矽奈米元件物理
SILICON NANOMETER DEVICES AND PHYSICS

The pn Junction Diode

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Outline

- Ideal Current-Voltage Relationship
- Minority Carrier Distribution
- Ideal pn Junction Current
- Reverse-Bias Generation Current
- Forward-Bias Recombination Current

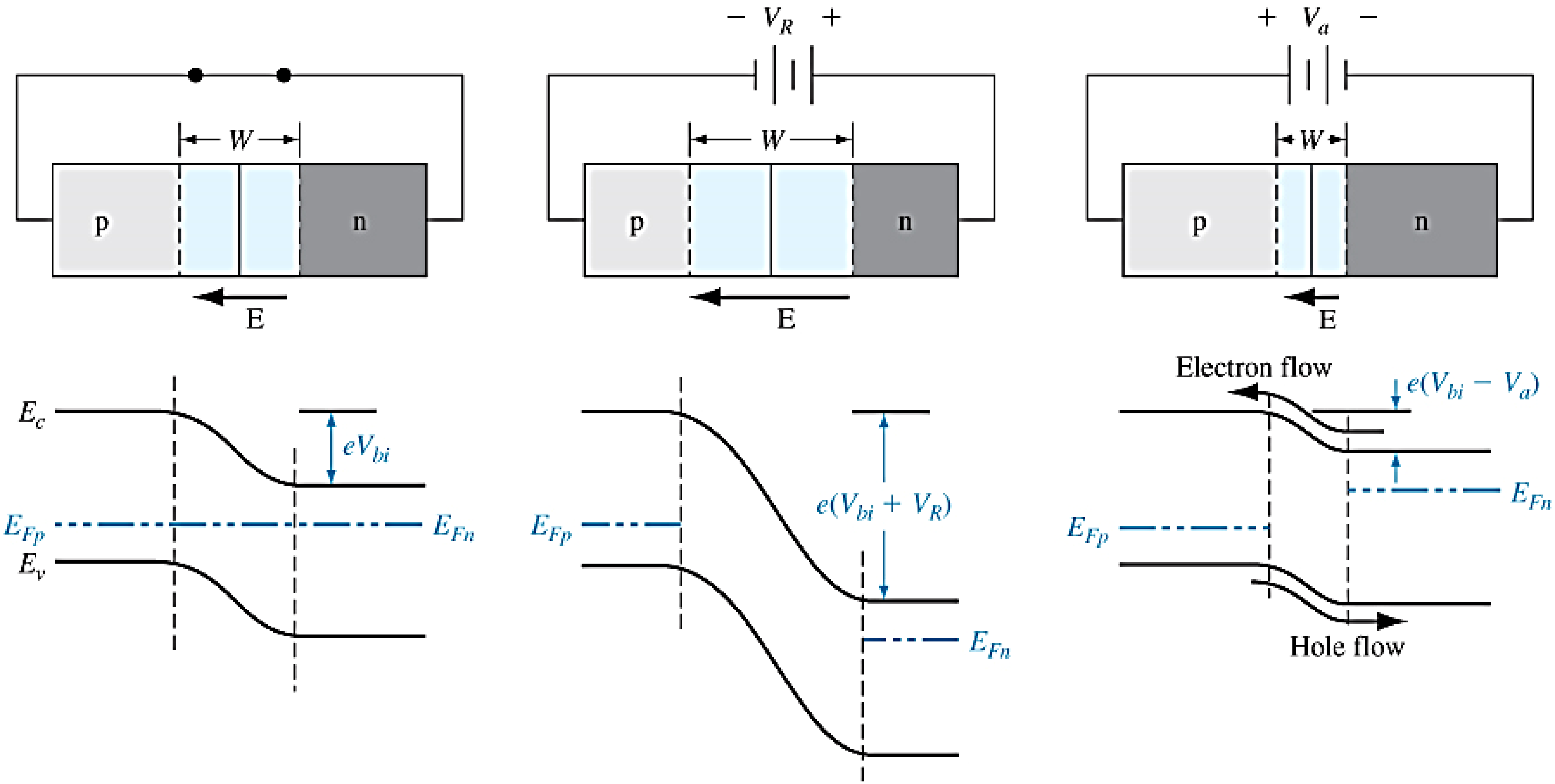
Notation for This Chapter

Table 8.1 | Commonly used terms and notation for this chapter

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

Energy Band Diagram

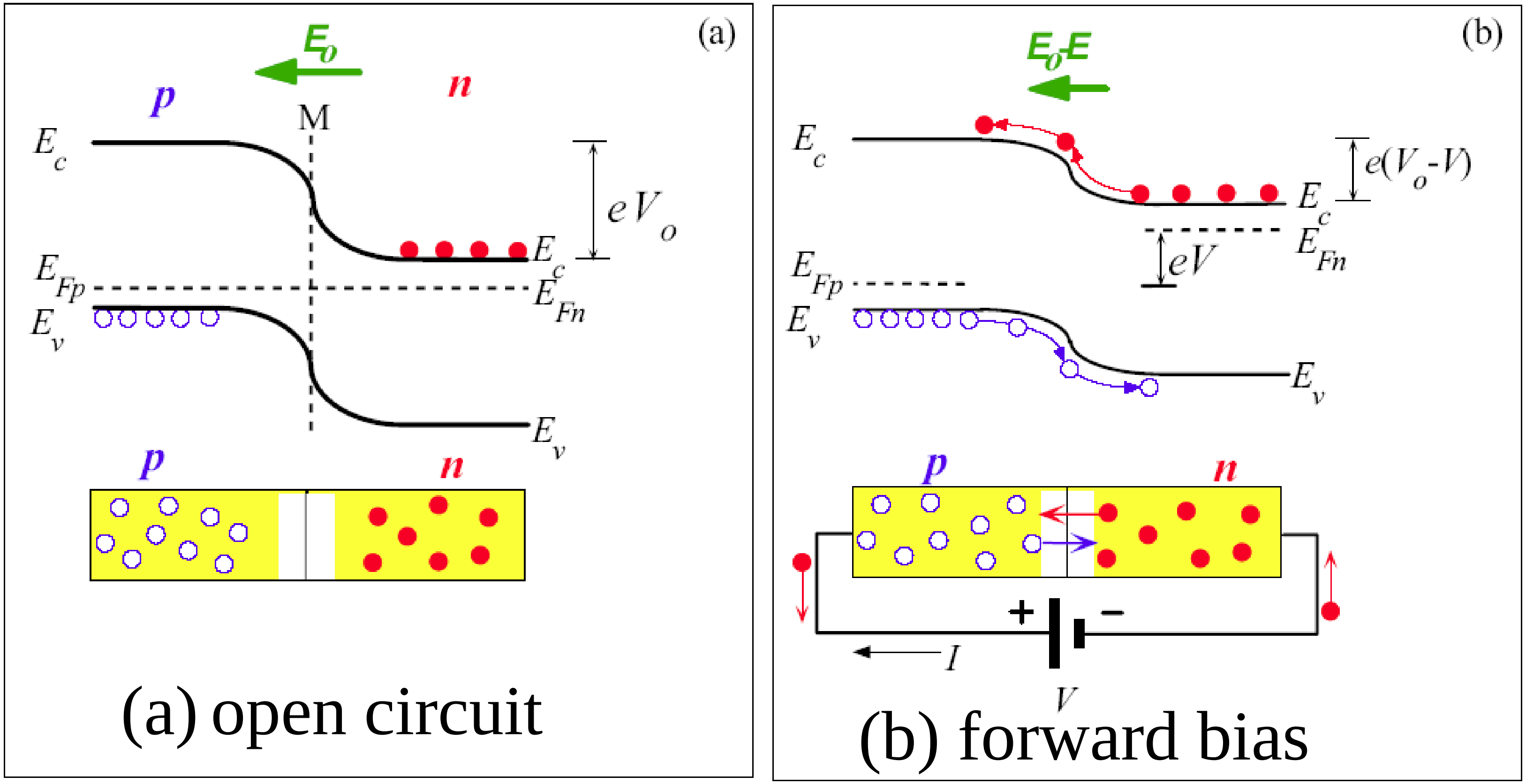
❖ If a positive voltage is applied to the p-region with respect to the n-region, the potential barrier is reduced. This bias condition is known as the forward bias.



Zero Applied Bias **Reverse Bias** **Forward Bias**

