# ELECTRONIC MATERIALS AND DEVICES

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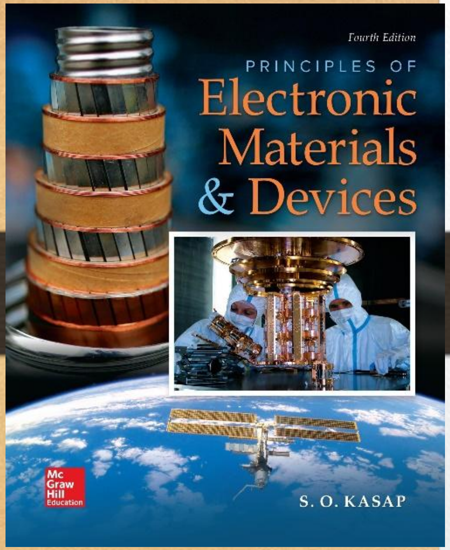
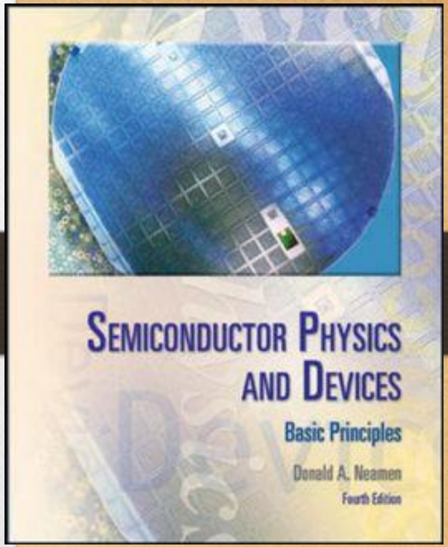



Dr. M. Saranya Nair
School of Electronics Engineering
VIT-Chennai Campus
E-mail : saranyanair.m@vit.ac.in

# MODULE 4



# ELECTRONIC MATERIALS AND DEVICES

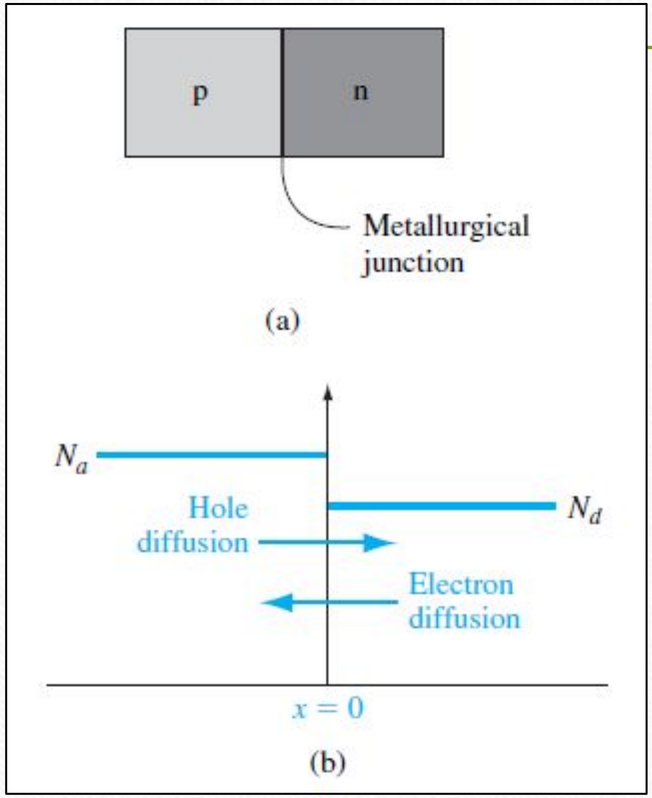
## MODULE 4

# Junction diodes

# PN JUNCTION

- **Upto this point, we have been considering the properties of the semiconductor material.**
- **We calculated electron and hole concentrations in thermal equilibrium and determined the position of the Fermi level.**
- **We then considered the non-equilibrium condition in which excess electrons and holes are present in the semiconductor.**
- **We now wish to consider the situation in which a p-type and an n-type semiconductor are brought into contact with one another to form a pn junction.**
- Most semiconductor devices contain at least one junction between p-type and n-type semiconductor regions.
- Semiconductor device characteristics and operation are intimately connected to these pn junctions

# BASIC STRUCTURE OF THE pn JUNCTION

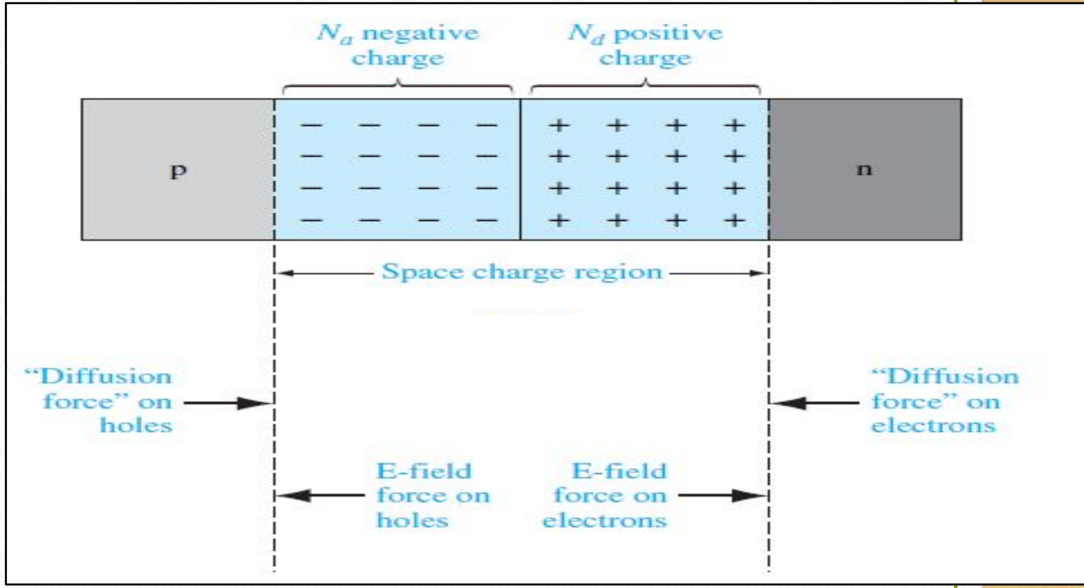



- The entire semiconductor is a single-crystal material in which one region is doped with acceptor impurity atoms to form the p region and the adjacent region is doped with donor atoms to form the n region. The interface separating the n and p regions is referred to as the *metallurgical junction.*

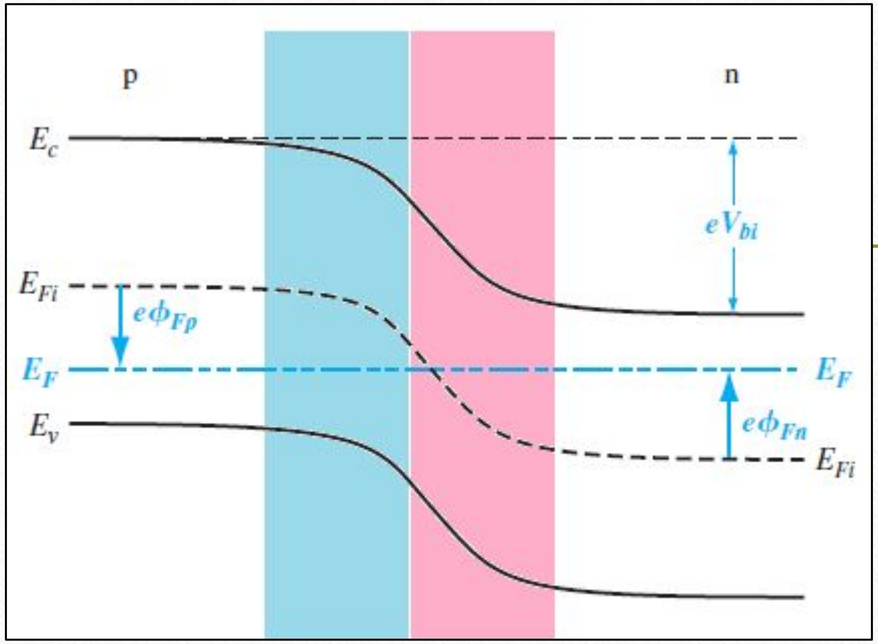
- *A step junction is considered* which indicates the doping concentration is uniform in each region and there is an abrupt change in doping at the junction.
- Initially, at the metallurgical junction, there is a very large density gradient in both electron and hole concentrations.

