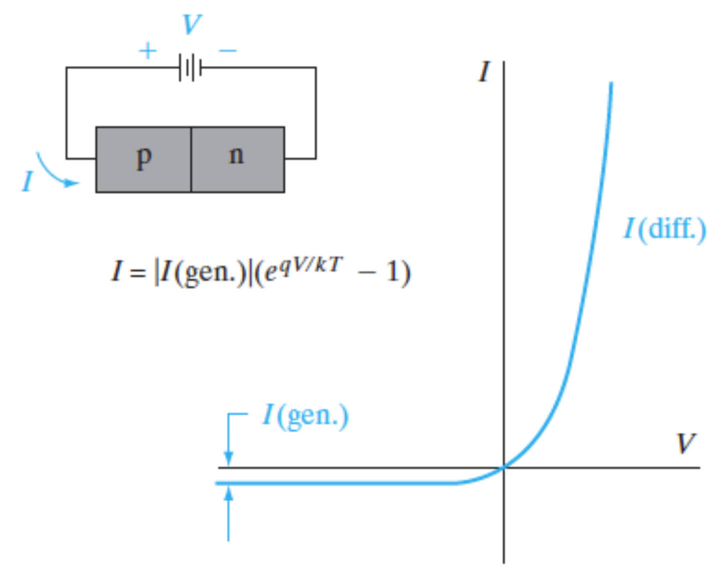
Biased Junctions



Effects of a bias at a p-n junction; transition region width and electric field, electrostatic potential, energy band diagram, and particle flow and current directions within W for (a) equilibrium, (b) forward bias, and (c) reverse bias. The electric fields vary linearly with position, as shown in figure, if the doping concentrations in the depletion regions are constant on either side of the junction. Since the electrostatic potential is obtained by integrating the (linearly varying) electric fields as shown in equation, the potential profiles (and band edges) vary as the square of distance from the depletion edges. Therefore, the shape of the band diagram in the depletion region is not linear but consists of two parabolic curves that join smoothly.

The drift current is relatively insensitive to the height of the potential barrier because the drift current is limited not by how fast carriers are swept down the barrier, but rather how often

The only current flowing in this p-n junction diode for negative V is the small current I(gen.) due to carriers generated in the transition region or minority carriers which diffuse to the junction and are collected.



An applied forward bias $V = V_f$ increases the probability that a carrier can diffuse across the junction, by the factor $\exp(qV_f/kT)$. The following equation is the ideal diode equation and it is valid for all V. The current $-I_0$ in reverse bias, is the negative generation current and is known as the *reverse saturation current*.

$$I = I_0(e^{qV/kT} - 1)$$

Carrier Injection

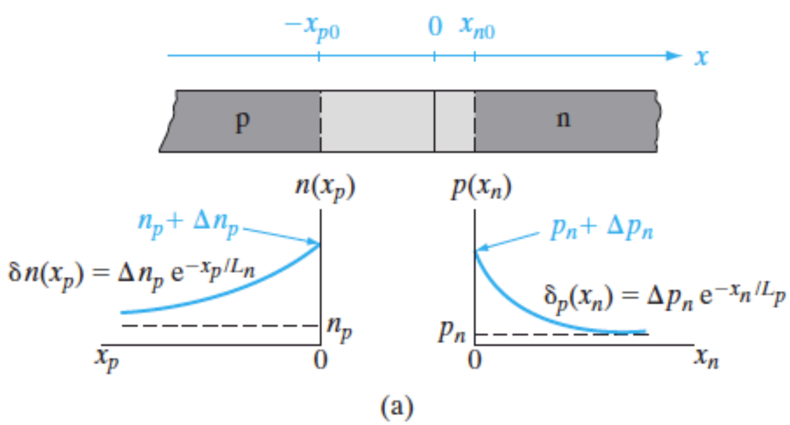
With bias applied to the junction, the 0 in the subscripts of x_{n0} and x_{p0} does not imply equilibrium. Instead, it signifies the origin of a new set of coordinates, $x_n = 0$ and $x_p = 0$.

$$\frac{p_p}{p_n} = e^{qV_0/kT} \xrightarrow{\text{with bias}} \frac{p(-x_{p0})}{p(x_{n0})} = e^{q(V_0-V)/kT} \longrightarrow \frac{p(x_{n0})}{p_n} = e^{qV/kT} \quad \text{taking } p(-x_{p0}) = p_p$$

