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The pn Junction and Metal-Semiconductor Contact

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Historical Insight

1874 - it was observed that a rectifier could be fabricated by pressing a metal wire on the surface of a metal sulfide

1935 – selenium rectifiers and silicon point contact diodes are being used (however, these devices are unreliable)

1949 – W. Shockley published his paper describing the characteristics of the pn junction

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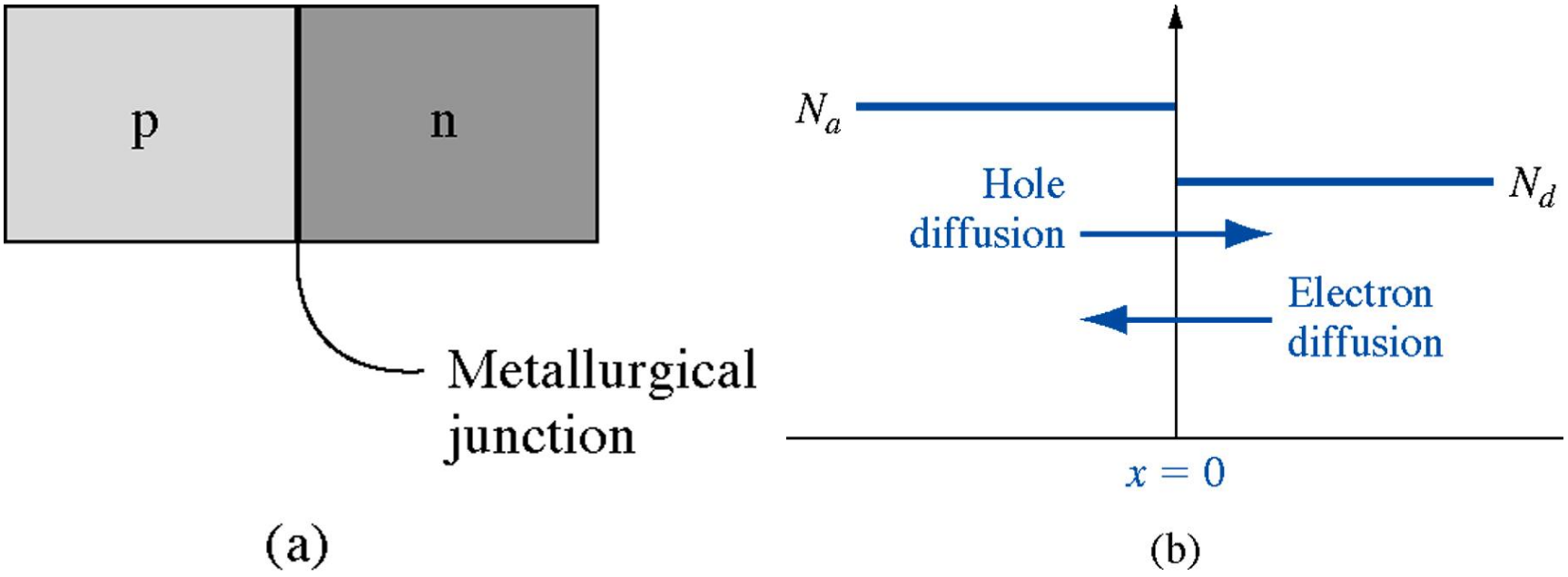
Basic Structure of the pn Junction



The interface separating the *n* and *p* regions is referred to as the *metallurgical junction* (a).

Figure (b) shows the impurity doping concentrations in the *p* and *n* regions. We will consider a *step junction* in which the doping concentrations are uniform in each region and there is an abrupt change in doping at the metallurgical junction.

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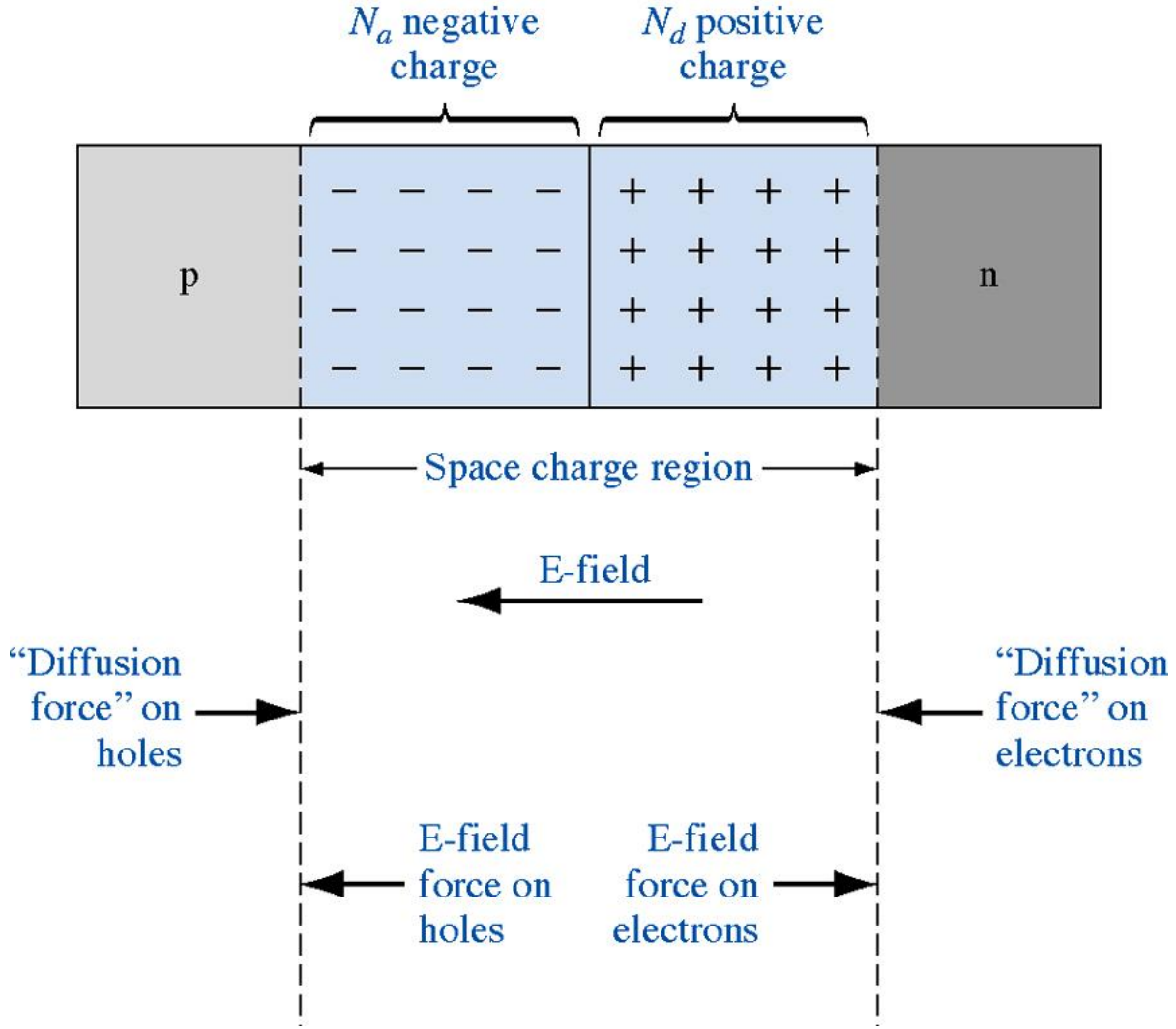
Basic Structure of the pn Junction