- Majority carrier electrons in the n region will begin diffusing into the p region, and majority carrier holes in the p region will begin diffusing into the n region.
- This diffusion process cannot continue indefinitely. As electrons diffuse from the n region, positively charged donor atoms are left behind. Similarly, as holes diffuse from the p region, they uncover negatively charged acceptor atoms.
- The net positive and negative charges in the n and p regions induce an electric field in the region near the metallurgical junction, in the direction from the positive to the negative charge, or from the n to the p region.

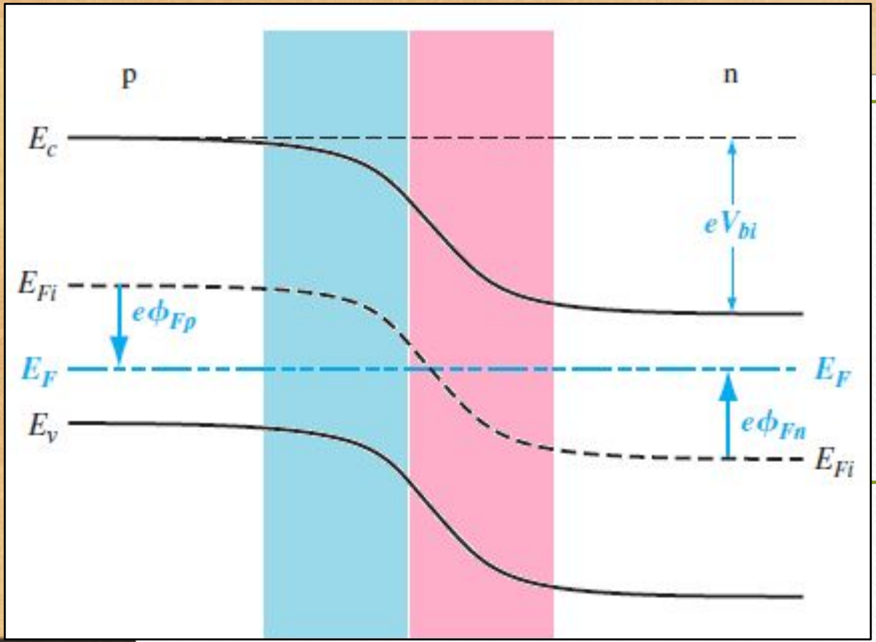
- Density gradients still exist, producing a "diffusion force" that acts on the majority carriers. The electric field in the space charge region produces another force on the electrons and holes, which is in the opposite direction to the diffusion force for each type of particle. In thermal equilibrium, the diffusion force and the E-field force exactly balance each other.



# ZERO APPLIED BIAS




- If we assume that no voltage is applied across the pn junction, then the junction is in **thermal equilibrium—the Fermi energy level is constant throughout the entire system.**
- 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.
- This potential barrier is referred to as the *built-in potential barrier* and is denoted by *Vbi*.
- This potential difference across the junction cannot be measured with a voltmeter because new potential barriers will be formed between the probes and the semiconductor




$$V_{bi} = |\phi_{Fn}| + |\phi_{Fp}|$$

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

We may derive another form of the equations for the thermal-equilibrium concentrations of electrons and holes. If we add and subtract an intrinsic Fermi energy

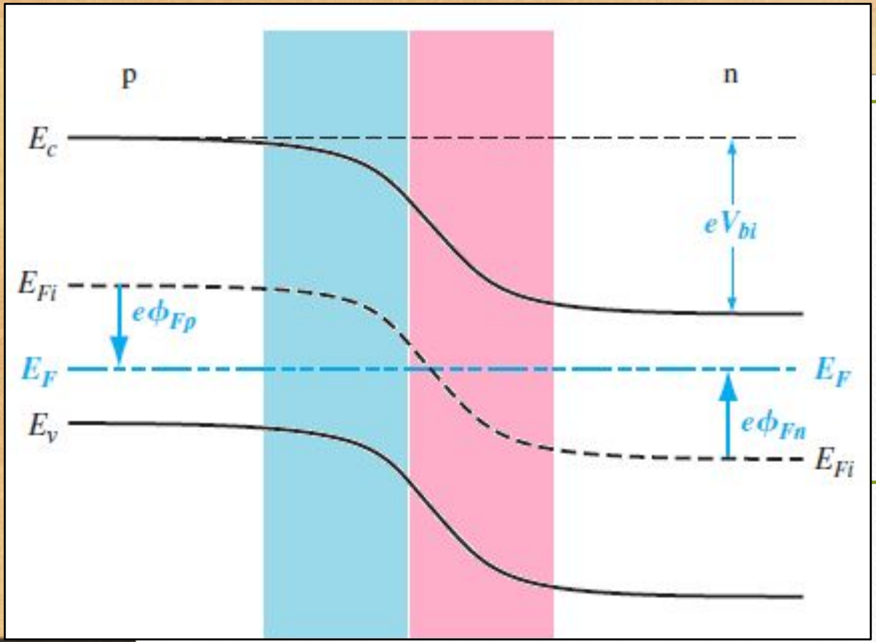
$$n_0 = N_c \exp\left[\frac{-(E_c - E_{Fi}) + (E_F - E_{Fi})}{kT}\right]$$

$$n_i = N_c \exp\left[\frac{-(E_c - E_{Fi})}{kT}\right]$$

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

$$\boxed{n_0 = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right]}$$

$$\boxed{p_0 = n_i \exp\left[\frac{-(E_F - E_{Fi})}{kT}\right]}$$




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

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

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

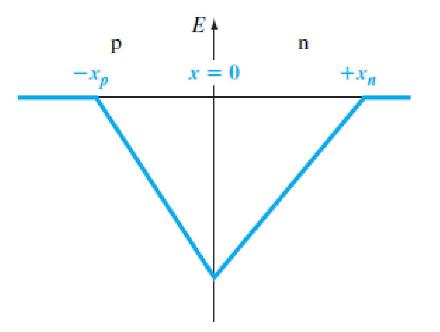
$$\boxed{V_{bi} = \frac{kT}{e}\ln\left(\frac{N_aN_d}{n_i^2}\right) = V_t\ln\left(\frac{N_aN_d}{n_i^2}\right)}$$

Calculate the built-in potential barrier in a pn junction. Consider a silicon pn junction at $T$ = 300 K with doping concentrations of $Na$ = 2 x $10^{17}$ /cm$^3$ and $Nd$ = $10^{15}$ /cm$^3$. (Ans:0.713)

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

**Table 4.2** | Commonly accepted values of $n_i$ at $T$ = 300 K

| | |
|---|---|
| Silicon | $n_i = 1.5 \times 10^{10}$ cm$^{-3}$ |
| Gallium arsenide | $n_i = 1.8 \times 10^{6}$ cm$^{-3}$ |
| Germanium | $n_i = 2.4 \times 10^{13}$ cm$^{-3}$ |




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,

$$\rho(x) = -eN_a \qquad -x_p < x < 0$$

$$\frac{d^2\phi(x)}{dx^2} = \frac{-\rho(x)}{\epsilon_s} = -\frac{d\mathrm{E}(x)}{dx}$$

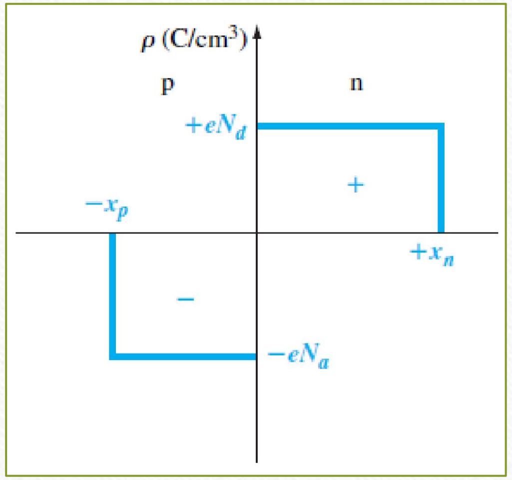
$$\rho(x) = eN_d \qquad 0 < x < x_n$$

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

$$\mathrm{E} = \int \frac{\rho(x)}{\epsilon_s}\,dx = -\int \frac{eN_a}{\epsilon_s}\,dx = \frac{-eN_a}{\epsilon_s}x + C_1$$

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

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




The constant of integration is determined by setting E = 0 at $x = -x_p$.