With forward bias, the equation above suggests a greatly increased minority carrier hole concentration at the edge of the transition region on the n side $p(x_{n0})$ than was the case at equilibrium. Conversely, the hole concentration $p(x_{n0})$ under reverse bias (V negative) is reduced below the equilibrium value p_n. The exponential increase of the hole concentration at x_{n0} with forward bias is an example of minority carrier injection. As the figure below suggests, a forward bias V results in a steady state injection of excess holes into the n region and electrons into the p region. We can easily calculate the excess hole concentration Δp_n at the edge of the transition region x_{n0} by subtracting the equilibrium hole concentration

$$\boxed{\Delta p_n = p(x_{n0}) - p_n = p_n(e^{qV/kT} - 1)}$$

$$\boxed{\Delta n_p = n(-x_{p0}) - n_p = n_p(e^{qV/kT} - 1)}$$



Rewriting the diffusion equation, we solve for the distribution of excess carriers.

$$\boxed{\delta n(x_p) = \Delta n_p e^{-x_p/L_n} = n_p(e^{qV/kT} - 1)e^{-x_p/L_n}}$$

$$\boxed{\delta p(x_n) = \Delta p_n e^{-x_n/L_p} = p_n(e^{qV/kT} - 1)e^{-x_n/L_p}}$$

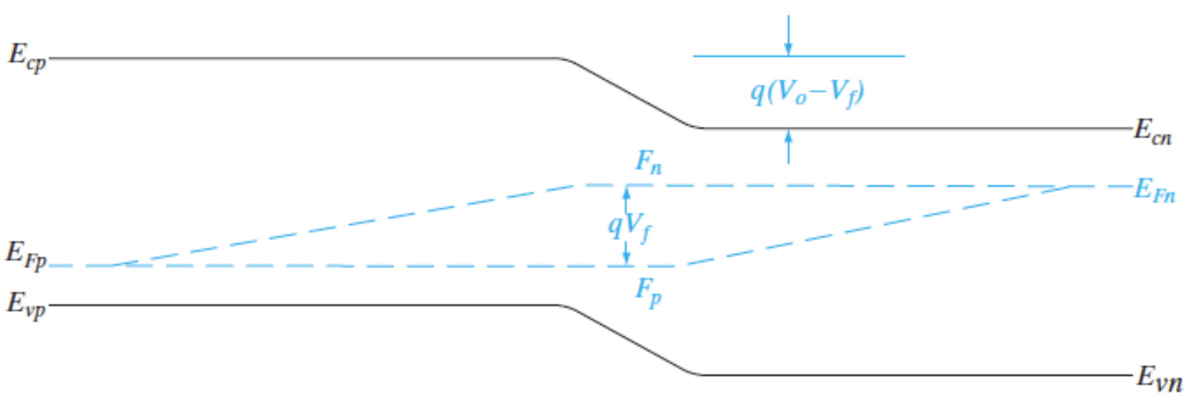


Figure: Forward-biased junction: (a) minority carrier distributions on the two sides of the transition region and definitions of distances x_n and x_p measured from the transition region edges; (b) variation of the quasi-Fermi levels with position.

The hole diffusion current at each position x_n is proportional to the excess hole concentration at that point. The hole diffusion current at any point x_n in the n material can be calculated as (from Eqn 4.40):