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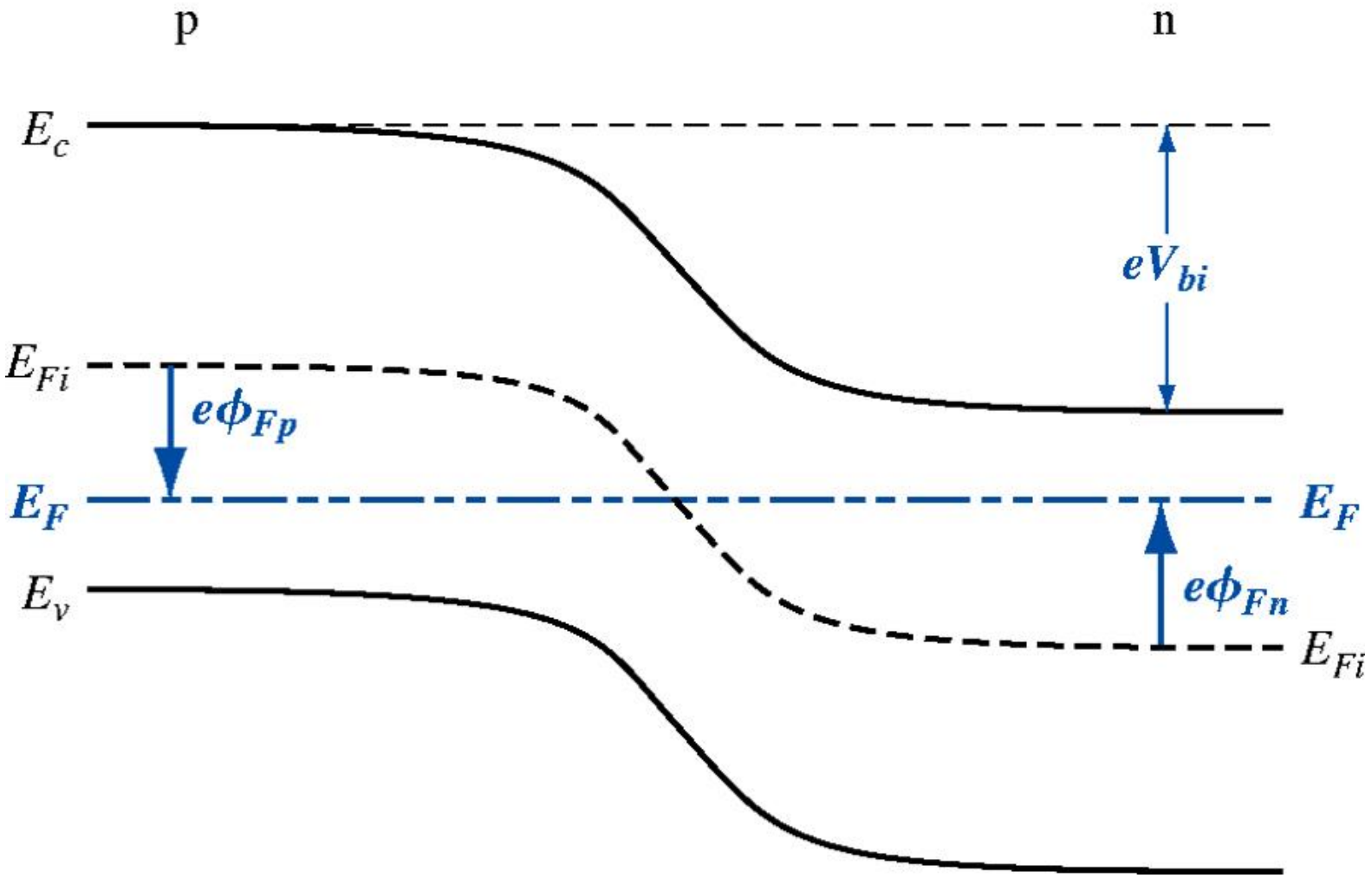
The pn Junction – Zero Applied Bias



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Built-In Potential Barrier

- With no voltage applied the *pn* junction is in thermal equilibrium;
- The Fermi energy level is constant throughout the entire system;
- The conduction and valence bands as well as the intrinsic Fermi energy must bend in the space charge region;
- Electrons in the conduction band of the *n* region see a potential barrier in trying to move into the conduction band of the *p* region – *built-in potential barrier* V_{bi};
- Holes in the valence band of the *p* region see a potential barrier in trying to move into the valence band of the *n* region;
- The potential V_{bi} maintains equilibrium, so no current is produced by this voltage;
- The intrinsic Fermi level is equidistant from the conduction band edge through the junction, thus the built-in potential barrier can be determined as the difference between the intrinsic Fermi levels in the *p* and *n* regions:

$$V_{bi} = \left|\phi_{Fn}\right| + \left|\phi_{Fp}\right| \qquad (1)$$

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Thermal Voltage

In the *n* region, the electron concentration in the conduction band is given by

$$n_0 = N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right] \qquad (2)$$

which also can be written in the form

$$n_0 = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right] \qquad (3)$$

where n_i and E_{Fi} are the intrinsic carrier concentration and the intrinsic Fermi energy. We can define the potential ϕ_{Fn} in the *n* region as

$$e\phi_{Fn} = E_F - E_{Fi} \qquad (4)$$

Equation (3) can then be written as

$$n_0 = n_i \exp\left[\frac{+(e\phi_{Fn})}{kT}\right] \qquad (5)$$

Taking the natural log of both sides of equation (5), setting $n_0 = N_d$, and solving for the potential, we obtain

$$\phi_{Fn} = \frac{+kT}{e} \ln\left(\frac{N_d}{n_i}\right) \qquad (6)$$

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Thermal Voltage (ctd)

Similarly, in the *p* region, the hole concentration is given by

$$p_0 = N_a = n_i \exp\left[\frac{E_{Fi} - E_F}{kT}\right] \tag{7}$$

where N_a is the acceptor concentration. We can define the potential ϕ_{Fp} in the *p* region as

$$e\phi_{Fp} = E_F - E_{Fi} \tag{8}$$

Combining equations (7) and (8), we find that

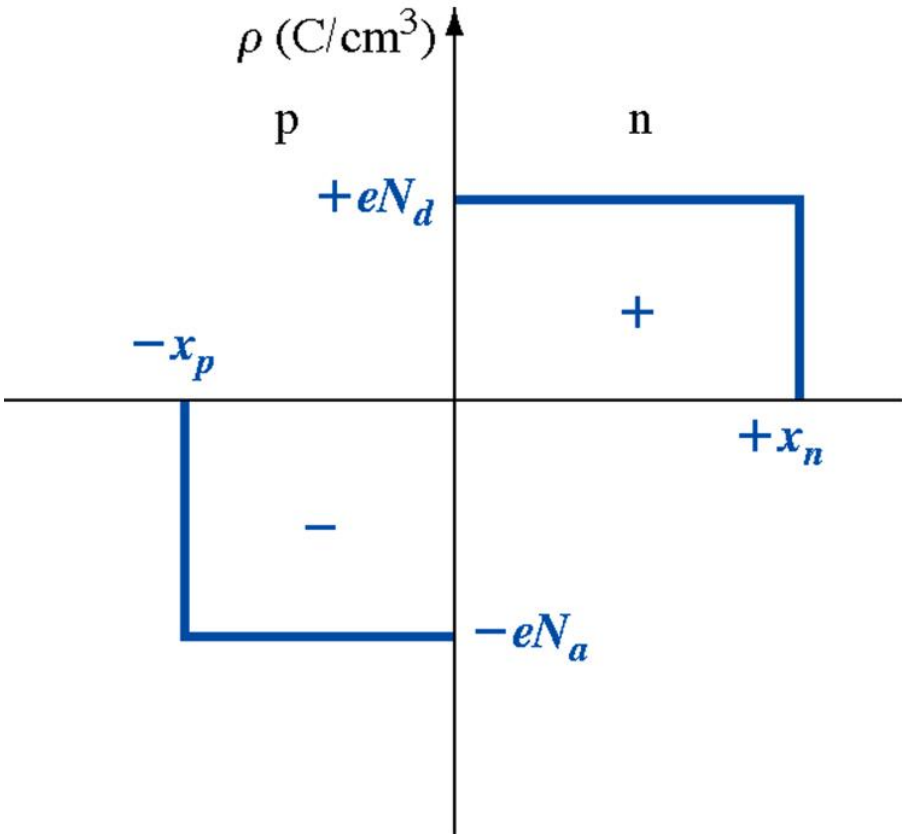
$$\phi_{Fp} = \frac{-kT}{e}\ln\left(\frac{N_a}{n_i}\right) \tag{9}$$

Finally, the built-in potential barrier for the step junction is found by substituting equations (6) and (9) into equation (1), which yields

$$V_{bi} = \frac{kT}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right) = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right) \tag{10}$$

where $V_t = kT/e$ is defined as the *thermal voltage*.

Electric Field



- Figure shows the volume charge density distribution in the *pn* junction assuming uniform doping and an abrupt junction approximation;
- We will assume that the space charge region abruptly ends in the *n* region at $x=+x_n$ and abruptly ends in the *p* region at $x=-x_p$
- The electric field is determined from Poisson's equation:

$$\frac{d^2\phi(x)}{dx^2} = \frac{-\rho(x)}{\varepsilon_s} = -\frac{dE(x)}{dx} \qquad (11)$$

where $\phi(x)$ is the electric potential, $E(x)$ is the electric field, $\rho(x)$ is the volume charge density, and ε_s is the permittivity of the semiconductor.

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Electric Field (p region)

The charge densities are

$$\rho(x) = -eN_a \qquad -x_p < x < 0$$
$$\rho(x) = eN_d \qquad 0 < x < x_n \qquad \text{(12a,b)}$$

The electric field in the *p* region is found by integrating equation (11). We have

$$E = \int \frac{\rho(x)}{\varepsilon_s} dx = -\int \frac{eN_a}{\varepsilon_s} dx = \frac{-eN_a}{\varepsilon_s} x + C_1 \qquad (13)$$

where C_1 is a constant of integration. The constant of integration is determined by setting $E=0$ at $x=-x_p$. The electric field in the *p* region is then given by

$$E = \frac{-eN_a}{\varepsilon_s}(x + x_p) \qquad -x_p \le x \le 0 \qquad (14)$$

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Electric Field (n region)

In the *n* region, the electric field is determined from

$$E = \int \frac{eN_d}{\varepsilon_s} dx = \frac{eN_d}{\varepsilon_s} x + C_2 \qquad (15)$$

where C_2 is again a constant of integration. The constant C_2 is determined by setting $E=0$ at $x=-x_n$. Then

$$E = \frac{-eN_d}{\varepsilon_s}(x_n - x) \qquad 0 \le x \le x_n \qquad (16)$$

The electric field is continuous at the metallurgical junction, or at $x=0$. Setting equations (14) and (16) equal to each other at $x=0$ gives

$$N_a x_p = N_d x_n \qquad (17)$$

Equation (17) states that the number of negative charges per unit area in the *p* region is equal to the number of positive charges per unit area in the *n* region.