Energy Band Diagram of PN Junction

- The Forward bias opposes the built in potential and reduces the barrier for carrier injection across the junction.
- When a forward bias is applied to a pn junction, a current will be induced in the device.

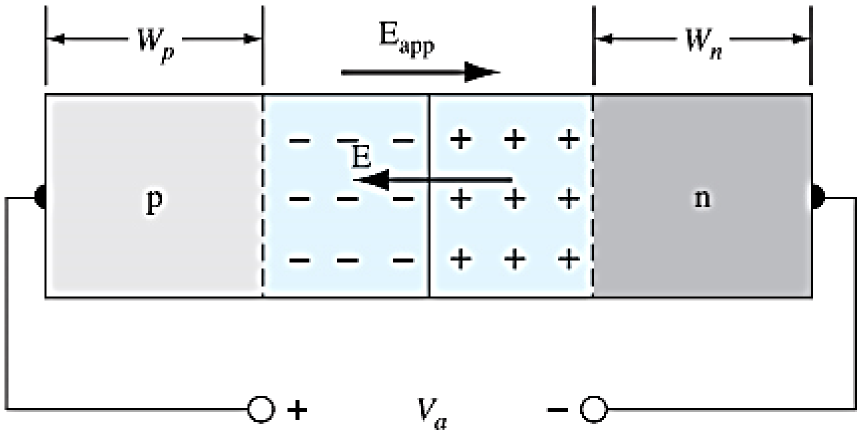


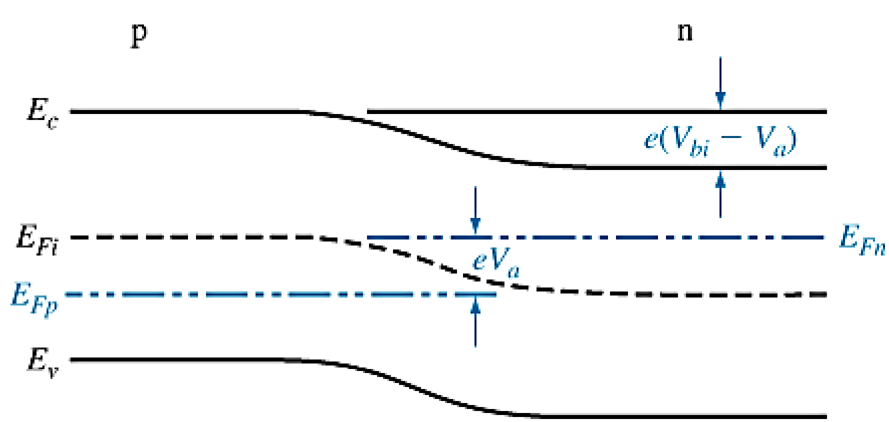
(a) open circuit

(b) forward bias

Ideal Current-Voltage Relationship

- Almost all of this bias voltage is across the junction region.
- The forward bias reduces the potential barrier and disturb the thermal equilibrium.
- The majority carrier electrons from the n-region are injected into the p-region, and the majority carrier holes from the p-region are injected into the n-region.