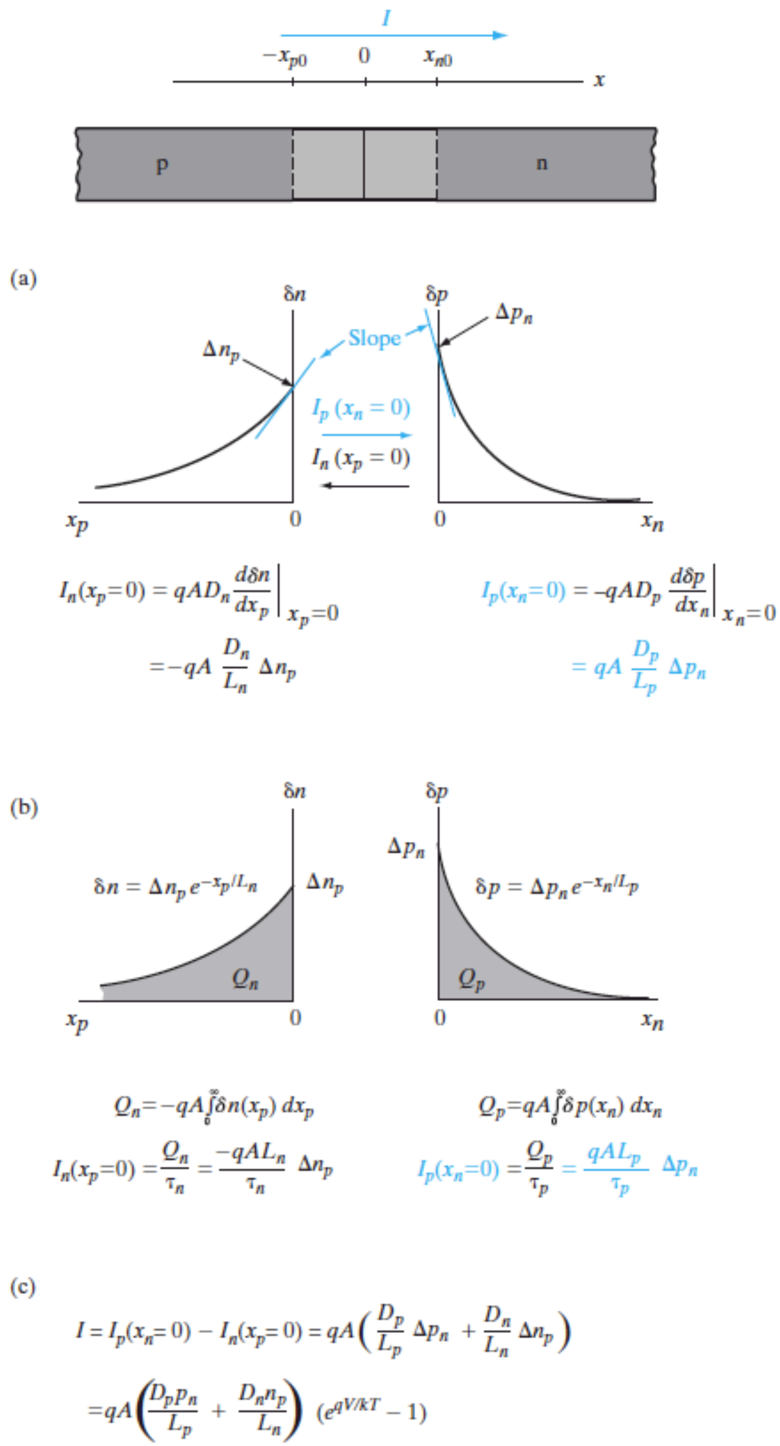
$$I_p(x_n) = -qAD_p\frac{d\delta p(x_n)}{dx_n} = qA\frac{D_p}{L_p}\Delta p_n e^{-x_n/L_p} = qA\frac{D_p}{L_p}\delta p(x_n)$$

$$I_n(x_p = 0) = -\frac{qAD_n}{L_n}\Delta n_p = -\frac{qAD_n}{L_n}n_p(e^{qV/kT} - 1)$$

$$I = I_p(x_n = 0) - I_n(x_p = 0) = \frac{qAD_p}{L_p}\Delta p_n + \frac{qAD_n}{L_n}\Delta n_p$$

diode equation:

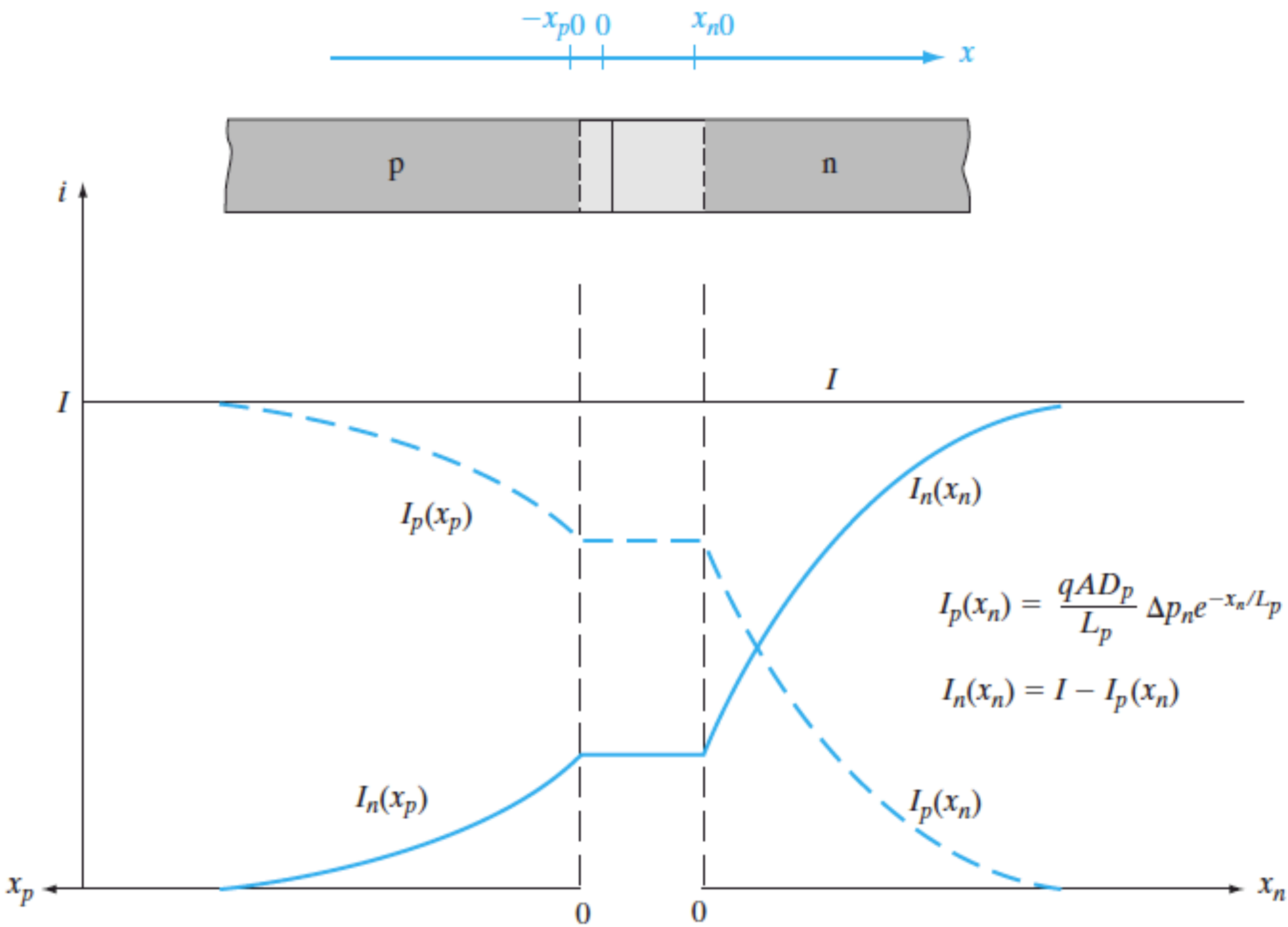
$$\boxed{I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)(e^{qV/kT} - 1) = I_0(e^{qV/kT} - 1)}$$