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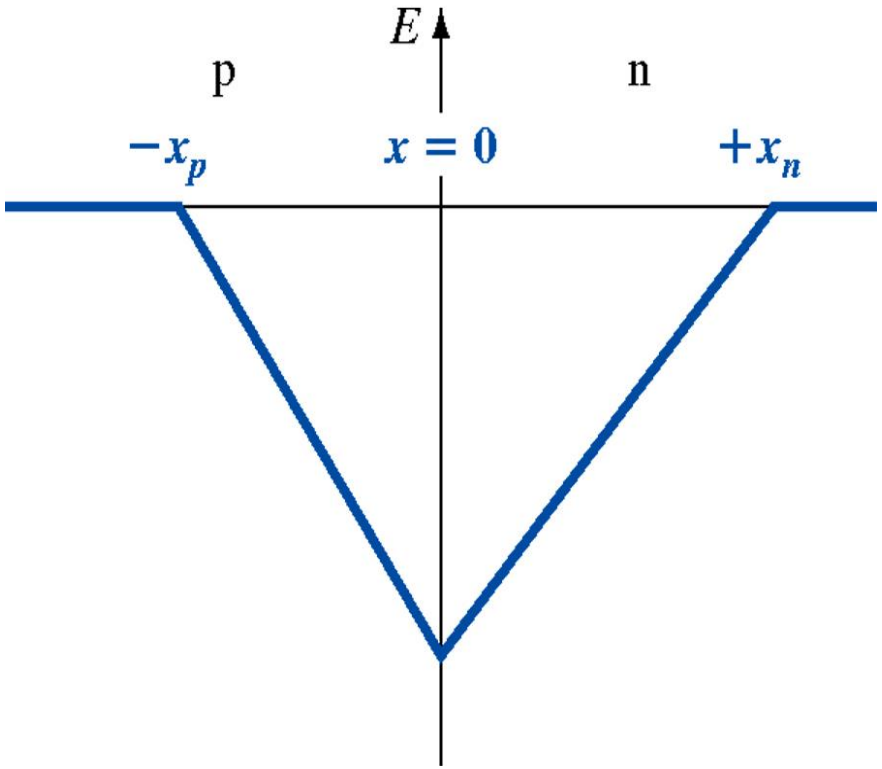
Electric Field Profile



- The electric field direction is from the *n* to the *p* region;
- For the uniformly doped *pn* junction, the *E* field is a linear function of distance through the junction, and the maximum occurs at the metallurgical junction
- An electric field exists in the depletion region even when no voltage is applied between *n* and *p* regions

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The Potential in the pn Junction

The potential in the *pn* junction is found by integrating the electric field. In the *p* region then we have

$$\phi(x) = -\int E(x)dx = \int \frac{eN_a}{\varepsilon_s}(x + x_p)dx \qquad (18)$$

$$\phi(x) = \frac{eN_a}{\varepsilon_s}\left(\frac{x^2}{2} + x_p x\right) + C_1' \qquad (19)$$

where C_1' is again a constant of integration. Lets set the potential equal to zero at $x=-x_p$. The constant of integration is then found as

$$C_1' = \frac{eN_a}{2\varepsilon_s}x_p^2 \qquad (20)$$

So the potential in the *p* region can now be written as

$$\phi(x) = \frac{eN_a}{2\varepsilon_s}(x + x_p)^2 \qquad -x_p \le x \le 0 \qquad (21)$$

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The Potential in the pn Junction

The potential in the *n* region is determined by integrating the electric field in the *n* region

$$\phi(x) = \int \frac{eN_d}{\varepsilon_s}(x_n - x)dx \tag{22}$$

$$\phi(x) = \frac{eN_d}{\varepsilon_s}\left(x_n x - \frac{x^2}{2}\right) + C_2' \tag{23}$$

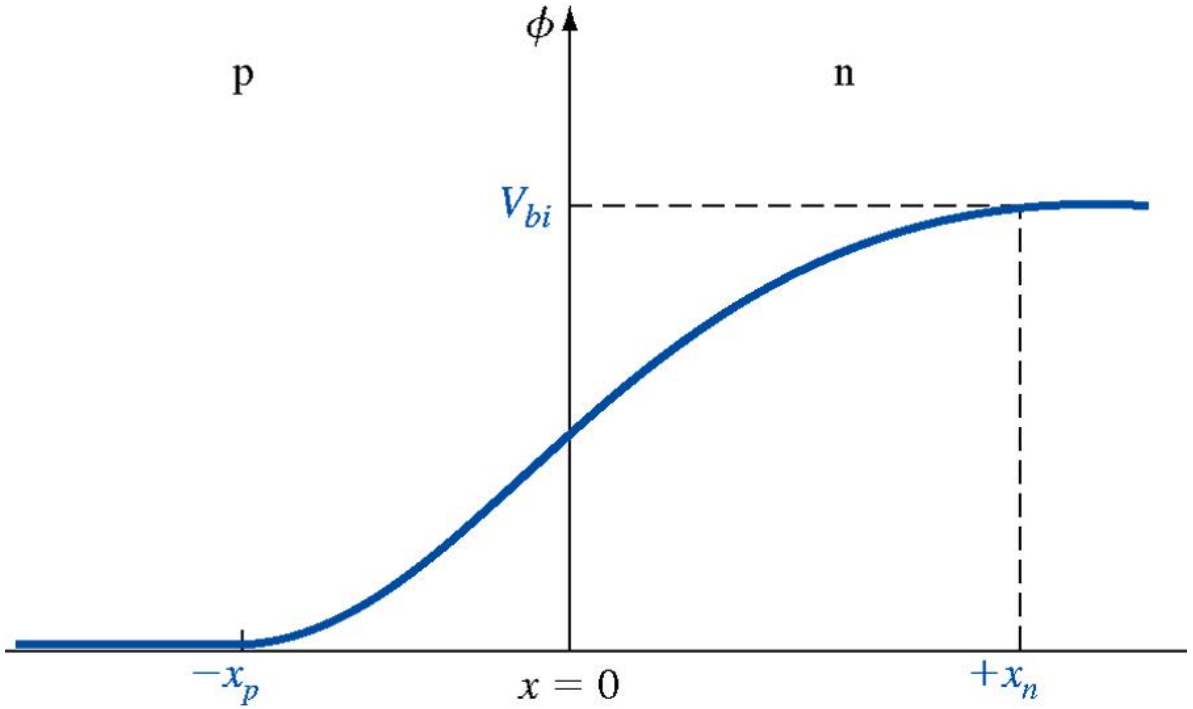
where C_2' is another constant of integration. The potential is a continuous function, so setting equation (21) equal to equation (23) at the metallurgical junction, or $x=0$, gives

$$C_2' = \frac{eN_a}{2\varepsilon_s}x_p^2 \tag{24}$$

The potential in the *n* region can thus be written as

$$\phi(x) = \frac{eN_d}{\varepsilon_s}\left(x_n x - \frac{x^2}{2}\right) + \frac{eN_a}{2\varepsilon_s}x_p^2 \qquad 0 \le x \le x_n \tag{25}$$

The Potential in the pn Junction



The magnitude of the potential at $x=x_n$ is equal to the built-in potential barrier. Then from the equation (25) we have

$$V_{bi} = \left|\phi\left(x = x_n\right)\right| = \frac{e}{2\varepsilon_s}\left(N_d x_n^2 + N_a x_p^2\right) \qquad (26)$$

Space Charge Width

The distance that the space charge region extends into the *p* and *n* regions from the metallurgical junction is known as the space charge width. From equation (17) we can write

$$x_p = \frac{N_d x_n}{N_a} \tag{27}$$

Then, substituting (27) into (26) and solving for x_n, we obtain

$$x_n = \left[\frac{2\varepsilon_s V_{bi}}{e} \left(\frac{N_a}{N_d} \right) \left(\frac{1}{N_a + N_d} \right) \right]^{1/2} \tag{28}$$

Similarly, if we solve for x_p from equation (17) and substitute into equation (26):

$$x_p = \left[\frac{2\varepsilon_s V_{bi}}{e} \left(\frac{N_d}{N_a} \right) \left(\frac{1}{N_a + N_d} \right) \right]^{1/2} \tag{29}$$