The electric field is also continuous at the metallurgical junction, or at $x = 0$. Setting Electric field Equations equal to each other at $x = 0$ gives

$$N_a x_p = N_d x_n$$

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

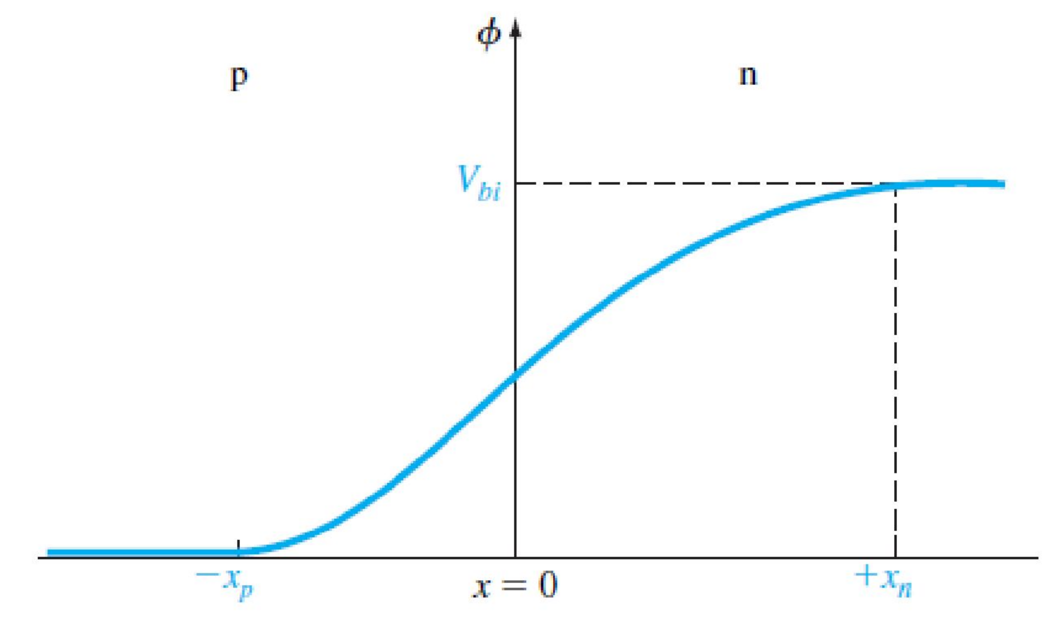
set the potential equal to zero at $x = -x_p$.

$$\phi(x) = \frac{eN_a}{\epsilon_s}\left(\frac{x^2}{2} + x_p \cdot x\right) + C_1'$$

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

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

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



# Space Charge Width

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

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

$$\boxed{x_n = \left\{\frac{2\epsilon_s V_{bi}}{e}\left[\frac{N_a}{N_d}\right]\left[\frac{1}{N_a + N_d}\right]\right\}^{1/2}}$$

A silicon pn junction at $T = 300$ K with zero applied bias has doping concentrations of $N_d = 5 \times 10^{16}$ cm$^{-3}$ and $N_a = 5 \times 10^{15}$ cm$^{-3}$. Determine $x_n$, $x_p$, $W$, and $|E_{max}|$.

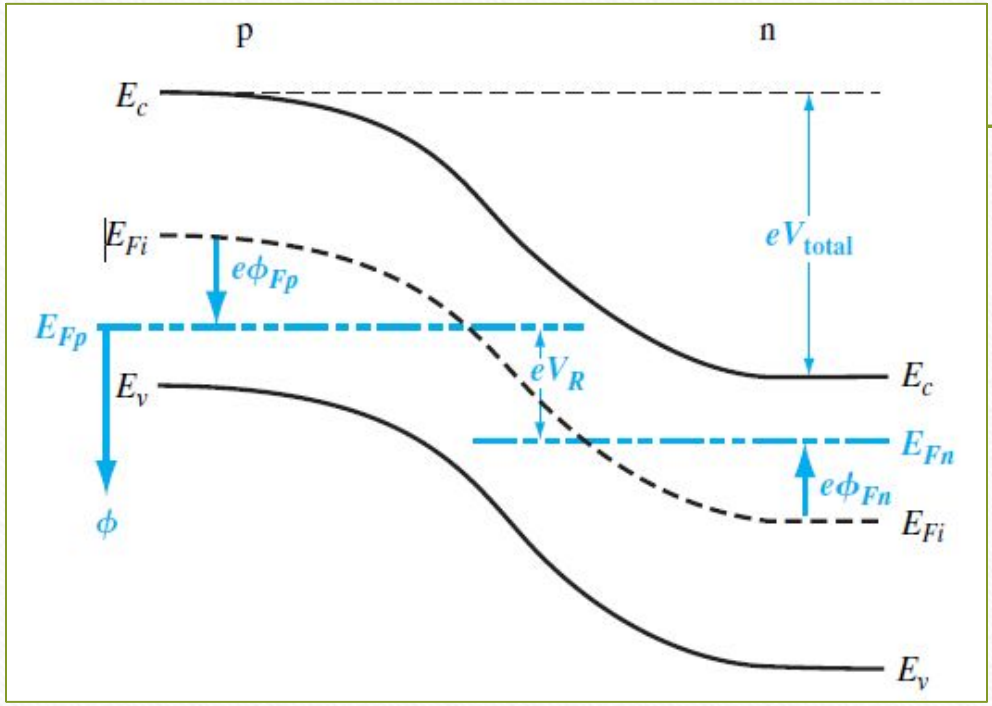
$$\boxed{x_p = \left\{\frac{2\epsilon_s V_{bi}}{e}\left[\frac{N_d}{N_a}\right]\left[\frac{1}{N_a + N_d}\right]\right\}^{1/2}}$$

$$W = \left\{\frac{2\epsilon_s V_{bi}}{e}\left[\frac{N_a + N_d}{N_a N_d}\right]\right\}^{1/2}$$

(Ans. $x_n = 4.11 \times 10^{-6}$ cm, $x_p = 4.11 \times 10^{-5}$ cm, $W = 4.52 \times 10^{-5}$ cm, $|E_{max}| = 3.18 \times 10^4$ V/cm)

# REVERSE APPLIED BIAS

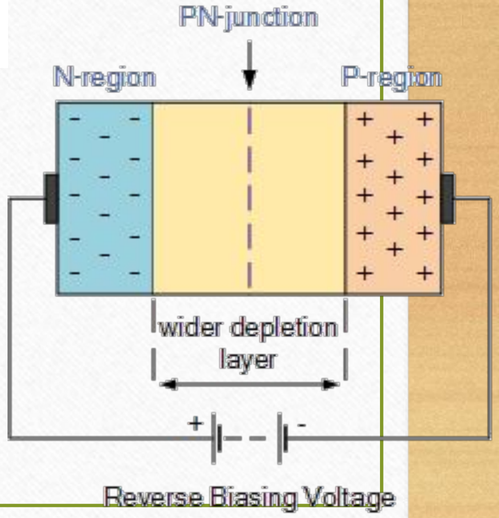
If we apply a potential between the p and n regions, we will no longer be in an equilibrium condition—the Fermi energy level will no longer be constant through the system.



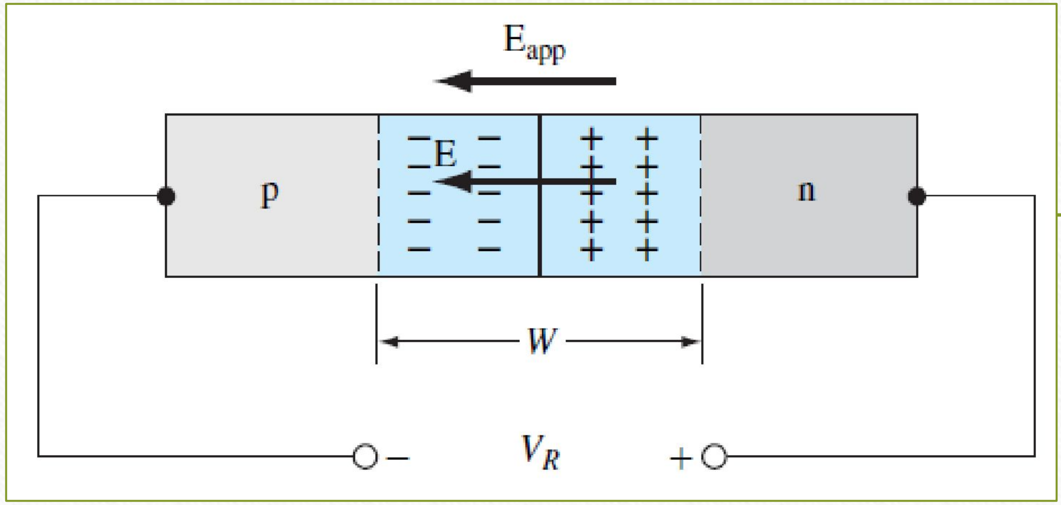

The total potential barrier, indicated by $V_{total}$, has increased. The applied potential is the reverse-biased condition. The total potential barrier is now given by

$$V_{\text{total}} = |\phi_{Fn}| + |\phi_{Fp}| + V_R$$

$$V_{\text{total}} = V_{bi} + V_R$$



# 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

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

$$E_{max} = \frac{-eN_d x_n}{\epsilon_s} = \frac{-eN_a x_p}{\epsilon_s}$$

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

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

Calculate the width of the space charge region in a pn junction when a reverse biased voltage is applied.