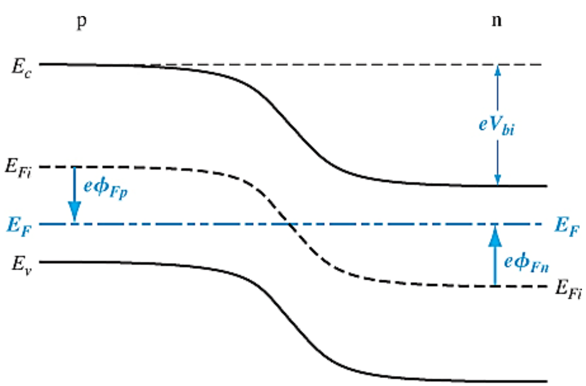




Ideal Current-Voltage Relationship

❖ Electron concentration in N-type: $n_{n0} \approx N_d$

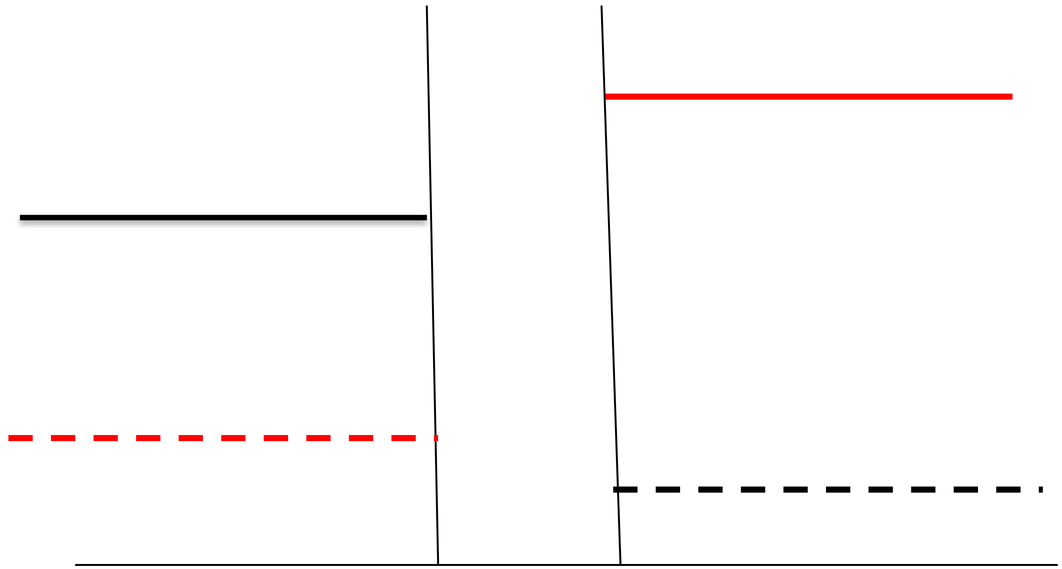
❖ Electron concentration in P-type: $n_{p0} \approx \dfrac{n_i^2}{N_a}$



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

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

❖ **The equation relates the minority carrier electron concentration on the p-type to the majority carrier electron concentration on the n-type of the junction**



Ideal Current-Voltage Relationship

❖ If we assume low-level injection, the majority carrier electron concentration on the n-side, n_{n0}, does not change significantly. The minority carrier electron concentration on the p-side, n_p, can deviate from its equilibrium value, n_{p0}, by orders of magnitude.

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

Applied Forward Bias

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

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

Ideal Current-Voltage Relationship

- The minority carrier electron concentration in the p-region becomes larger than its equilibrium value when a forward bias is applied.

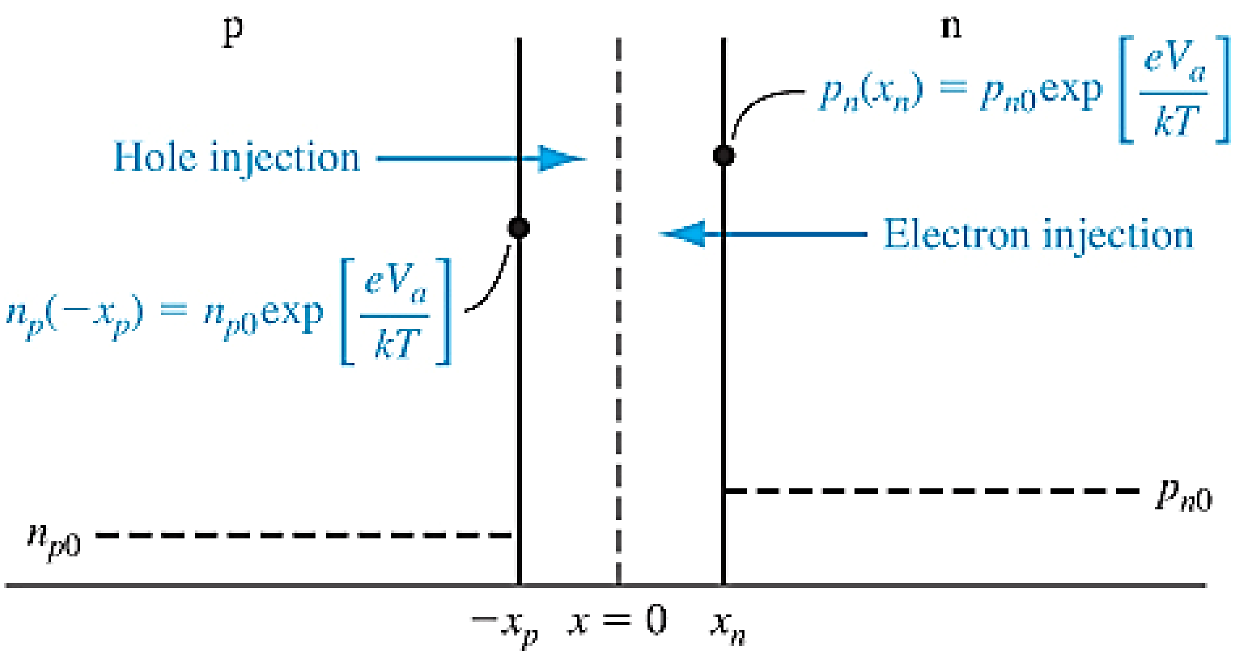
$$\boxed{n_p = n_{p0} \exp\left(\frac{eV_a}{kT}\right)}$$

- The same derivation can be applied for the minority carrier holes in the n-region.