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Total Space Charge Width

The total depletion or space charge width W is the sum of the two components

$$W = x_n + x_p \tag{30}$$

Using equations (28) and (29), we obtain

$$W = \left[\frac{2\varepsilon_s V_{bi}}{e} \left(\frac{N_a + N_d}{N_a N_d} \right) \right]^{1/2} \tag{31}$$

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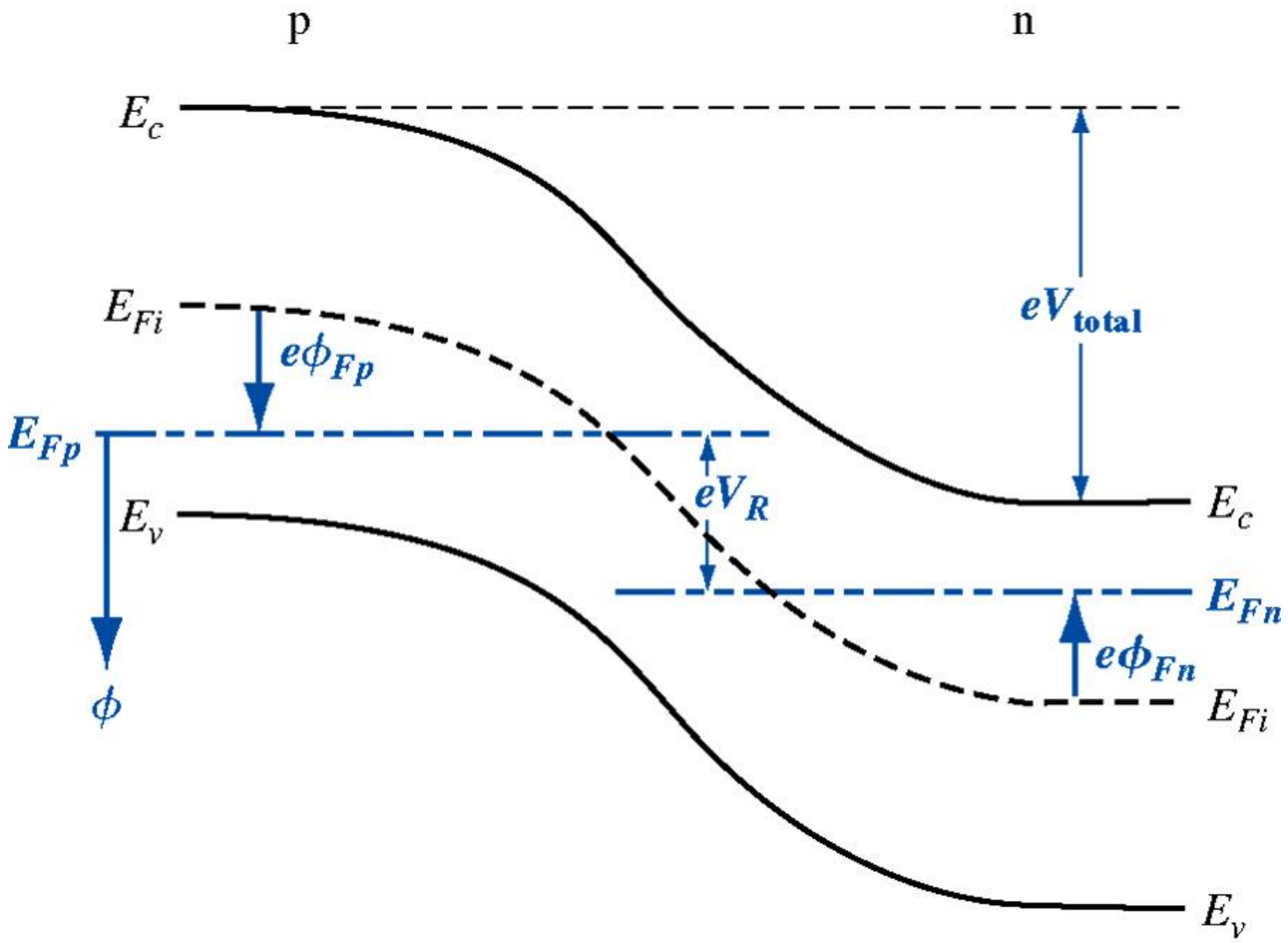
The pn Junction – Reverse Bias



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Reverse-Bias Voltage

- As the positive potential is downward, the Fermi level on the *n* side is now below the Fermi level on the *p* side;
- The difference between the two is equal to the applied voltage in units of energy;
- The total potential barrier, indicated by V_{total}, has increased. The total potential barrier

$$V_{total} = |\phi_{Fn}| + |\phi_{Fp}| + V_R \qquad (1)$$

where V_R is the magnitude of the applied reverse-bias voltage. Equation (1) can be rewritten as

$$V_{total} = V_{bi} + V_R \qquad (2)$$

where V_{bi} is the same built-in potential we had defined in thermal equilibrium.

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Space Charge Width and Electric Field

In all of the previous equations, the built-in potential barrier can be replaced by the total potential barrier. The total space charge width can be written as

$$W = \left[\frac{2\varepsilon_s (V_{bi} + V_R)}{e} \left(\frac{N_a + N_d}{N_a N_d} \right) \right]^{1/2} \qquad (3)$$

Showing that the total space charge width increases as we apply a reverse-bias voltage. For the space charge widths in the *p* and *n* regions we can find

$$x_p = \left[\frac{2\varepsilon_s (V_{bi} + V_R)}{e} \left(\frac{N_d}{N_a} \right) \left(\frac{1}{N_a + N_d} \right) \right]^{1/2} \qquad (4)$$

$$x_n = \left[\frac{2\varepsilon_s (V_{bi} + V_R)}{e} \left(\frac{N_a}{N_d} \right) \left(\frac{1}{N_a + N_d} \right) \right]^{1/2} \qquad (5)$$

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Peak Electric Field

Since x_n and x_p increase with reverse-bias voltage, the magnitude of the electric field also increases;

The maximum electric field still occurs at the metallurgical junction:

$$E_{\max} = \frac{-eN_d x_n}{\varepsilon_s} = \frac{-eN_a x_p}{\varepsilon_s} \qquad (6)$$

If we use either (4) or (5), then

$$E_{\max} = -\left[\frac{2e(V_{bi} + V_R)}{\varepsilon_s}\left(\frac{N_a N_d}{N_a + N_d}\right)\right]^{1/2} \qquad (7)$$

or

$$E_{\max} = \frac{-2(V_{bi} + V_R)}{W} \qquad (8)$$

where W is the total space charge width.

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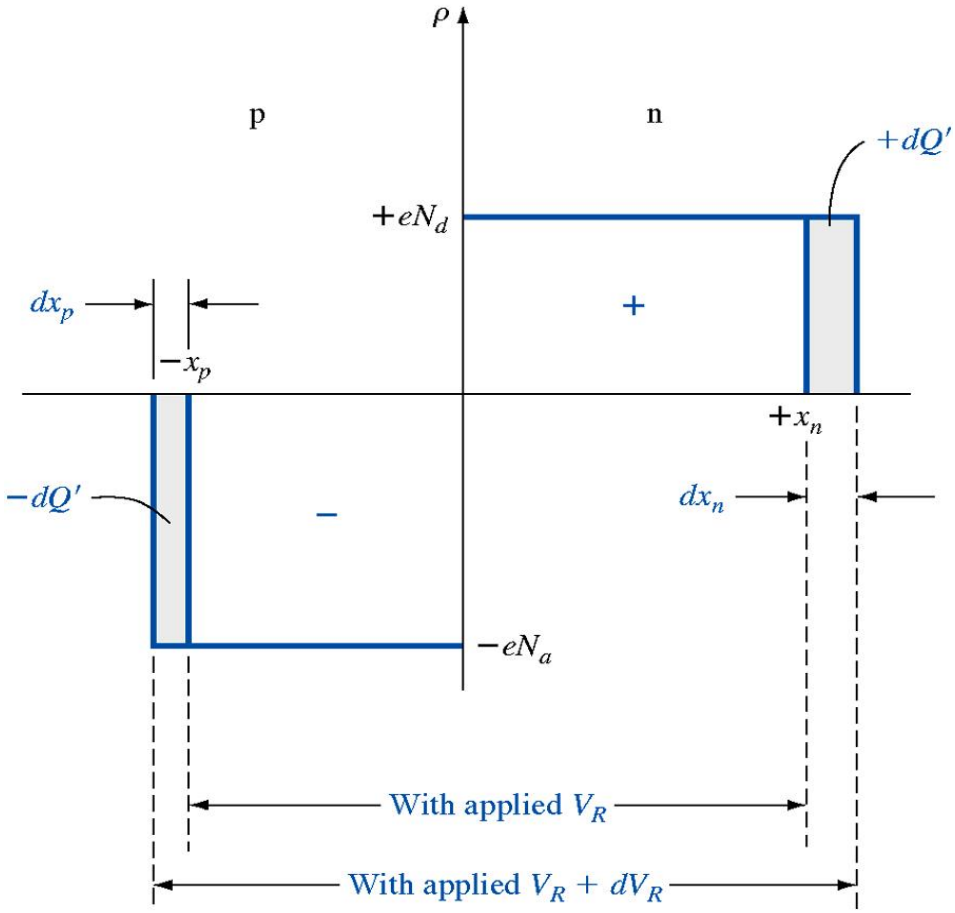
Junction Capacitance