Consider a silicon pn junction at $T$ = 300 K with doping concentrations of $Na=10^{16}/cm^3$ and $Nd=10^{15}/cm^3$. Assume that $ni = 1.5\times10^{10}/cm^3$ and $VR$ = 5 V.

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

$$W = 2.83 \times 10^{-4} \text{ cm} = 2.83\ \mu\text{m}$$

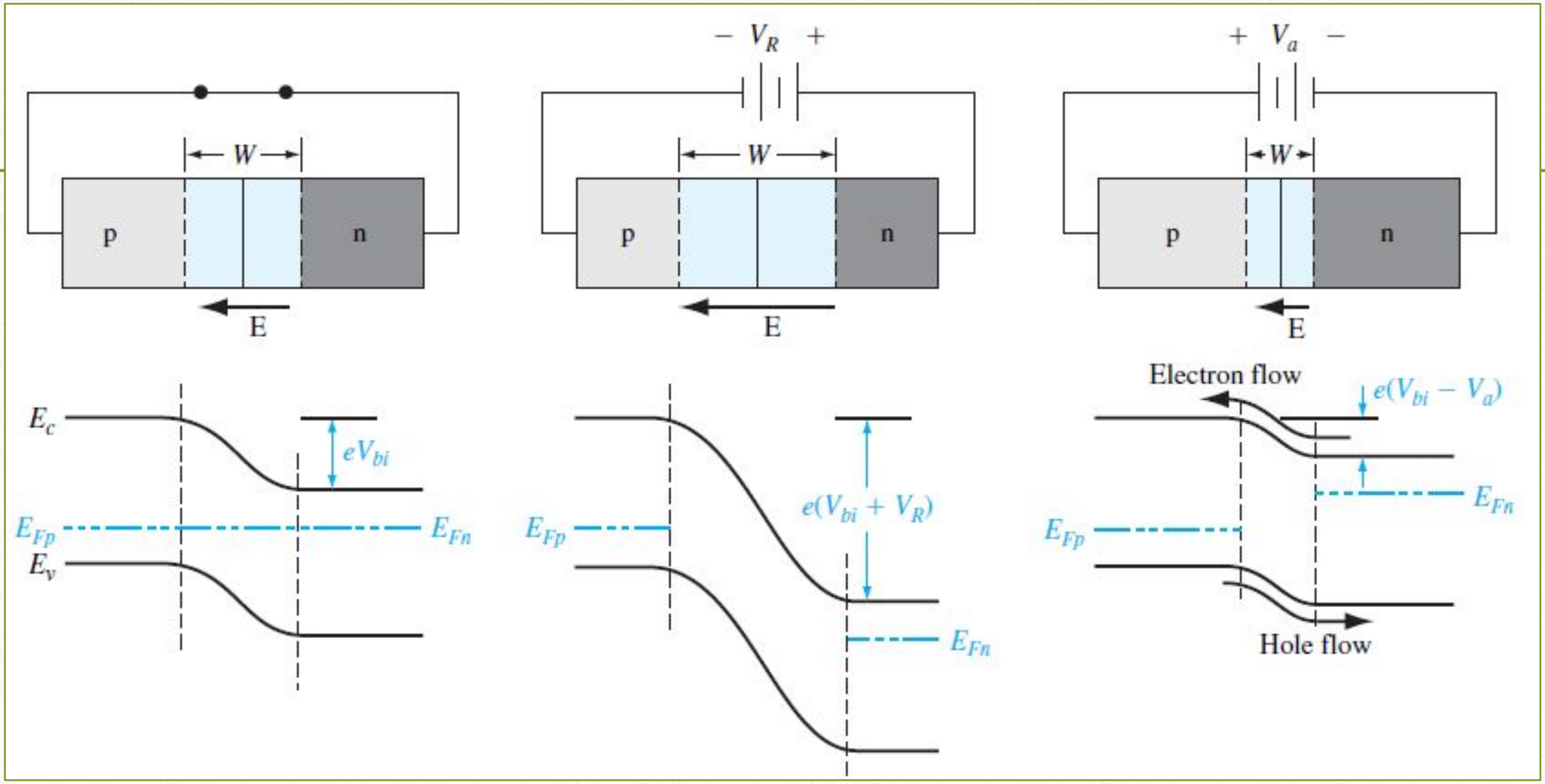
Design a pn junction to meet maximum electric field and voltage specifications.

Consider a silicon pn junction at $T$ = 300 K with a p-type doping concentration of $Na = 2 \times 10^{17}$ /cm$^3$. Determine the n-type doping concentration such that the maximum electric field is Emax = $2.5 \times 10^5$ V/cm at a reverse-biased voltage of $V_R$ = 25 V.

$N_d = 8.43 \times 10^{15}\ \text{cm}^{-3}$

# FORWARD APPLIED BIAS

When a forward-bias voltage is applied to a pn junction, a current will be induced in the device.



# FORWARD APPLIED BIAS

- The total potential barrier is now reduced.
- The smaller potential barrier means that the electric field in the depletion region is also reduced.
- The smaller electric field means that the electrons and holes are no longer held back in the n and p regions, respectively.
- There will be a diffusion of holes from the p region across the space charge region where they will flow into the n region. Similarly, there will be a diffusion of electrons from the n region across the space charge region where they will flow into the p region.
- The flow of charge generates a current through the pn junction.

# Ideal Current–Voltage Relationship

| Term | Meaning |
|---|---|
| $N_a$ | Acceptor concentration in the p region of the pn junction |
| $N_d$ | Donor concentration in the n region of the pn junction |
| $n_{n0} = N_d$ | Thermal-equilibrium majority carrier electron concentration in the n region |
| $p_{p0} = N_a$ | Thermal-equilibrium majority carrier hole concentration in the p region |
| $n_{p0} = n_i^2/N_a$ | Thermal-equilibrium minority carrier electron concentration in the p region |
| $p_{n0} = n_i^2/N_d$ | Thermal-equilibrium minority carrier hole concentration in the n region |
| $n_p$ | Total minority carrier electron concentration in the p region |
| $p_n$ | Total minority carrier hole concentration in the n region |
| $n_p(-x_p)$ | Minority carrier electron concentration in the p region at the space charge edge |
| $p_n(x_n)$ | Minority carrier hole concentration in the n region at the space charge edge |
| $\delta n_p = n_p - n_{p0}$ | Excess minority carrier electron concentration in the p region |
| $\delta p_n = p_n - p_{n0}$ | Excess minority carrier hole concentration in the n region |

# Ideal Current–Voltage Relationship

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

If we divide the equation by $V_t = kT/e$, take the exponential of both sides, and then take the reciprocal

$$\frac{n_i^2}{N_a N_d} = \exp\left(\frac{-eV_{bi}}{kT}\right)$$

$$n_{n0} \approx N_d$$

$$n_{p0} = n_{n0} \exp\left(\frac{-eV_{bi}}{kT}\right)$$

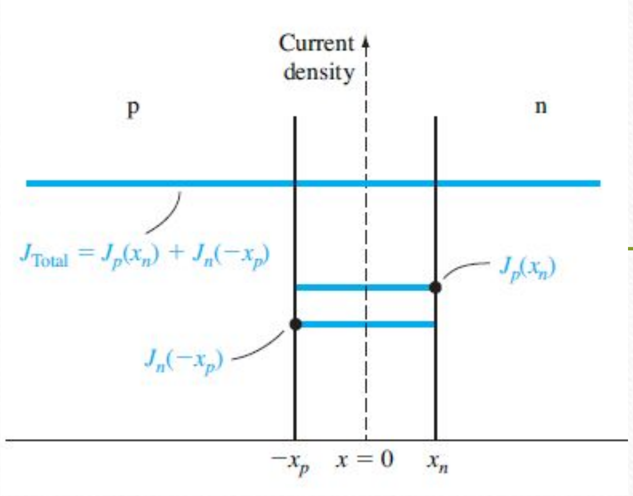
$$n_{p0} \approx \frac{n_i^2}{N_a}$$

$$n_p = n_{n0} \exp\left(\frac{-e(V_{bi} - V_a)}{kT}\right) = n_{n0} \exp\left(\frac{-eV_{bi}}{kT}\right) \exp\left(\frac{+eV_a}{kT}\right)$$

$$\boxed{n_p = n_{p0} \exp\left(\frac{eV_a}{kT}\right)}$$

$$\boxed{p_n = p_{n0} \exp\left(\frac{eV_a}{kT}\right)}$$

# Ideal pn Junction Current




$$J_p(x_n) = -eD_p \left.\frac{d(\delta p_n(x))}{dx}\right|_{x=x_n}$$

$$\delta p_n(x) = p_n(x) - p_{n0} = p_{n0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\exp\left(\frac{x_n - x}{L_p}\right)$$

$$\boxed{J_p(x_n) = \frac{eD_p p_{n0}}{L_p}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]}$$