Two methods for calculating junction current from the excess minority carrier distributions: (a) diffusion currents at the edges of the transition region; (b) charge in the distributions divided by the minority carrier lifetimes; (c) the diode equation.

Forward Bias

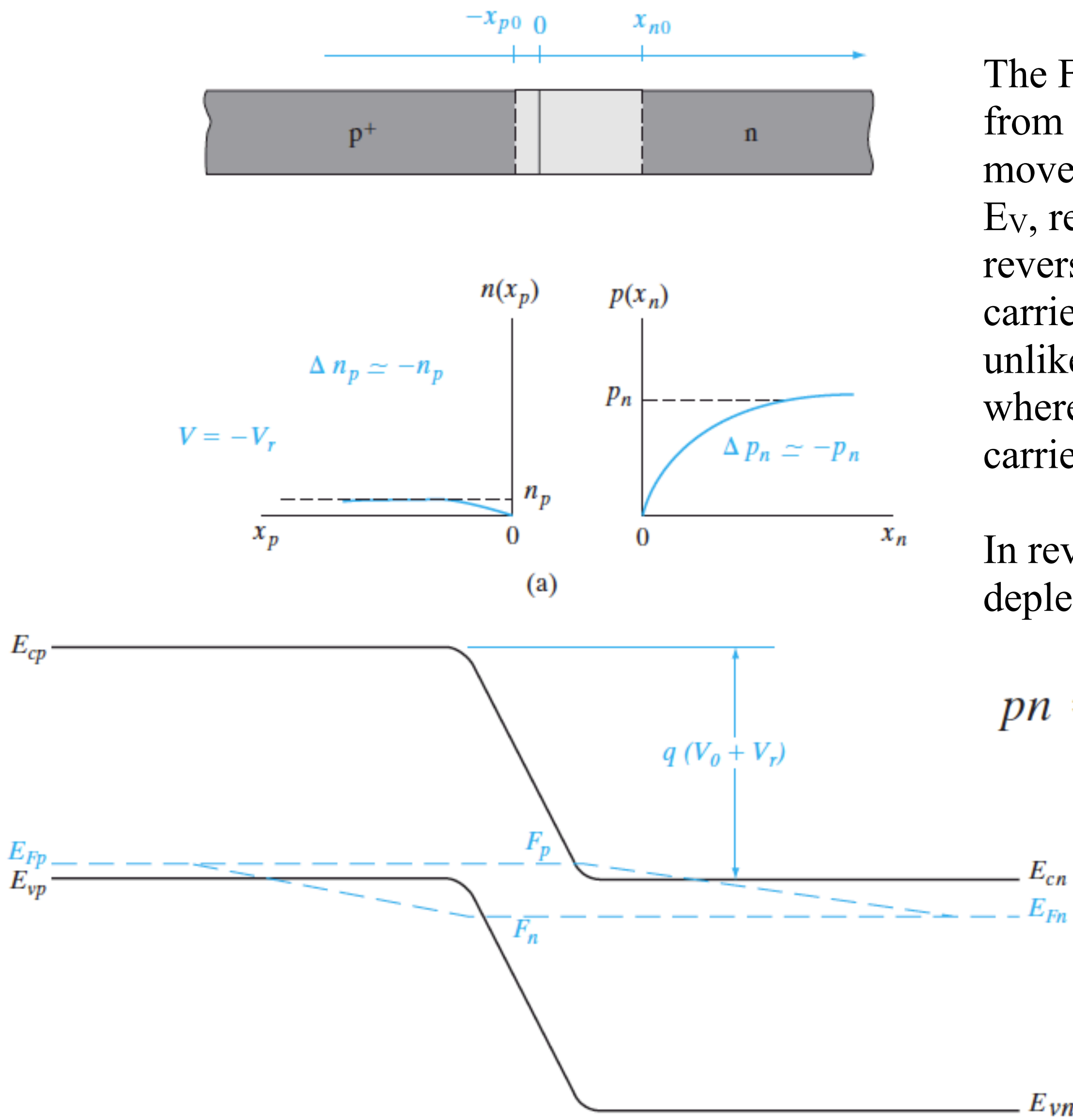
Electron and hole components of current in a forward-biased p-n junction. In this example, we have a higher injected minority hole current on the n side than electron current on the p side because we have a lower n doping than p doping.