Since we have a separation of positive and negative charges in the depletion region, a capacitance is associated with the *pn* junction



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Junction Capacitance (ctd)

The junction capacitance is defined as

$$C' = \frac{dQ'}{dV_R} \tag{9}$$

where

$$dQ' = eN_d dx_n = eN_a dx_p \tag{10}$$

so that

$$C' = \left[\frac{e\varepsilon_s N_a N_d}{2(V_{bi} + V_R)(N_a + N_d)} \right]^{1/2} \tag{11}$$

Exactly the same capacitance expression is obtained by considering the space charge region extending into the *p* region x_p. The junction capacitance is also referred to as the *depletion layer capacitance.*

If we compare the equation for the total depletion width *W* with the equation for the junction capacitance, we obtain

$$C' = \frac{\varepsilon_s}{W} \tag{12}$$

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One-Sided Junctions

Consider a special *pn* junction called the one-sided junction. If, for example, $N_a >> N_d$, this junction is referred to as p^+n junction. The total space charge width reduces to

$$W \approx \left[\frac{2\varepsilon_s (V_{bi} + V_R)}{eN_d}\right]^{1/2} \tag{13}$$

Considering the expressions for x_n and x_p, we have for p^+n junction

$$x_p << x_n \tag{14}$$

and

$$W \approx x_n \tag{15}$$

Almost the entire space charge layer extends into the low-doped region of the junction. The junction capacitance reduces to

$$C' \approx \left[\frac{e\varepsilon_s N_d}{2(V_{bi} + V_R)}\right]^{1/2} \tag{16}$$

or

$$\left(\frac{1}{C'}\right)^2 \approx \frac{2(V_{bi} + V_R)}{e\varepsilon_s N_d} \tag{17}$$

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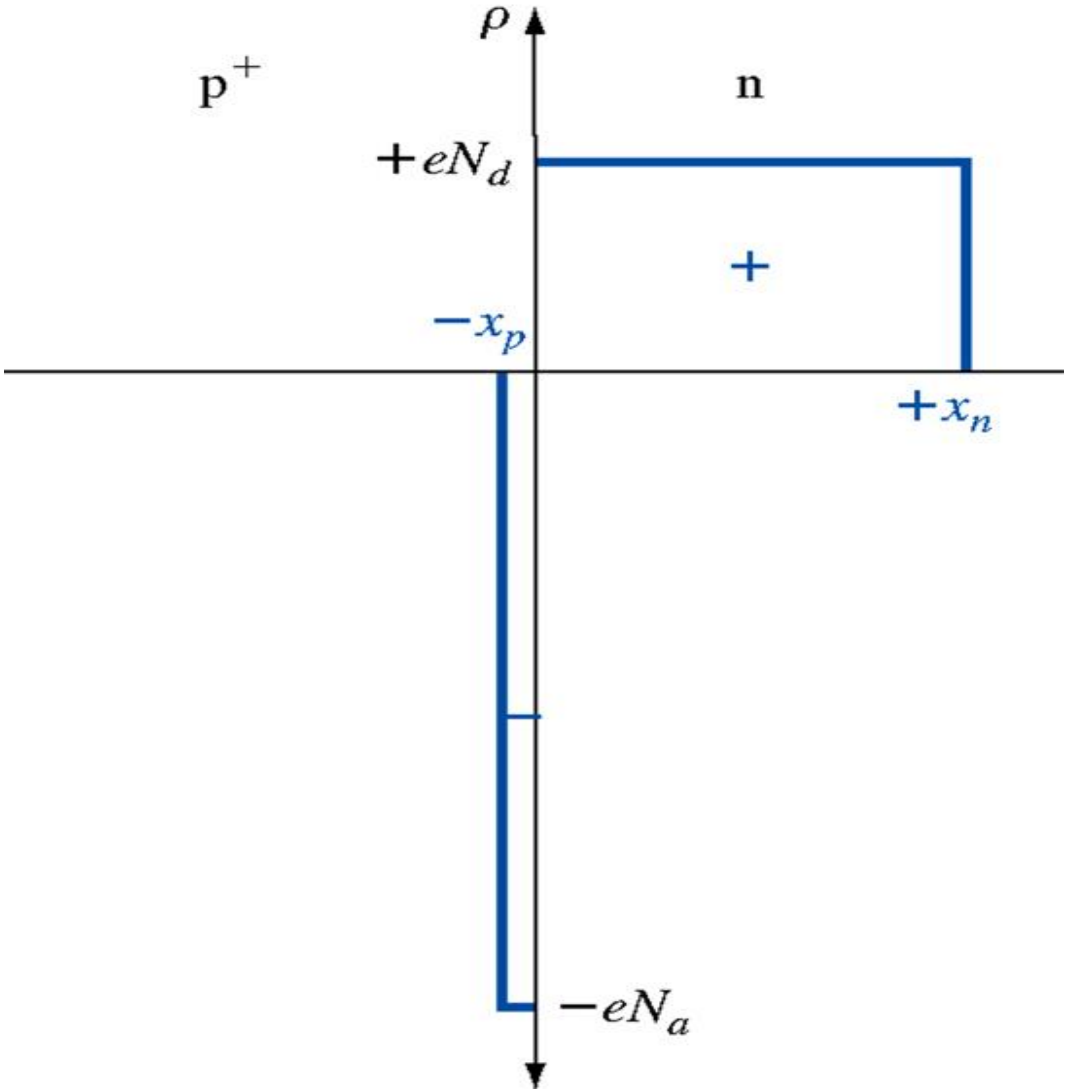
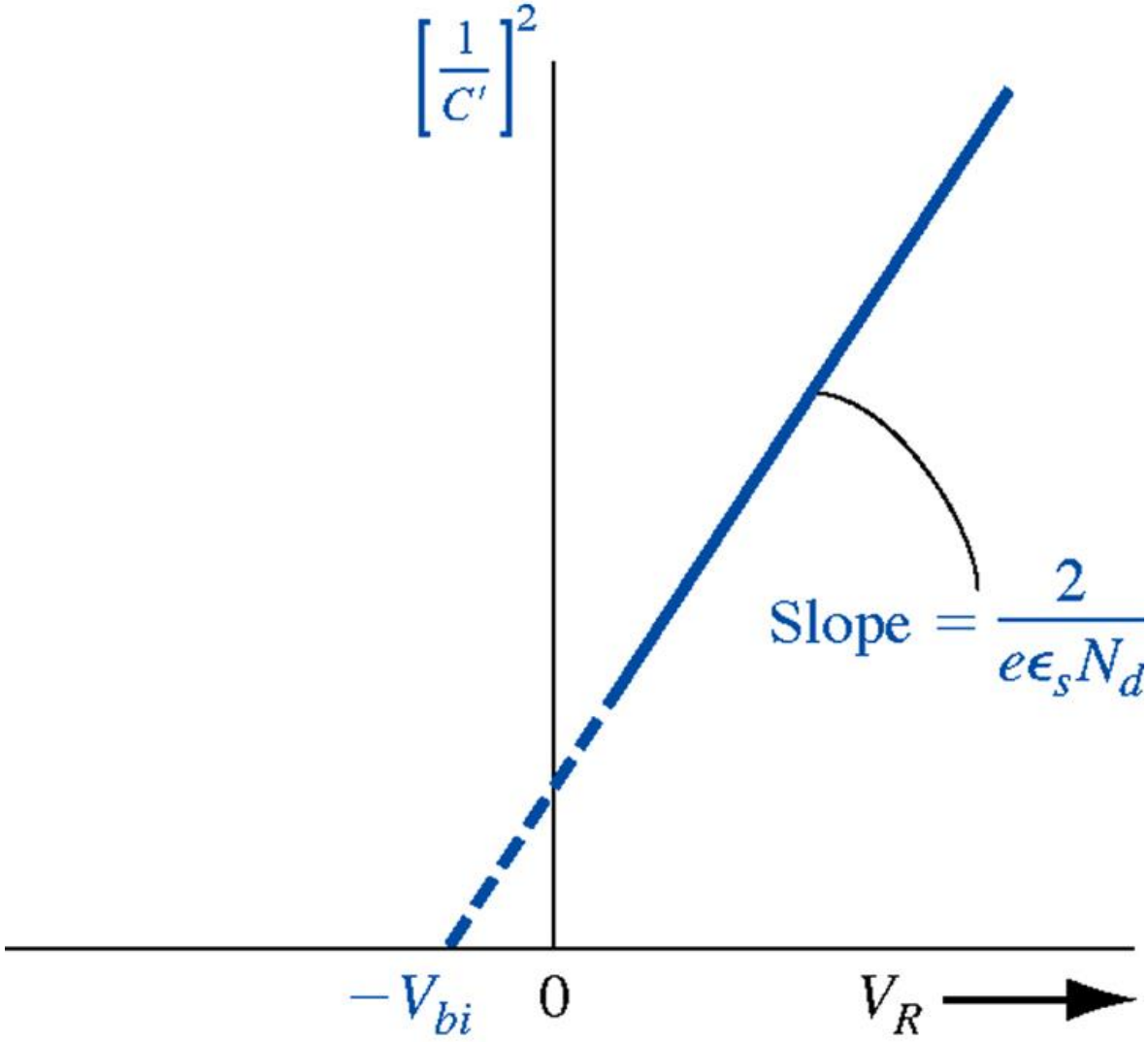
Space Charge Density of a One-Sided Junction