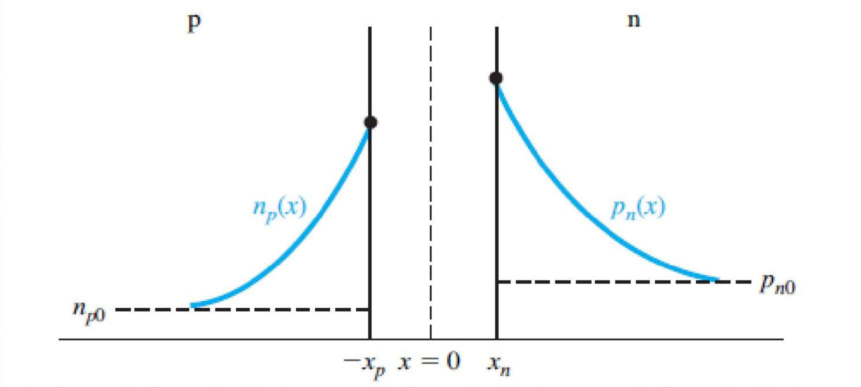
$$L_p^2 = D_p \tau_{p0}$$

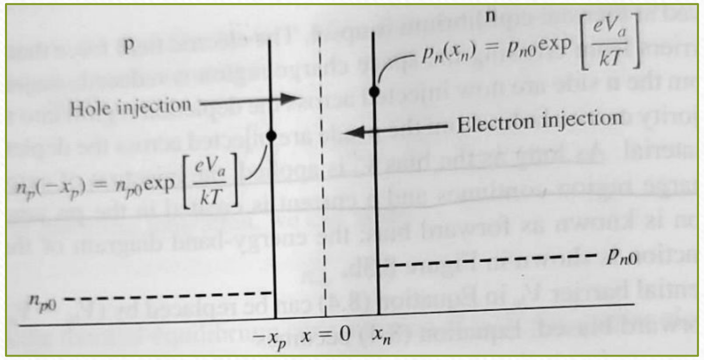
$$J_n(-x_p) = eD_n \left.\frac{d(\delta n_p(x))}{dx}\right|_{x=-x_p}$$

$$\delta n_p(x) = n_p(x) - n_{p0} = n_{p0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\exp\left(\frac{x_p + x}{L_n}\right)$$

$$\boxed{J_n(-x_p) = \frac{eD_n n_{p0}}{L_n}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]}$$

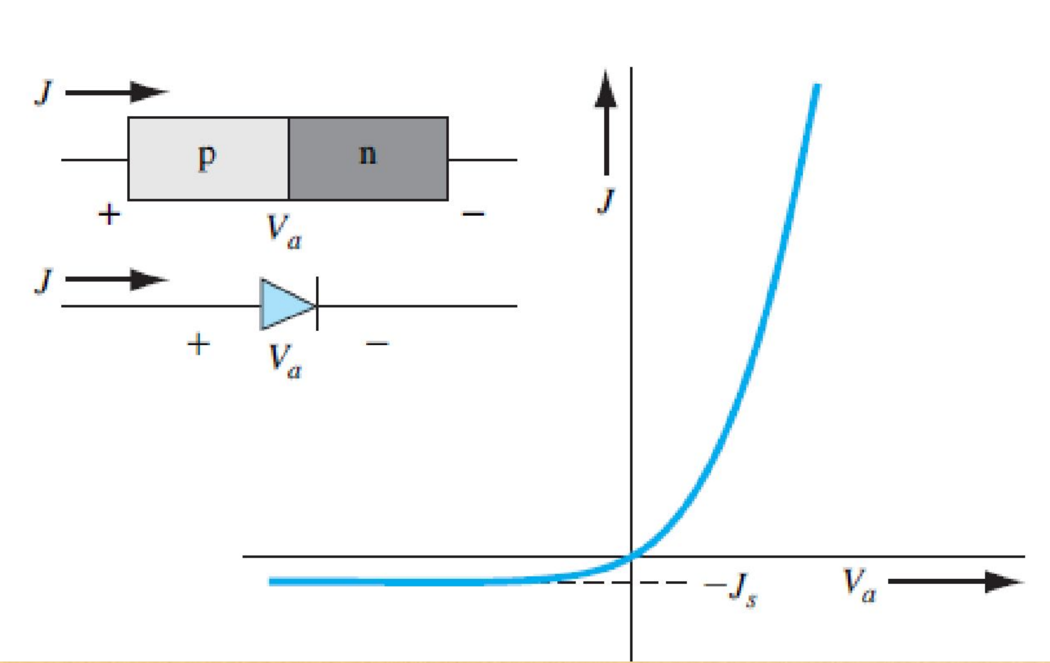
$$L_n^2 = D_n \tau_{n0}.$$


p
n
$n_p(x)$
$p_n(x)$
$n_{p0}$
$p_{n0}$
$-x_p$ $x = 0$ $x_n$


p
n
$p_n(x_n) = p_{n0}\exp\left[\frac{eV_a}{kT}\right]$
Hole injection
Electron injection
$n_p(-x_p) = n_{p0}\exp\left[\frac{eV_a}{kT}\right]$
$p_{n0}$
$n_{p0}$
$-x_p$ $x = 0$ $x_n$

$$J = J_p(x_n) + J_n(-x_p) = \left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}\right]\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

$$\boxed{J_s = \left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}\right]}$$




$$\boxed{J = J_s\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]}$$

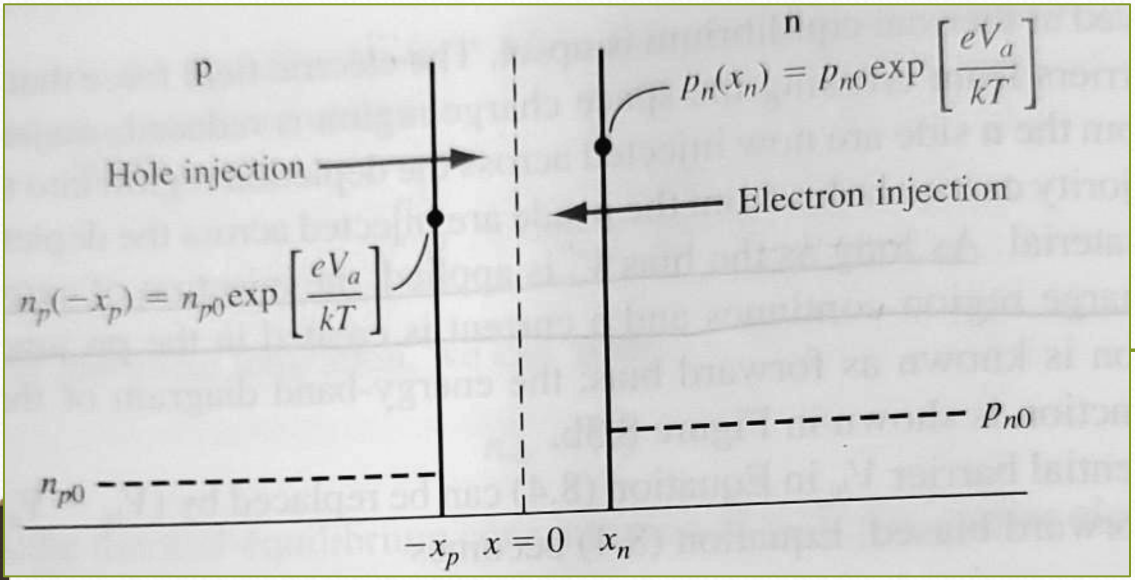
Determine the ideal reverse-saturation current density in a silicon pn junction at $T$ = 300 K. Consider the following parameters in a silicon pn junction:

$N_a = N_d = 10^{16}\ \text{cm}^{-3}$ $\quad$ $n_i = 1.5 \times 10^{10}\ \text{cm}^{-3}$

$D_n = 25\ \text{cm}^2/\text{s}$ $\quad$ $\tau_{p0} = \tau_{n0} = 5 \times 10^{-7}\ \text{s}$

$D_p = 10\ \text{cm}^2/\text{s}$ $\quad$ $\epsilon_r = 11.7$

$$J_s = \left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}\right]$$




Calculate the minority carrier concentrations at the edge of the space charge regions in a forward-biased pn junction.