Reverse Bias

$$\Delta p_n = p_n(e^{q(-V_r)/kT} - 1) \simeq -p_n \quad \text{for } V_r \gg kT/q$$

and similarly $\Delta n_p \simeq -n_p$.



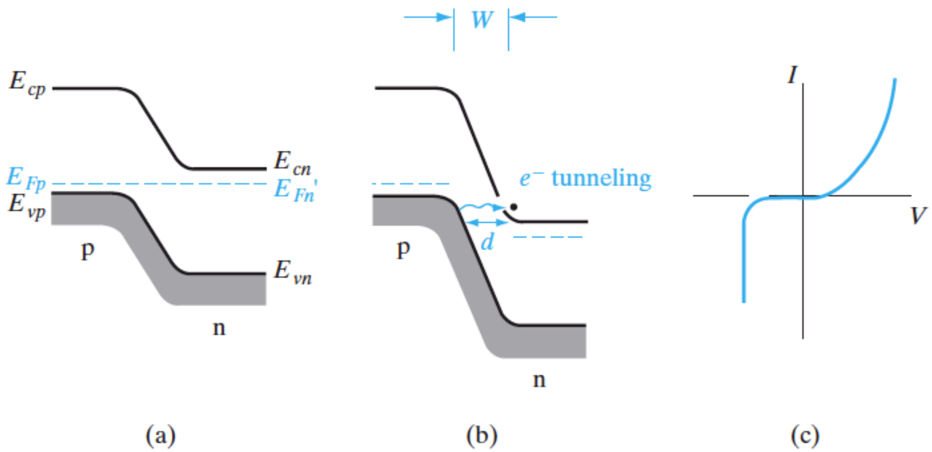
The F_n moves farther away from E_C (close to E_V) and F_p moves farther away from E_V, reflecting the fact that in reverse bias we have fewer carriers than in equilibrium, unlike the forward bias case where we have an excess of carriers.

In reverse bias, in the depletion region, we have:

$$pn = n_i^2 e^{(F_n - F_p)/kT} \approx 0$$

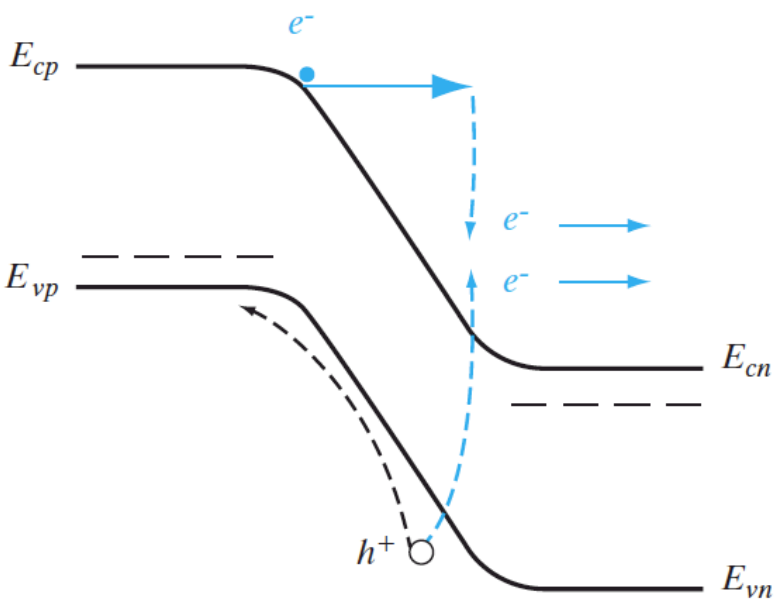
Reverse Bias Breakdown

Zener Breakdown:



The Zener effect: (a) heavily doped junction at equilibrium; (b) reverse bias with electron tunneling from p to n; (c) I–V characteristic.