$1/C'^2$ Versus V_R



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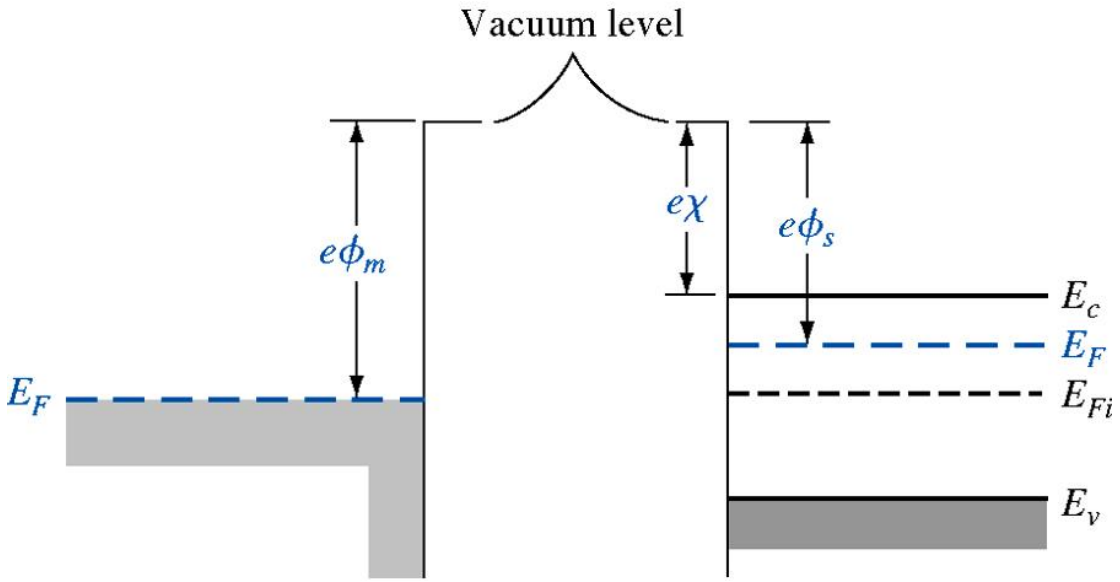
Metal-Semiconductor Contact (Schottky Barrier)

Figure below shows the ideal energy-band diagram for a particular metal and *n*-type semiconductor before making contact.



$\phi_m > \phi_s$

The parameter ϕ_m is the metal work function (measured in volts), ϕ_s is the semiconductor work function, and χ is known as the *electron affinity*.

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Work Function, Electron Affinity for Some Materials

Element	Work Function, ϕ_m
Ag, silver	4.26
Al, aluminium	4.28
Au, gold	5.1
Cr, chromium	4.5
Mo, molybdenum	4.6
Ni, nickel	5.15
Pd, palladium	5.12
Pt, platinum	5.65
Ti, titanium	4.33
W, tungsten	4.55

Element	Electron Affinity, χ
Ge, germanium	4.13
Si, silicon	4.01
GaAs, gallium arsenide	4.07
AlAs, aluminium arsenide	3.5

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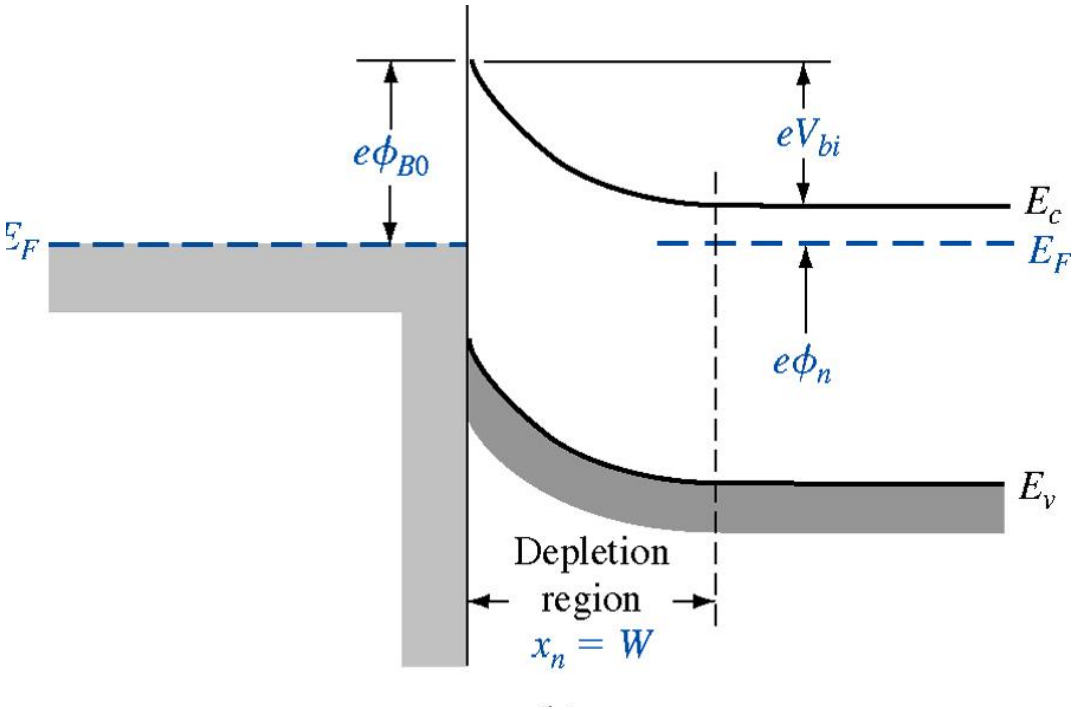
Ideal Energy-Band Diagram



Electrons from semiconductor flow into the lower energy states in the metal;

Positively charged donors remain in the semiconductor, creating a space charge region;

The parameter ϕ_{B0} is the ideal barrier height of the semiconductor contact, the potential barrier seen by electrons in the metal trying to move into the semiconductor

Schottky Barrier Height

This barrier is known as the *Schottky barrier* and is given, ideally, by

$$\phi_{B0} = \left(\phi_m - \chi\right) \tag{18}$$

On the semiconductor side, V_{bi} is the built-in potential barrier, the barrier seen by electrons in the conduction band trying to move into the metal:

$$V_{bi} = \phi_{B0} - \phi_n \tag{19}$$

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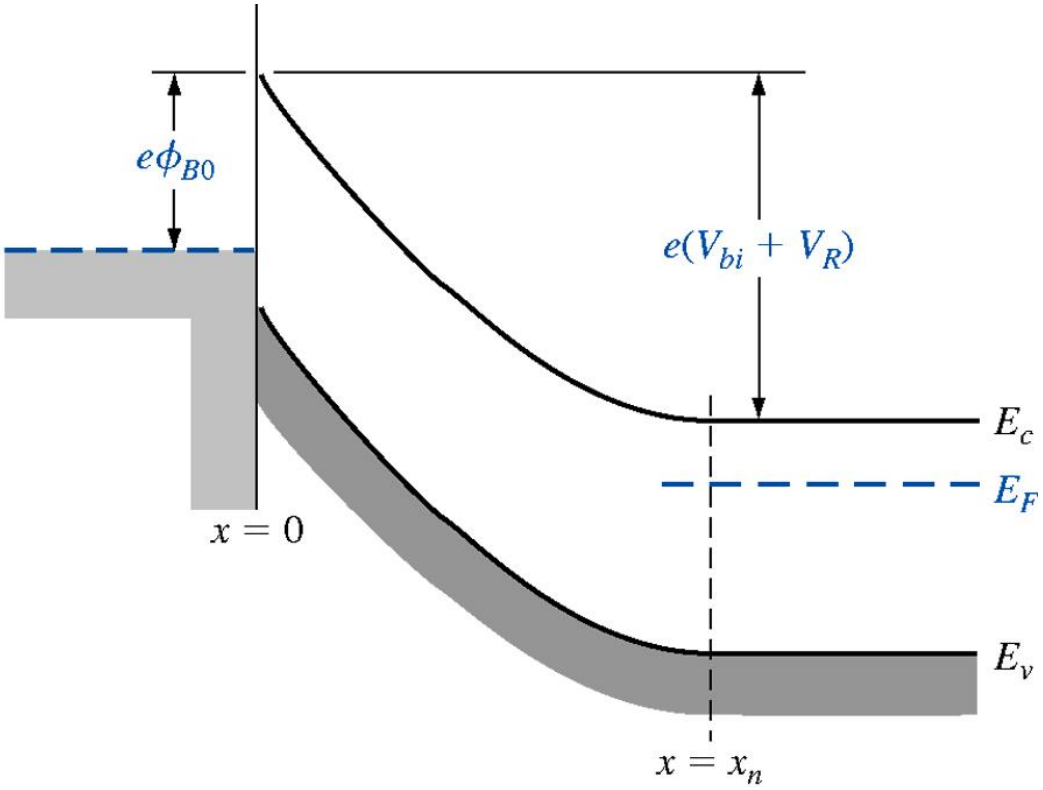
The Schottky Junction – Reverse Bias