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

Excess Minority Carrier

- Excess carriers are subjected to the diffusion processes due to the applied forward bias.
- The minority electron concentration decreases into the p-region and the minority hole concentration decreases into the n-region due to recombination.



Example

- Consider a silicon pn junction at T = 300 K with n_i= $1.5\text{x}10^{10}$ cm^{-3}. Assume N_d=$1\text{x}10^{16}$ cm^{-3} and V_a=0.6V. Calculate the minority hole concentration at the edge of the space charge region.

$$p_n(x_n) = p_{no} \exp\left(\frac{eV_a}{kT}\right)$$

$$p_{no} = \frac{n_i^2}{N_d} = \frac{(1.5 \times 10^{10})^2}{10^{16}} = 2.25 \times 10^4 \text{ cm}^{-3}$$

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

The minority carrier hole concentration increases by many orders of magnitude.

Outline

- Ideal Current-Voltage Relationship
- **Minority Carrier Distribution**
- Ideal pn Junction Current
- Reverse-Bias Generation Current
- Forward-Bias Recombination Current

Distribution of Minority Carrier

- The ambipolar transport equation describes the distribution of the excess minority carriers as a function of time and space. For the minority **holes** in the **n-type**, we have: $\delta p_n = p_n - p_{n0}$

$$D_p \frac{\partial^2 (\delta p_n)}{\partial x^2} - \mu_p \mathrm{E} \frac{\partial (\delta p_n)}{\partial x} + g' - \frac{\delta p_n}{\tau_{p0}} = \frac{\partial (\delta p_n)}{\partial t}$$

- Assume that the electric field is zero in both the neutral n- and p-regions. Thus, for $x > x_n$, $E = 0$ and $g' = 0$. If we consider the steady state, so $\partial(\delta p_n)/\partial t = 0$

$$D_p \frac{d^2(\delta p_n)}{dx^2} - \frac{\delta p_n}{\tau_{p0}} = 0 \qquad (x > x_n)$$

Distribution of Minority Carrier

- Let $L^2_p = D_p \tau_{n0}$

$$\frac{d^2(\delta p_n)}{dx^2} - \frac{\delta p_n}{L_p^2} = 0 \qquad (x > x_n)$$

- Let $L^2_n = D_n \tau_{n0.}$ For the minority **electrons** in the **p-type**, we have:

$$\frac{d^2(\delta n_p)}{dx^2} - \frac{\delta n_p}{L_n^2} = 0 \qquad (x < x_p)$$

- The general solutions are:

$$\delta p_n(x) = p_n(x) - p_{n0} = Ae^{x/L_p} + Be^{-x/L_p} \qquad (x \geq x_n)$$

$$\delta n_p(x) = n_p(x) - n_{p0} = Ce^{x/L_n} + De^{-x/L_n} \qquad (x \leq -x_p)$$

Distribution of Minority Carrier

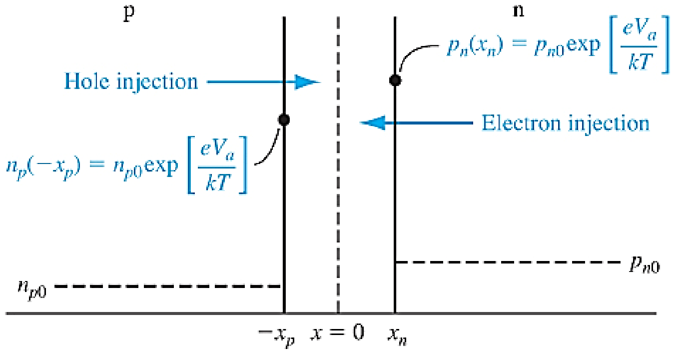
$$\delta p_n(x) = p_n(x) - p_{n0} = Ae^{x/L_p} + Be^{-x/L_p} \qquad (x \geq x_n)$$

$$\delta n_p(x) = n_p(x) - n_{p0} = Ce^{x/L_n} + De^{-x/L_n} \qquad (x \leq -x_p)$$

❖ Boundary conditions:

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

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



$p_n(x \to +\infty) = p_{n0}$ ⇨ A=0

$n_p(x \to -\infty) = n_{p0}$ ⇨ D=0

Distribution of Minority Carrier

$$\delta p_n(x) = p_n(x) - p_{n0} = Ae^{x/L_p} + Be^{-x/L_p} \qquad (x \geq x_n)$$