Avalanche Breakdown:



Electron hole pair created by impact ionization. In the band diagram, a primary electron gains KE due to the EF of the depletion region and creates an EHP (secondary). The primary electron loses most of its KE in the process.

Capacitance of pn Junction

There are basically two types of capacitance associated with a junction: (1) the junction capacitance due to the dipole in the transition region and (2) the charge storage capacitance arising from the lagging behind of voltage as current changes, due to charge storage effects. Both of these capacitances are important, and they must be considered in designing p-n junction devices for use with time-varying signals. The junction capacitance (1) is dominant under reverse-bias conditions, and the charge storage capacitance (2) is dominant when the junction is forward biased.

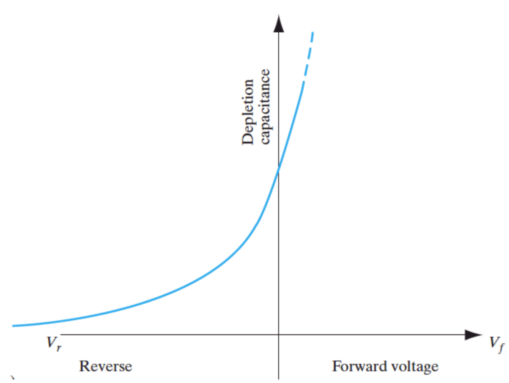
Junction Capacitance

$$W = \left[\frac{2\epsilon V_0}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2} \quad (equilibrium) \qquad W = \left[\frac{2\epsilon(V_0 - V)}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2} \quad (with\ bias)$$

$$C = \left|\frac{dQ}{dV}\right|$$

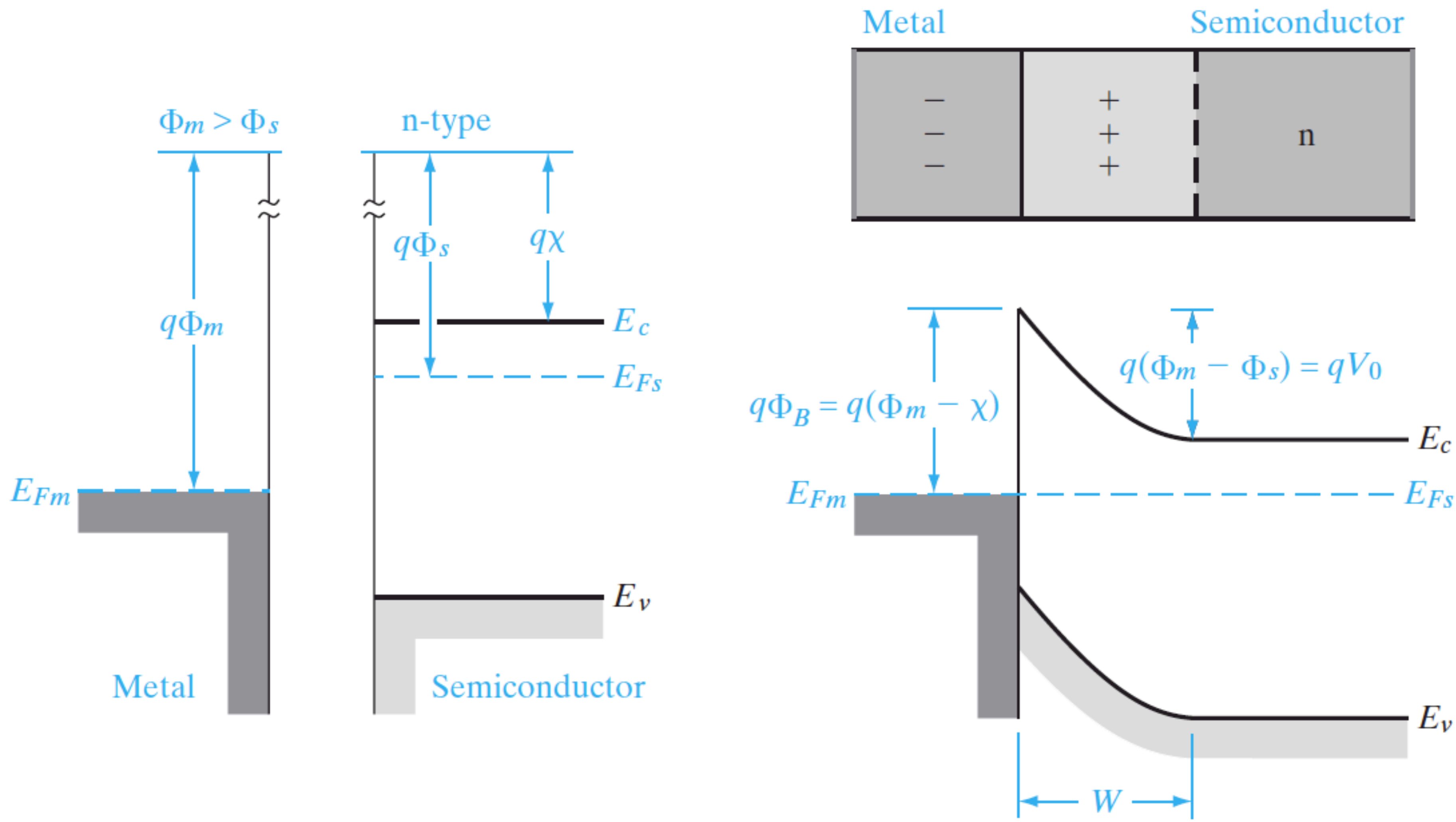
$$|Q| = qA\frac{N_d N_a}{N_d + N_a}W = A\left[2q\epsilon(V_0 - V)\frac{N_d N_a}{N_d + N_a}\right]^{1/2}$$