If we apply a positive voltage to the semiconductor with respect to the metal, the barrier height increases:



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The Schottky Junction – Reverse Bias

If we apply Poisson's equation to this reverse-biased Schottky junction, we find the depletion width to be

$$x_n = \left[\frac{2\varepsilon_s (V_{bi} + V_R)}{eN_d} \right]^{1/2} \qquad (20)$$

The reverse-biased Schottky junction also has a capacitance given by

$$C' = \left[\frac{e\varepsilon_s N_d}{2(V_{bi} + V_R)} \right]^{1/2} \qquad (21)$$

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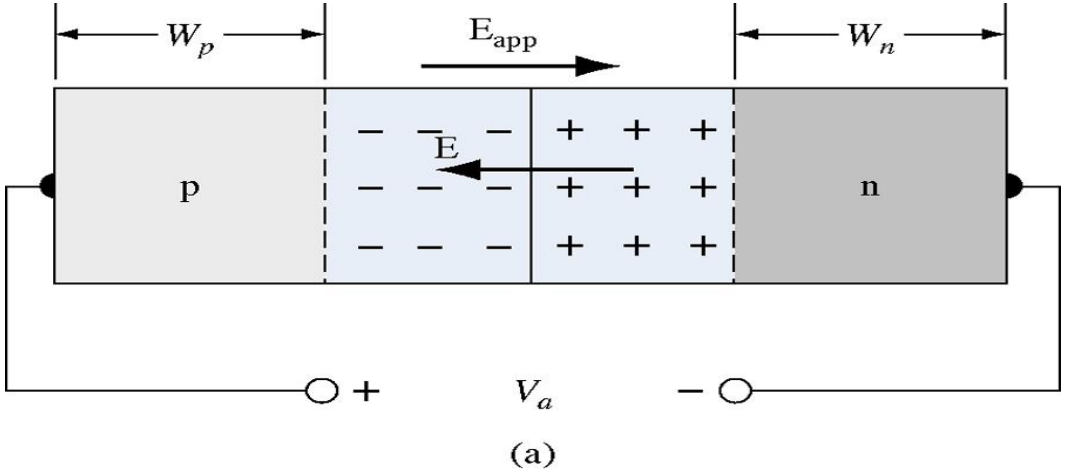
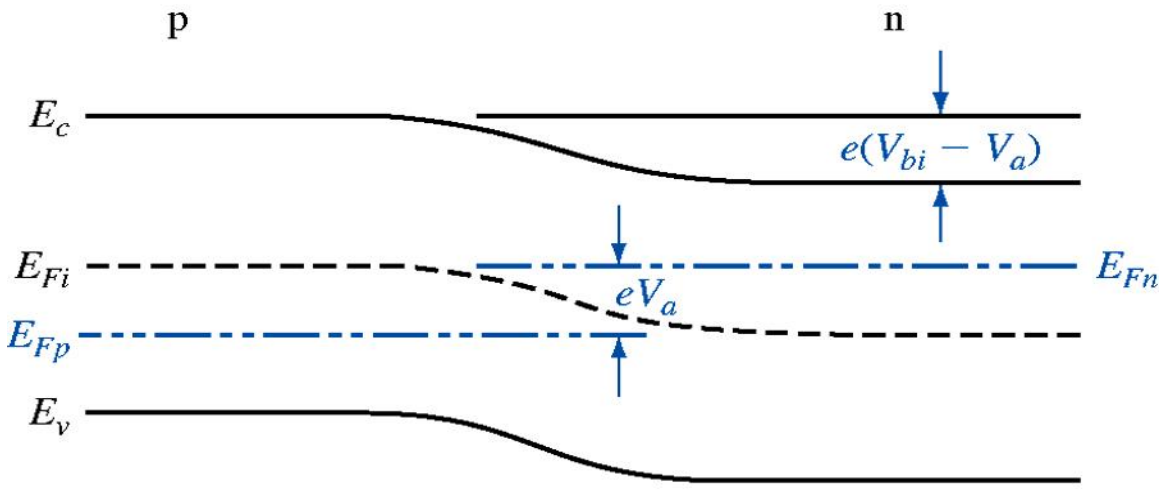
The pn Junction – Forward Bias



(a)



(b)

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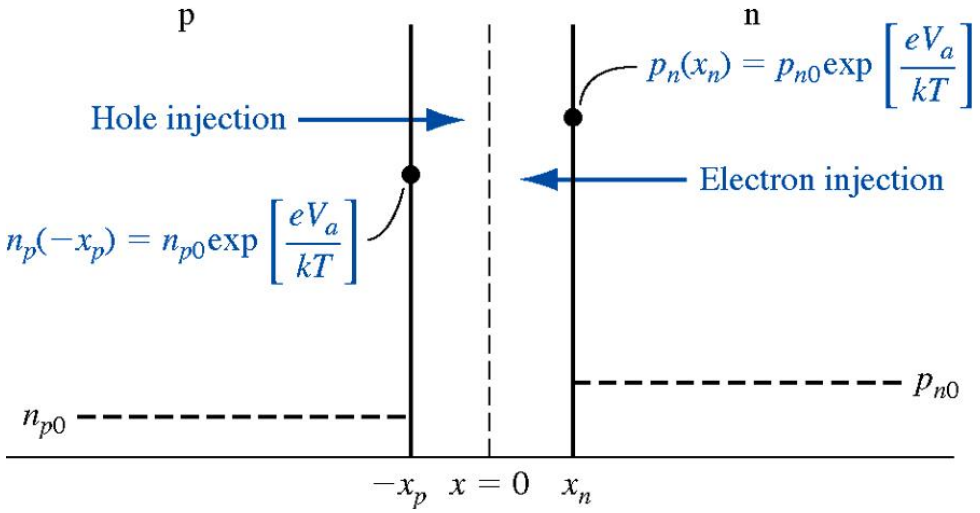
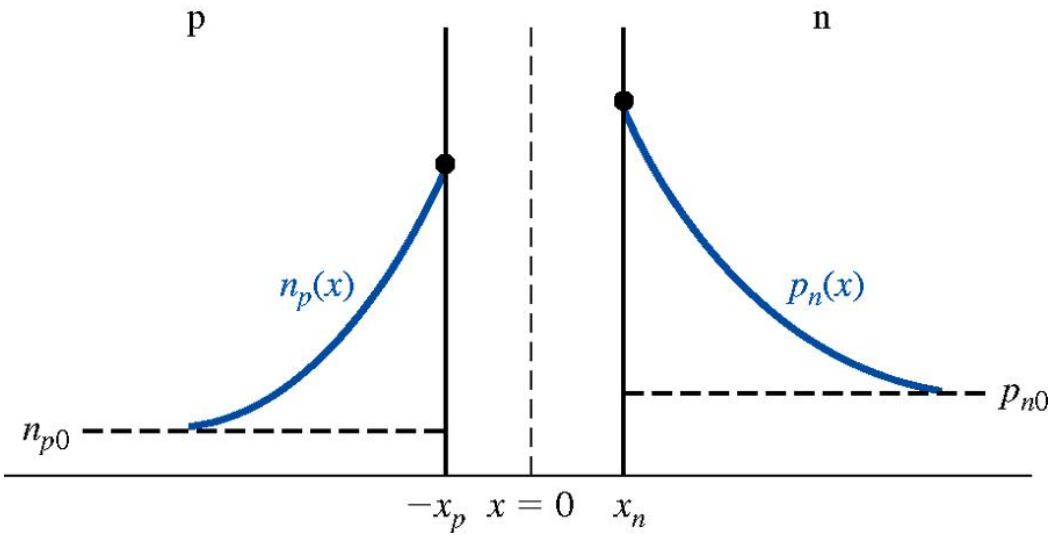
Minority Carriers Concentrations





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Ideal Diode Equation

There are gradients in the minority carrier concentrations so that diffusion currents are induced in the *pn* junction. An analysis of the diffusion currents produces the relationship:

$$I_D = I_S\left[\exp\left(\frac{V_a}{V_t}\right)-1\right] \qquad (1)$$

where I_S is called the reverse saturation current and is a function of the doping concentrations, diffusion coefficients, and the cross-sectional area of the *pn* junction, V_t is the thermal voltage (kT/e), and V_a is the applied to the *pn* junction voltage. Typical values of the reverse-saturation current for silicon *pn* junctions are in the range $10^{-14}<I_S<10^{-12}$ A.