X=X$_n$

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

$$p_{n0}\exp\left(\frac{eV_a}{kT}\right) - p_{n0} = Be^{-x_n/L_p}$$

$$n_{p0}\exp\left(\frac{eV_a}{kT}\right) - n_{p0} = Ce^{-x_p/L_n}$$

$$B = p_{n0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]e^{x_n/L_p}$$

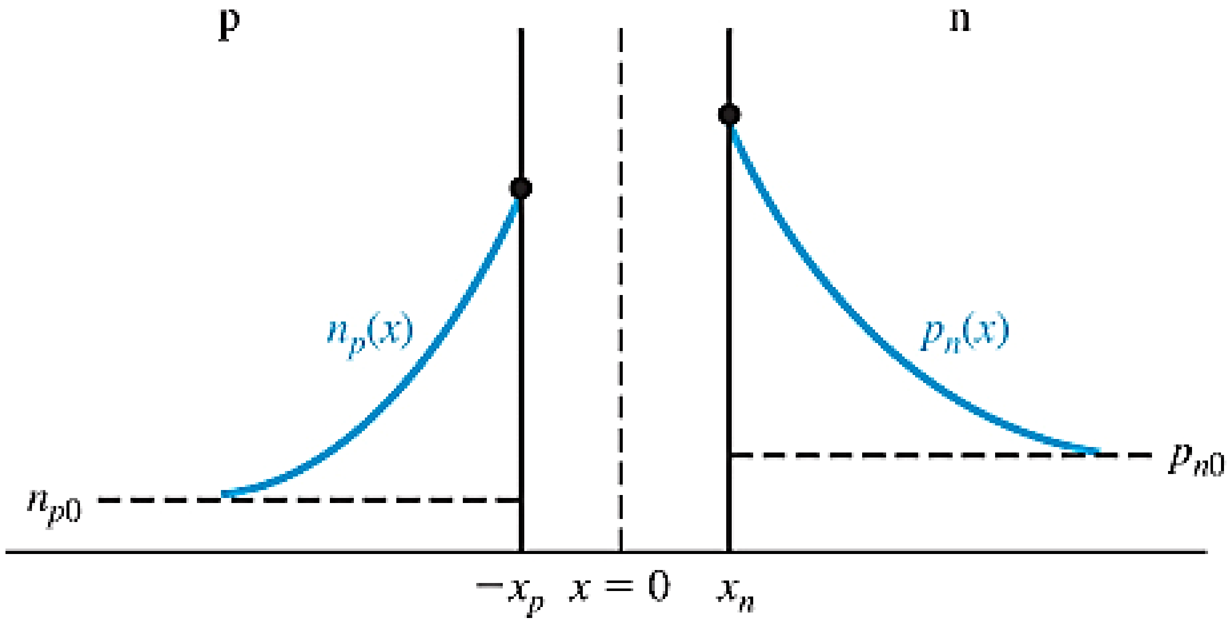
$$C = n_{p0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]e^{x_p/L_n}$$

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

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

Distribution of Minority Carrier

- A **forward-bias** voltage lowers the built-in potential barrier of a pn junction so that electrons from n-region are injected across the space charge region to create excess minority carriers in the p-region.
- These excess electrons diffuse into the bulk p-region, where they recombine with the majority holes. The excess minority carrier electron concentration decreases with distance from the junction.



Outline

- Ideal Current-Voltage Relationship
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- **Ideal pn Junction Current**
- Reverse-Bias Generation Current
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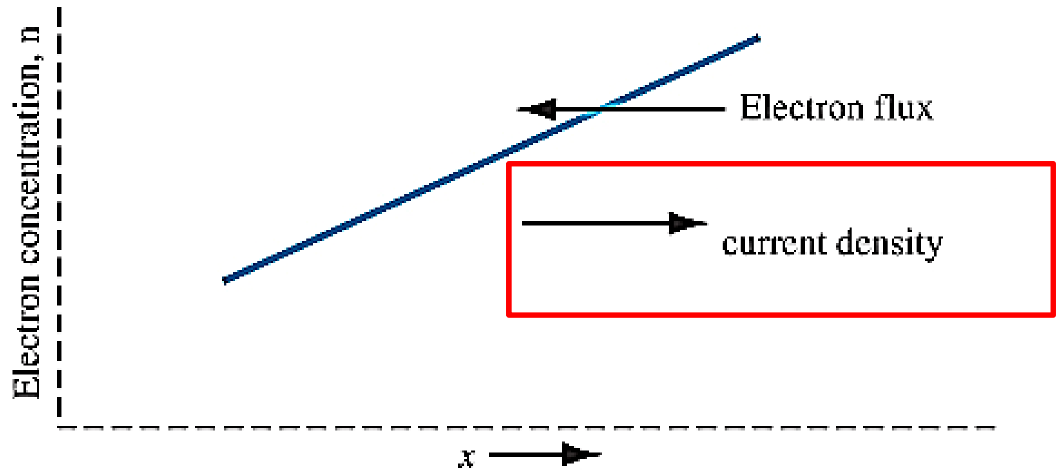
Diffusion Current Density

❖ For electrons:

\+   + direction

$$\boxed{J_{nx|dif} = eD_n \frac{dn}{dx}}$$

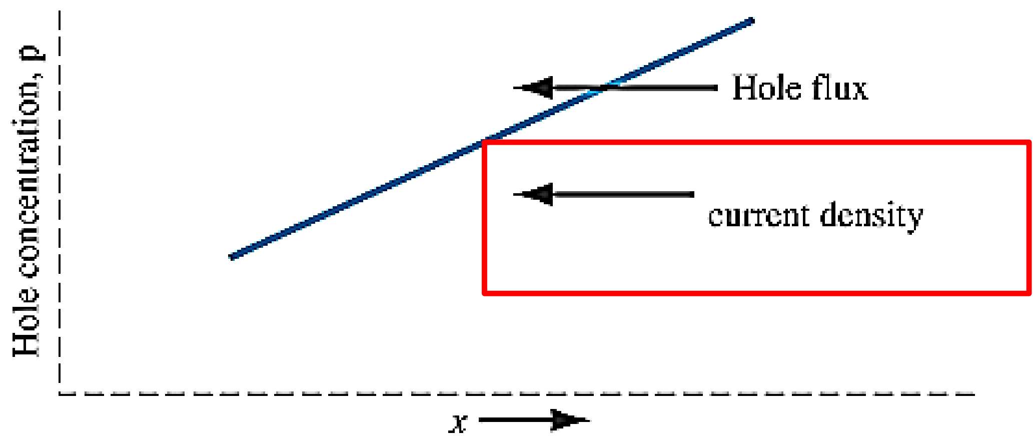


❖ For holes:

—   +

$$\boxed{J_{px|dif} = -eD_p \frac{dp}{dx}}$$

different direction



D is the diffusion coefficient (cm^2/s)

Total Current (Drift & Diffusion)

- Total Electron Current Due to Drift and Diffusion

$$J_e = en\mu_e \mathcal{E}_x + eD_e \frac{dn}{dx}$$

- Total Hole Current Due to Drift and Diffusion

$$J_h = ep\mu_h \mathcal{E}_x - eD_h \frac{dp}{dx}$$

- Total current density in 3D:

$$J = \underbrace{en\mu_n \mathrm{E} + ep\mu_p \mathrm{E}}_{\text{Drift}} + \underbrace{eD_n \nabla n - eD_p \nabla p}_{\text{Diffusion}}$$

Ideal Current-Voltage Relationship

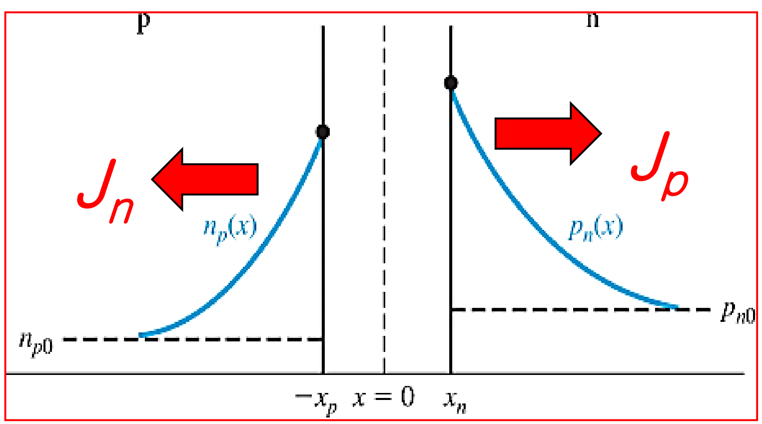
- The total current will be the sum of the electron and hole currents at any spatial location, including both drift and diffusion currents.
- The total current is a constant through the entire pn structure.

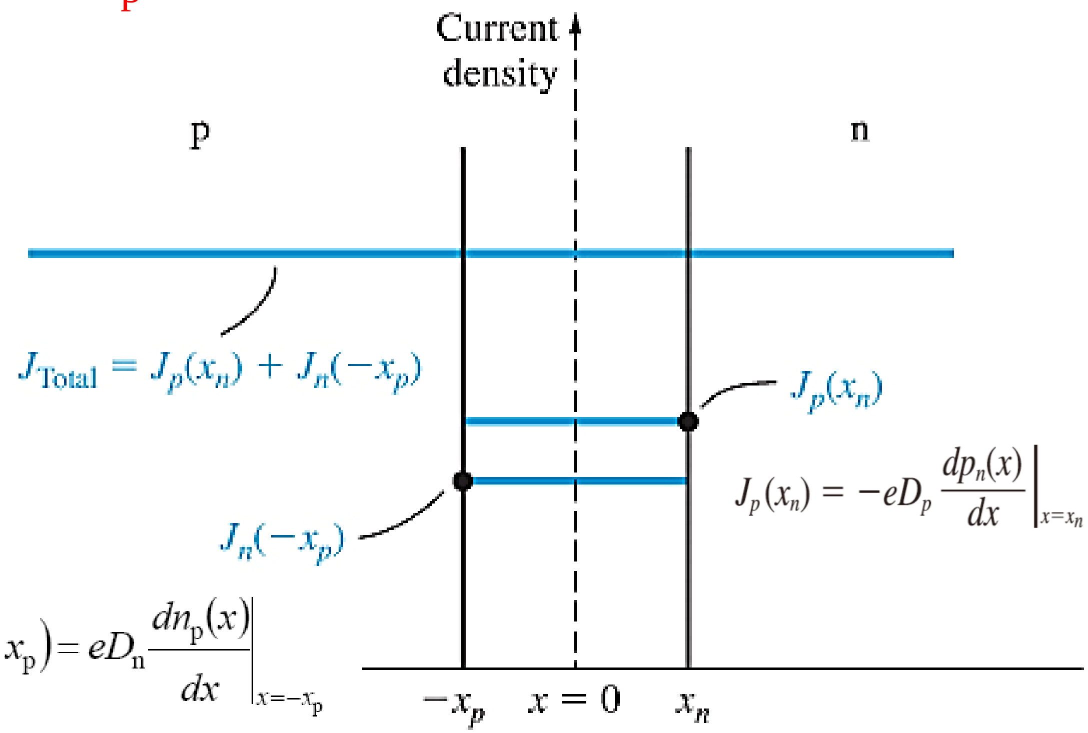
- The individual electron and hole currents are continuous functions through the pn structure
- The individual electron and hole currents are constant throughout the depletion region.

Ideal Current-Voltage Relationship

- Because the **<u>electric field (E) at the space charge edges is assumed zero</u>**, the hole drift current at $x=x_n$ and electron drift current at $x=-x_p$ is neglected.
- Because the electron and hole currents are **<u>constant throughout the depletion region</u>**, only hole diffusion current at $x=x_n$ and electron diffusion current at $x=-x_p$ need to be considered.