$$C_j = \left|\frac{dQ}{d(V_0 - V)}\right| = \frac{A}{2}\left[\frac{2q\epsilon}{(V_0 - V)}\frac{N_d N_a}{N_d + N_a}\right]^{1/2} \qquad C_j = \epsilon A\left[\frac{q}{2\epsilon(V_0 - V)}\frac{N_d N_a}{N_d + N_a}\right]^{1/2} = \frac{\epsilon A}{W}$$



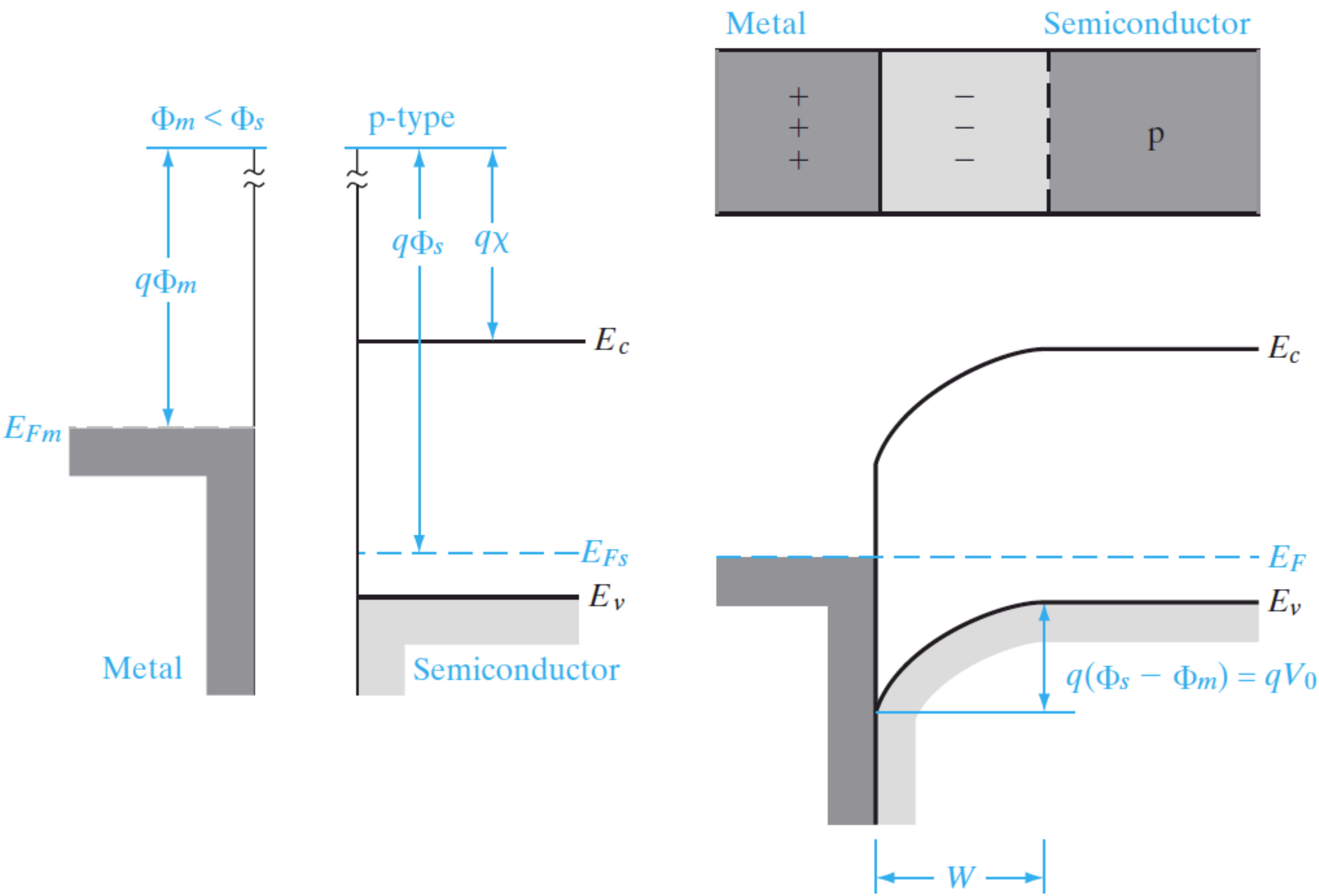
Metal Semiconductor Junctions

Ex1:



A Schottky barrier formed by contacting an n-type semiconductor with a metal having a larger work function: (a) band diagrams for the metal and the semiconductor before joining; (b) equilibrium band diagram for the junction.

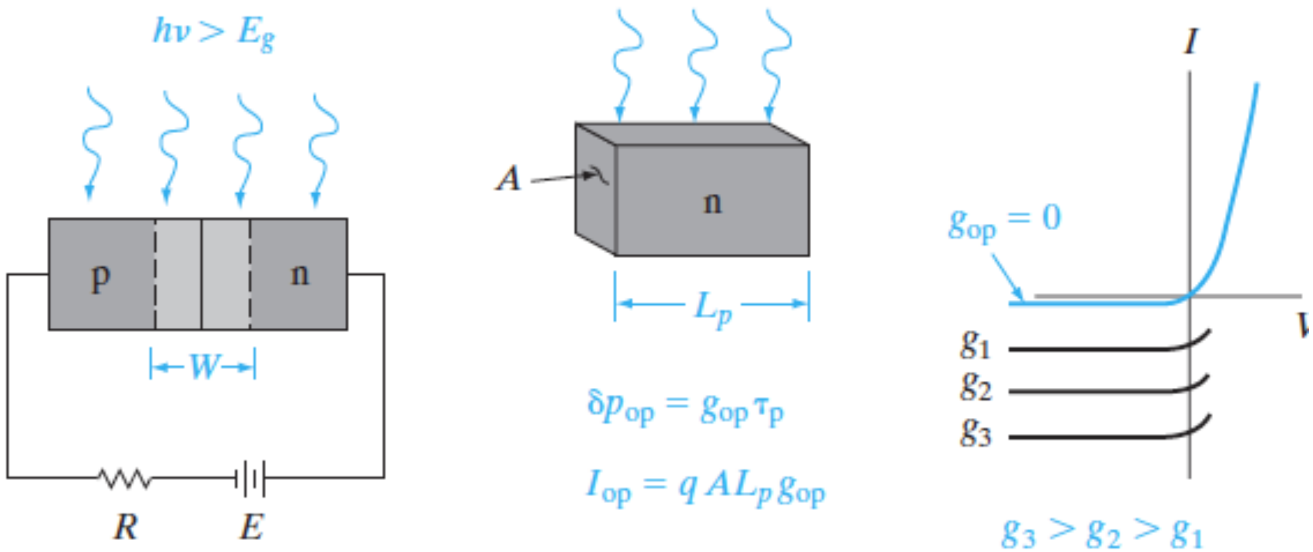
Ex2:



A Schottky barrier between a p-type semiconductor and a metal having a smaller work function: (a) band diagrams before joining; (b) band diagram for the junction at equilibrium.

Optoelectronic Devices

Current and Voltage in an illuminated junction



(a) (b) (c)

Optical generation of carriers in a p-n junction: (a) absorption of light by the device; (b) current I_{op} resulting from EHP generation within a diffusion length of the junction on the n side; (c) I–V characteristics an illuminated junction.

$$\boxed{I_{op} = qAg_{op}(L_p + L_n + W)}$$

LED: Light Emitting Diode

Forward biased direct bandgap, minority carrier injection for diffusion + radiative recombination at E_g.
SPONTANEOUS Emission: random phase and direction.

Use ideal diode equation to solve problems.

<u>LASER: Light Amplification by Stimulated Emission Radiation</u>

Direct bandgap. Acts like LED till threshold voltage is reached, after threshold LASER starts lasing. STIMULATED emission: Same phase and direction
<u>Carrier Inversion:</u> Need to have enough injected carriers. By pushing the quasi Fermi levels into the conduction and valence bands. This means that we do NOT have free states at the band edges which therefore BLOCKS absorption and promotes Emission. The energy given needs to be > E_g/q

Solar Cells

$$Fill\ Factor\ (FF) = \frac{V_{mp}I_{mp}}{V_{oc}I_{sc}}$$

$$Efficiency\ (\eta) = \frac{V_{oc}I_{sc}FF}{P_{in}}$$