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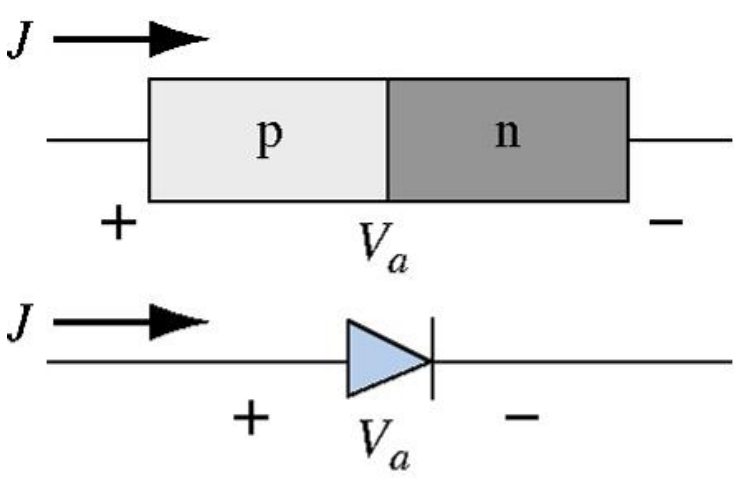
Plot of Ideal I-V Characteristics



$$V_a > 0.1V$$

$$I_D \approx I_S \exp\left(\frac{V_a}{V_t}\right)$$

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The Schottky Barrier Junction

The basic process in the rectifying contact with an *n*-type semiconductor is by transport of electrons over the potential barrier, which can be described by the thermionic emission theory.

The net current density in the metal-semiconductor junction can be written as

$$J = J_{s\to m} - J_{m\to s} \tag{2}$$

which is defined to be positive in the direction from the metal to the semiconductor. In the ideal case:

$$J = \left[A^* T^2 \exp\left(\frac{-e\phi_{BO}}{kT} \right) \right] \left[\exp\left(\frac{eV_a}{kT} \right) - 1 \right] \tag{3}$$

where

$$A^* \equiv \frac{4\pi e m_n^* k^2}{h^3} \tag{4}$$

The parameter A^* is called the effective Richardson constant for thermionic emission. Equation (3) can be written as

$$J = J_{sT} \left[\exp\left(\frac{eV_a}{kT} \right) - 1 \right] \tag{5}$$

where J_{sT} is the reverse-saturation current density.

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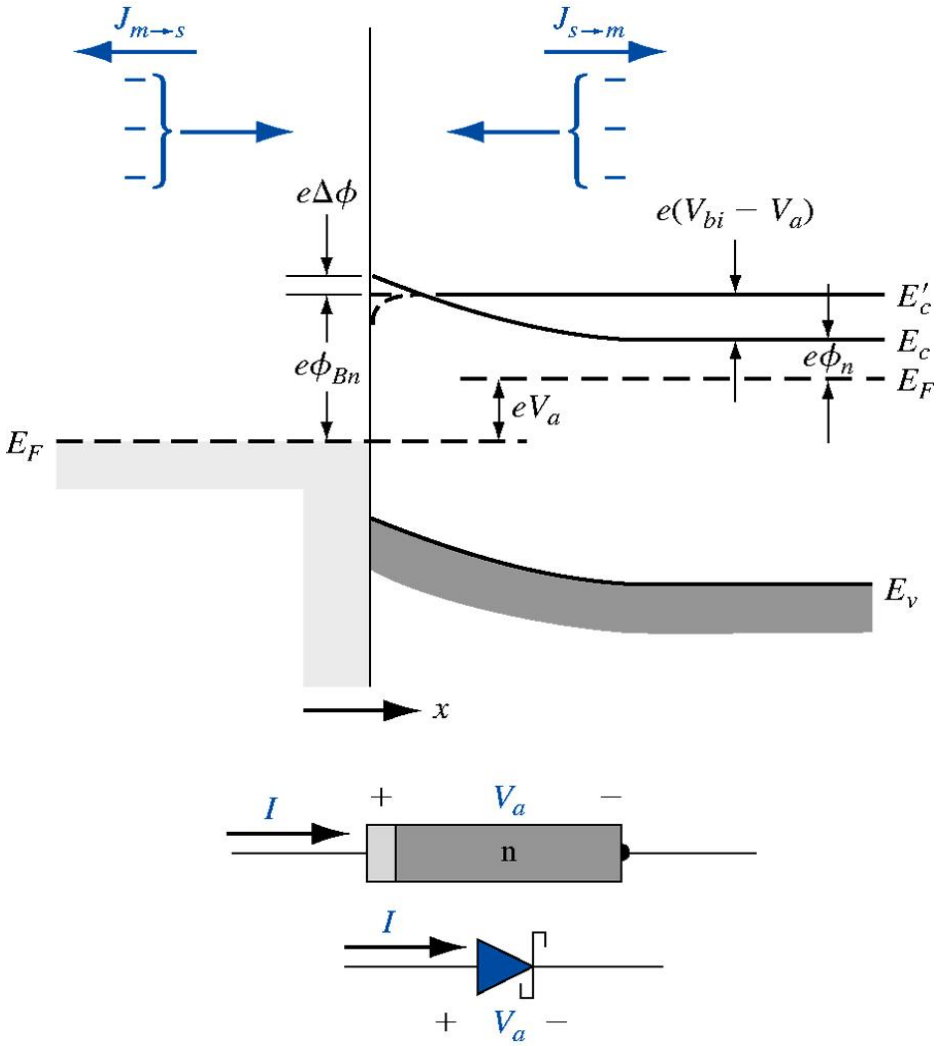
Energy-Band Diagram of a Forward-Biased Schottky Diode



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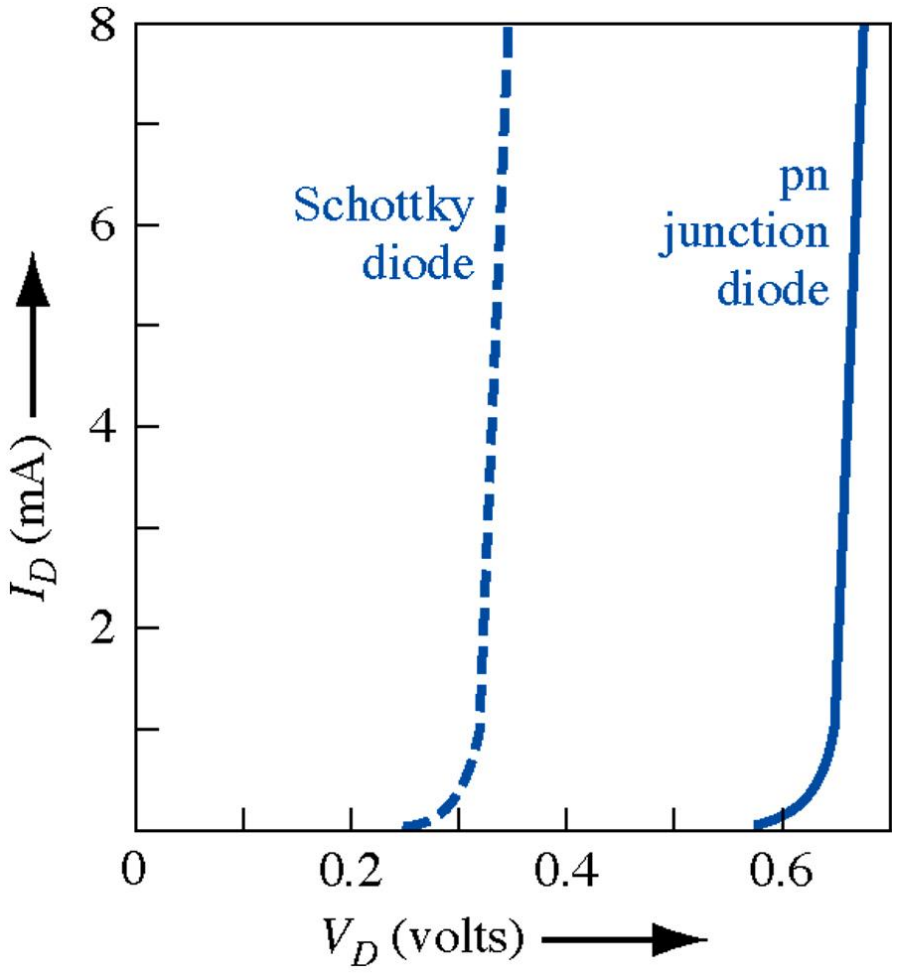
Schottky Diode and pn Junction Diode



There are two important differences:

1. Differences in the magnitudes of the reverse-saturation current densities
2. Difference in the switching characteristics