Consider a silicon pn junction at $T$ = 300 K. Assume the doping concentration in the n region is $Nd = 10^{16}$ $cm^3$ and the doping concentration in the p region is N$a$ = 6 x $10^{15}$ $cm^3$, and assume that a forward bias of 0.60 V is applied to the pn junction.

$$n_p(-x_p) = 3.75 \times 10^4 \exp\left(\frac{0.60}{0.0259}\right) = 4.31 \times 10^{14}\ \text{cm}^{-3}$$

$$p_n(x_n) = 2.25 \times 10^4 \exp\left(\frac{0.60}{0.0259}\right) = 2.59 \times 10^{14}\ \text{cm}^{-3}$$

Design a pn junction diode to produce particular electron and hole current densities at a given forward-bias voltage.

Consider a silicon pn junction diode at $T = 300$ K. Design the diode such that $J_n = 20$ A /cm$^2$ and $J_p = 5$ A /cm$^2$ at $V_a = 0.65$ V. Assume the remaining semiconductor parameters are as given in previous problem.

| | |
|---|---|
| $N_a = N_d = 10^{16}\ \text{cm}^{-3}$ | $n_i = 1.5 \times 10^{10}\ \text{cm}^{-3}$ |
| $D_n = 25\ \text{cm}^2/\text{s}$ | $\tau_{p0} = \tau_{n0} = 5 \times 10^{-7}\ \text{s}$ |
| $D_p = 10\ \text{cm}^2/\text{s}$ | $\epsilon_r = 11.7$ |

$$J = J_p(x_n) + J_n(-x_p) = \left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}\right]\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

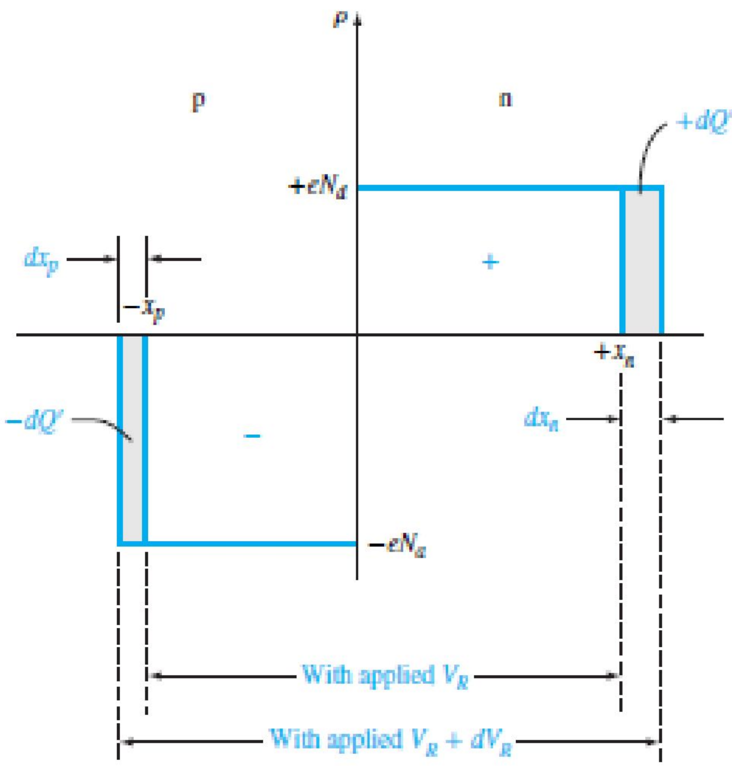
# Junction Capacitance

- Since we have a separation of positive and negative charges in the depletion region, a capacitance is associated with the pn junction. Figure shows the charge densities in the depletion region for applied reverse-biased voltages of $V_R$ and $V_R + dV_R$.
- An increase in the reverse-biased voltage will uncover additional positive charges in the n region and additional negative charges in the p region.
- The junction capacitance is defined as

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

$$dQ' = eN_d\,dx_n = eN_a\,dx_p$$

- The differential charge $dQ$ is in units of C/cm$^2$ so that the capacitance $C$ is in units of farads per square centimeter F/cm$^2$), or capacitance per unit area.



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

$$C' = \frac{dQ'}{dV_R} = eN_d \frac{dx_n}{dV_R}$$

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

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.*

Consider a silicon pn junction at $T$ = 300 K with doping concentrations of $Na$=$10^{16}$/cm$^3$ and $Nd$ =$10^{15}$ /cm$^3$. Assume that $ni$ = 1.5x$10^{10}$/cm$^3$ and $VR$ = 5 V.

Calculate the junction capacitance of a pn junction.

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

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

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

# One-Sided Junctions

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

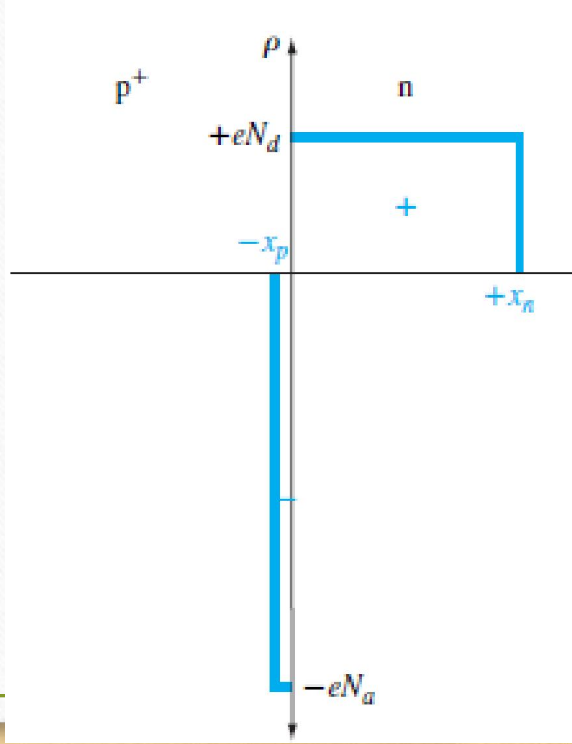
$$W \approx \left\{ \frac{2\epsilon_s (V_{bi} + V_R)}{eN_d} \right\}^{1/2}$$

Considering the expressions for *xn* and *xp,* we have for the p⁺n junction
*xp << xn.* Almost the entire space charge layer extends into the low-doped region of the junction.