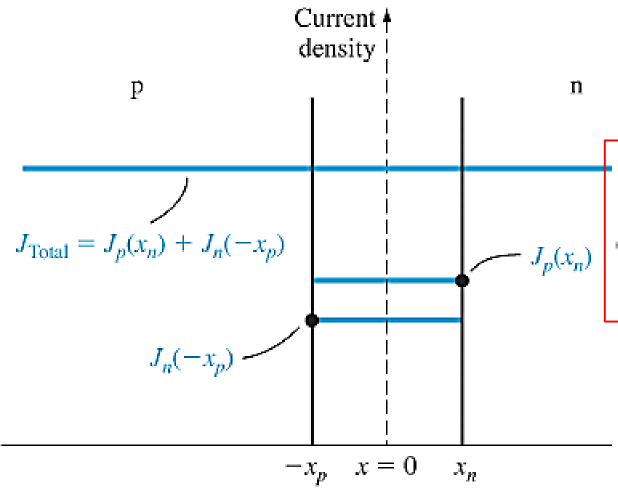
Excess minority carrier distribution under forward bias





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

Ideal Current-Voltage Relationship



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

$$\left.\frac{dp_n(x)}{dx}\right|_{x=x_n} = -\frac{1}{L_p} p_{n0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

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

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

$$\left.\frac{dn_p(x)}{dx}\right|_{x=-x_p} = \frac{1}{L_n} n_{p0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

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

Ideal Current-Voltage Relationship

❖ Total current density of *pn* junction diode:

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

$$\boxed{J_s = \left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}\right]} = \boxed{J_{so} = \left[\left(\frac{eD_h}{L_h N_d}\right) + \left(\frac{eD_e}{L_e N_a}\right)\right] n_i^2}$$

Ideal-diode equation

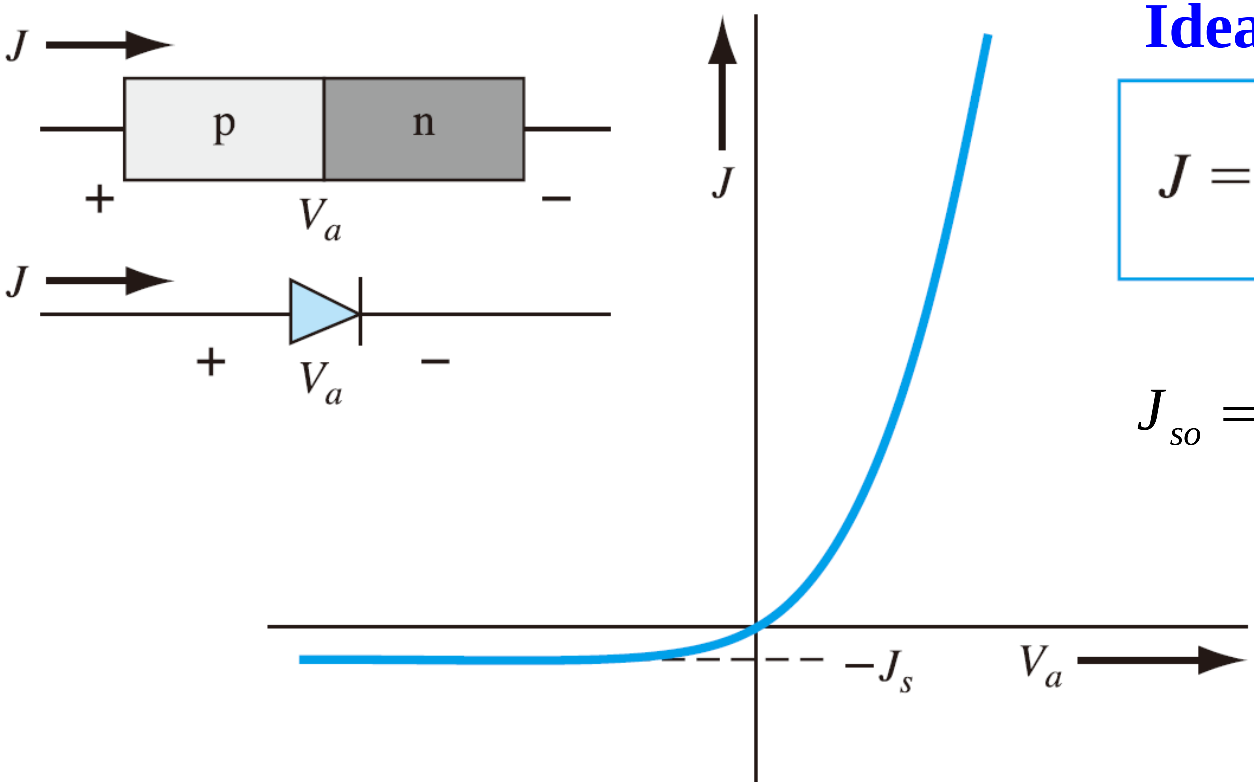
$$\boxed{J = \boxed{J_s}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]}$$

D_n: Diffusion coefficient of excess minority electron in p-type
L_n: Diffusion length of excess minority electron in p-type
τ_n : Lifetime of excess minority electron in p-type

$$L = \sqrt{D\,\tau}$$

Ideal Current-Voltage Relationship

- If V_a becomes negative by a few kT/e volts, then the reverse-bias current density becomes independent of the reverse-bias voltage. J_s is called the **reverse-saturation current density**.