$$x_p \ll x_n$$

$$W \approx x_n$$

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

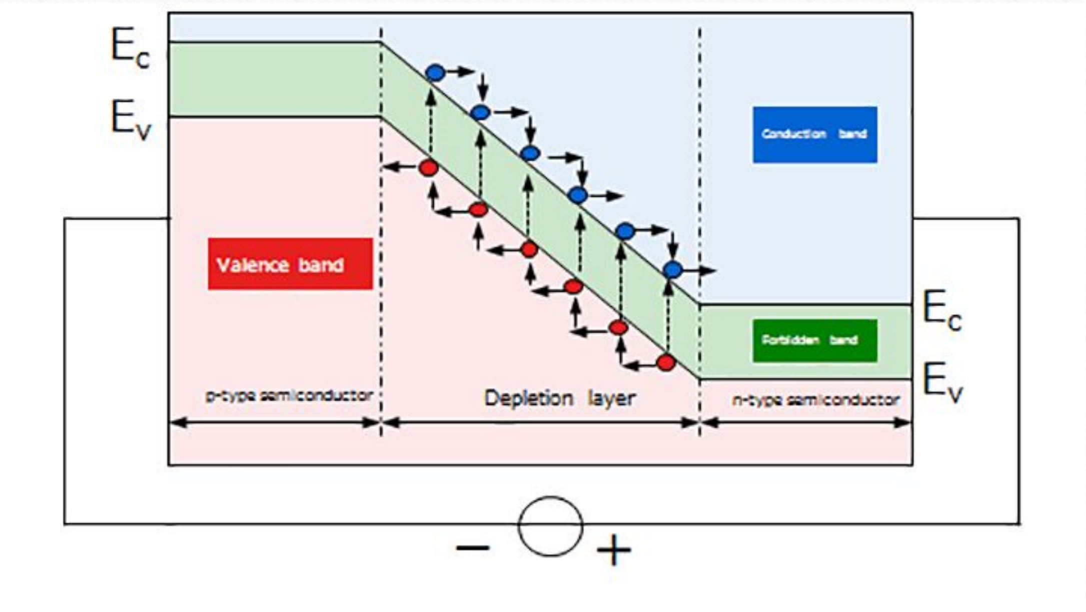


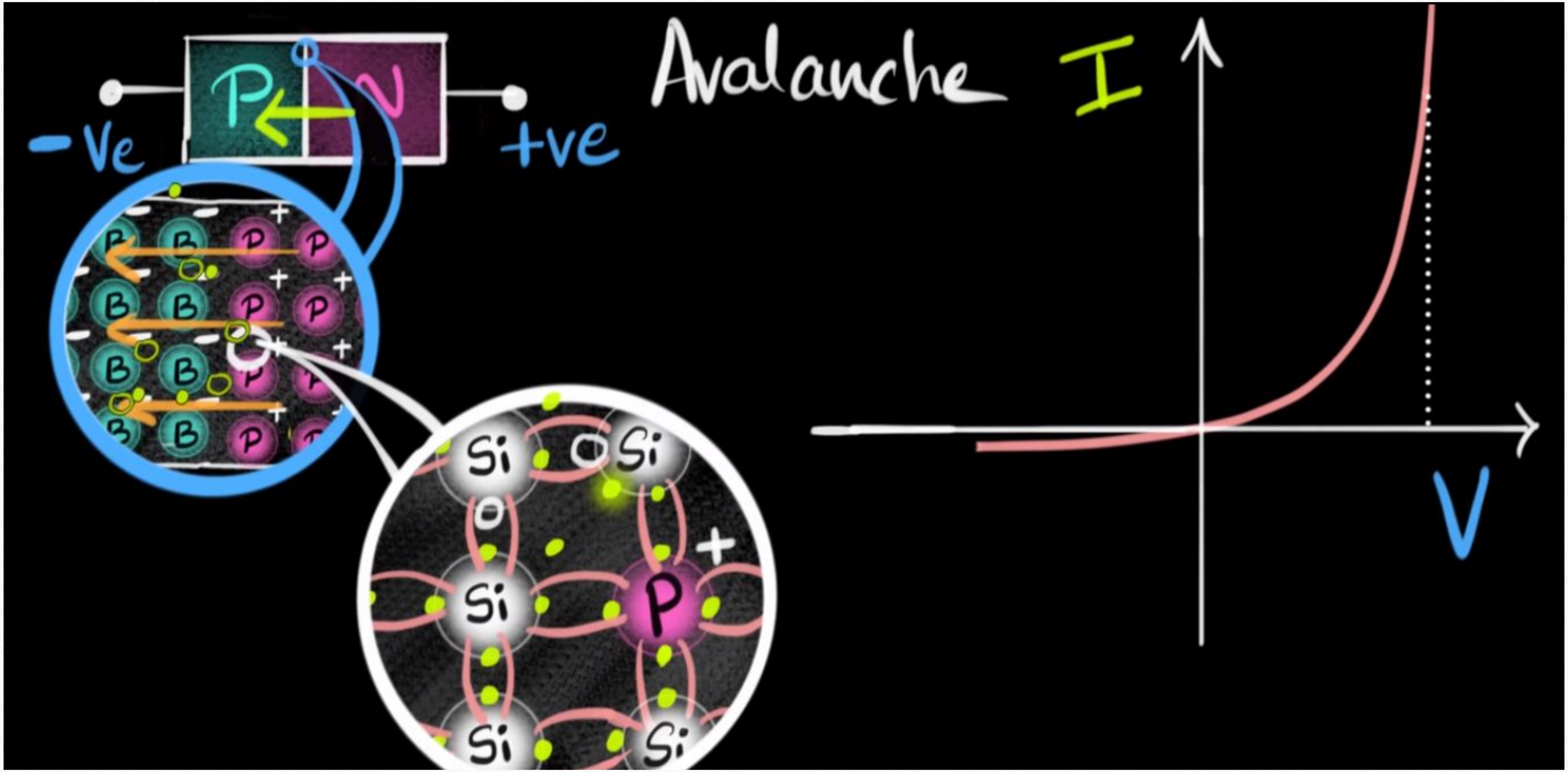
An ideal one-sided silicon $p^+n$ junction at $T$ = 300 K is uniformly doped on both sides of the metallurgical junction. It is found that the doping relation is $N_a = 80\ N_d$ and the built-in potential barrier is $V_{bi}$ = 0.740 V. A reverse-biased voltage of $V_R$ = 10 V is applied. Determine (*a*) $N_a$, $N_d$; (*b*) $x_p$, $x_n$; (*c*) $|E_{max}|$; and (*d*) $Cj$. Repeat the same problem for zero bias condition.

# JUNCTION BREAKDOWN

- The reverse-biased voltage should not increase without limit; at some particular voltage, the reverse-biased current will increase rapidly. The applied voltage at this point is called the breakdown voltage.
- Two physical mechanisms give rise to the reverse-biased breakdown in a pn junction: the Zener effect and the avalanche effect.

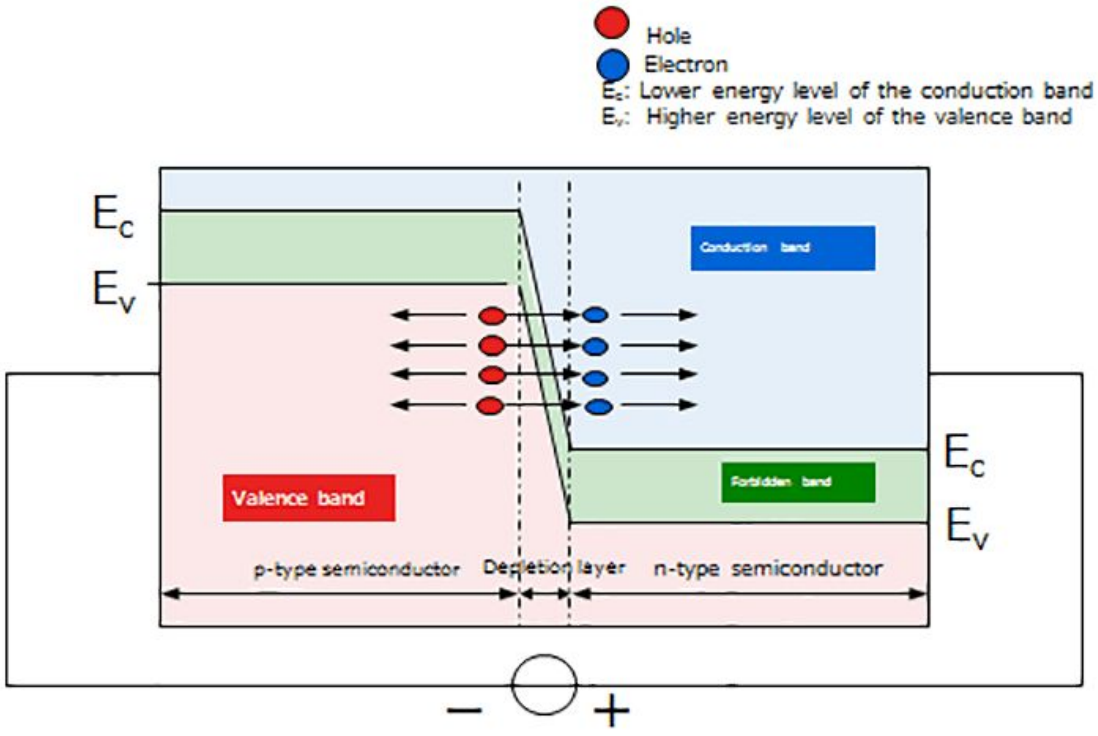
When a pn junction is reverse-biased, a small quantity of electrons passes through the pn junction. These electrons are accelerated in the depletion layer by an electric field, acquiring large kinetic energy. The accelerated electrons collide with the atoms in a crystal lattice, ionizing them and creating electron holes. The electrons of these atoms are excited to the conduction band and knocked out, becoming free electrons. The free electrons are also accelerated and collide with other atoms, creating more electron-hole pairs and leading to further knocking-out processes. This phenomenon is called avalanche breakdown.

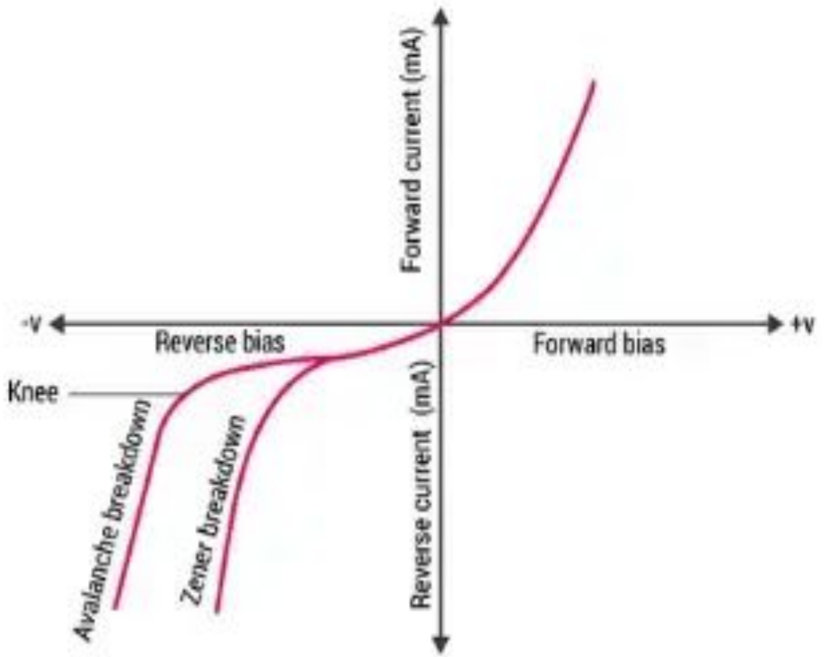


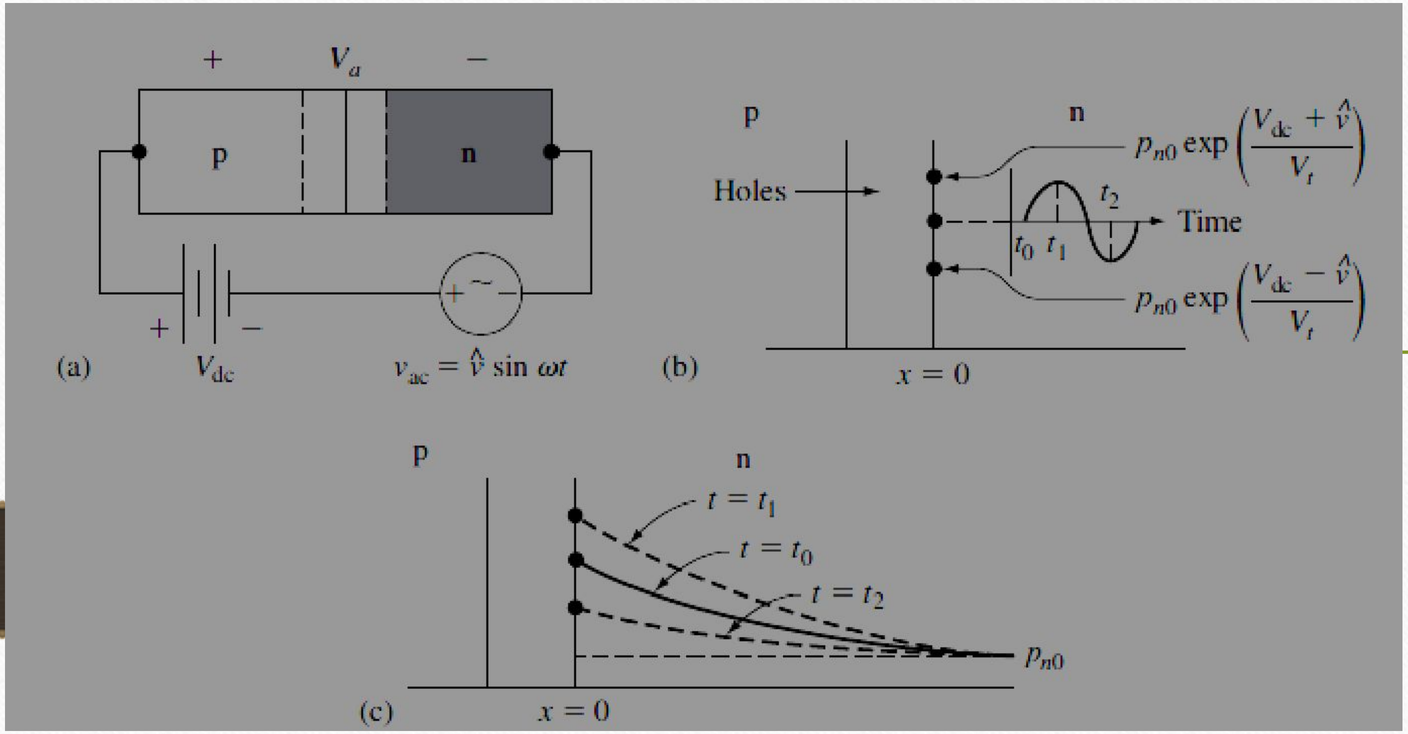


P
N
-Ve
+ve
Avalanche
I
V
B
P
Si

Zener breakdown occurs in highly doped pn junctions through a tunneling mechanism. In a highly doped junction, the conduction and valence bands on opposite sides of the junction are sufficiently close during reverse bias that electrons may tunnel directly from the valence band on the p side into the conduction band on the n side.



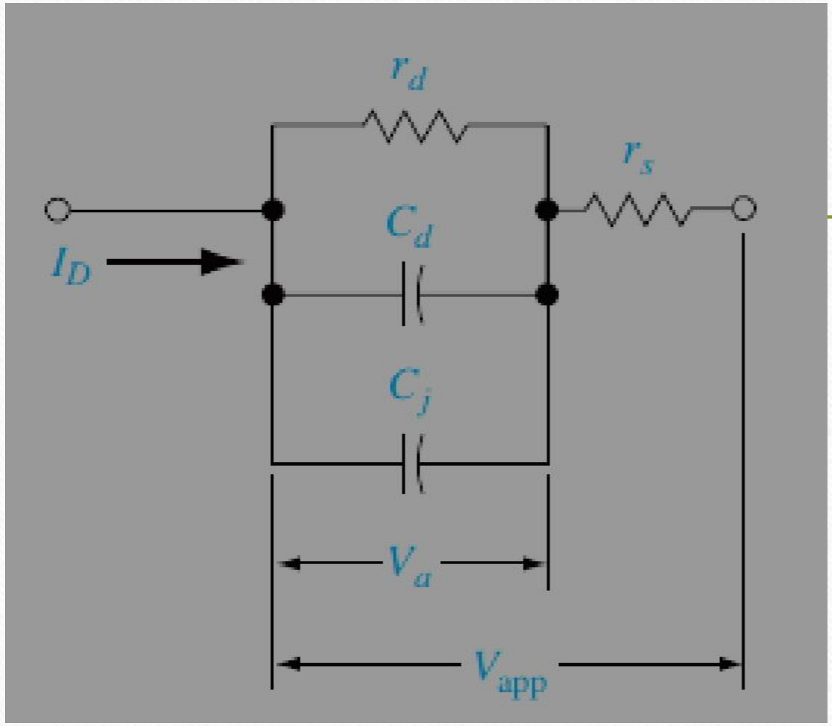






## *Diffusion capacitance*

The mechanism of charging and discharging of holes in the n region and electrons in the p region leads to a capacitance. This capacitance is called *diffusion capacitance*. **The magnitude of the diffusion capacitance in a forward-biased pn junction is usually substantially larger than the junction capacitance.**

## Complete Equivalent Circuit of PN Junction




$$V_{app} = V_a + Ir_s$$

# EQUIVALENT CIRCUITS
# SMALL-SIGNAL MODEL OF THE pn JUNCTION

$$J = J_s\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

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

$I_D$ is the diode current and $I_s$ is the diode reverse-saturation current

Assume that the diode is forward-biased with a dc voltage $V_0$ producing a dc diode current $I_{DQ}$. If we now superimpose a small, low-frequency sinusoidal voltage, then a small sinusoidal current will be produced, superimposed on the dc current. The ratio of sinusoidal current to sinusoidal voltage is called the **incremental conductance**

$$g_d = \left.\frac{dI_D}{dV_a}\right|_{V_a=V_0}$$

$$r_d = \left.\frac{dV_a}{dI_D}\right|_{I_D=I_{DQ}}$$

$$g_d = \left.\frac{dI_D}{dV_a}\right|_{V_a=V_0} = \left(\frac{e}{kT}\right) I_s \exp\left(\frac{eV_0}{kT}\right) \approx \frac{I_{DQ}}{V_t}$$

$$\boxed{r_d = \frac{V_t}{I_{DQ}}}$$

The incremental resistance is also known as the *diffusion resistance.*