Ideal diode equation:

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

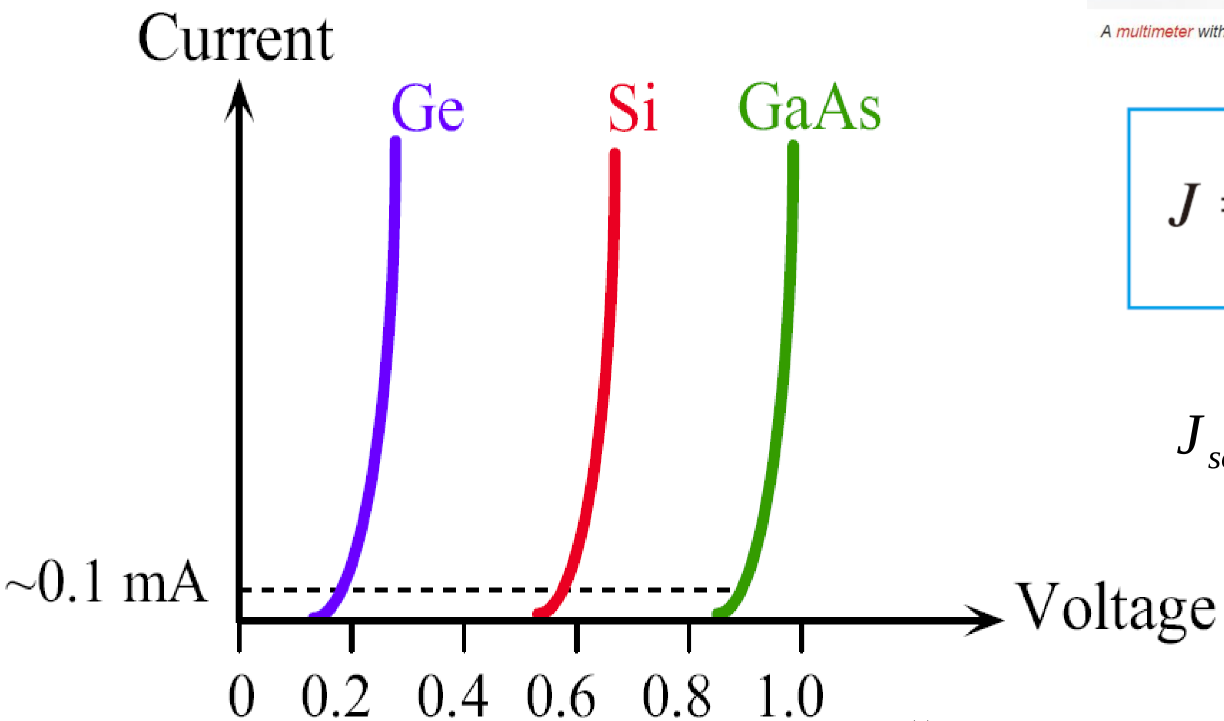
$$J_{so} = \left[\left(\frac{eD_h}{L_h N_d}\right) + \left(\frac{eD_e}{L_e N_a}\right)\right] n_i^2$$

Forward Bias: Diffusion Current

- I-V characteristics of Ge, Si, and GaAs pn junctions.

A multimeter with a diode setting can be used to measure (the minimum of) a diode's forward voltage drop.

Cut in Voltage



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

$$J_{so} = \left[\left(\frac{eD_h}{L_h N_d}\right) + \left(\frac{eD_e}{L_e N_a}\right)\right] n_i^2$$

$$\boxed{n_i^2 = N_c N_v \exp\left[\frac{-E_g}{kT}\right]}$$

https://learn.sparkfun.com/tutorials/diodes/real-diode-characteristics

Example

- Determine the idea reverse-saturation current density in a Si pn junction at T=300K.

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

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

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

$$J_s = \frac{eD_n n_{p0}}{L_n} + \frac{eD_p p_{n0}}{L_p} \qquad J_s = en_i^2\left(\frac{1}{N_a}\sqrt{\frac{D_n}{\tau_{n0}}} + \frac{1}{N_d}\sqrt{\frac{D_p}{\tau_{p0}}}\right)$$

$$J_s = (1.6 \times 10^{-19})(1.5 \times 10^{10})^2\left(\frac{1}{10^{16}}\sqrt{\frac{25}{5 \times 10^{-7}}} + \frac{1}{10^{16}}\sqrt{\frac{10}{5 \times 10^{-7}}}\right)$$

$$J_s = 4.16 \times 10^{-11}\ \text{A/cm}^2$$

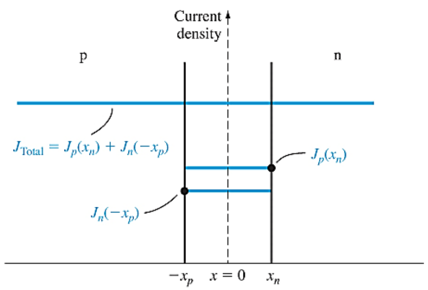
The ideal reverse-bias saturation current density is quite small.

Example

Example: consider a silicon pn junction at $T = 300$ K that is forward biased at $V_a = 0.60$ V. Consider the p-region to be doped to $N_a = 3 \times 10^{15}$ cm^{-3} and assume the following parameters for the minority carrier electrons: $D_n = 25$ cm^2/s, $\tau_{n0} = 10^{-7}$ s. Determine the electron diffusion current density at the edge of the space charge region.

$$J_n(-x_p) = \frac{eD_n n_{p0}}{L_n}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] = e\sqrt{\frac{D_n}{\tau_{n0}}}\frac{n_i^2}{N_a}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

$$J_n(-x_p) = (1.6\times 10^{-19})\sqrt{\frac{25}{10^{-7}}}\frac{(1.5\times 10^{10})^2}{3\times 10^{15}}\left[\exp\left(\frac{0.60}{0.0259}\right) - 1\right] = 2.18\text{A/cm}^2$$



Example

- Determine the N_a and N_d in a Si pn junction at T=300K such that J_n=20 A/cm^2 and J_p=5 A/cm^2 at V_a=0.65V.

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

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

$$J_n = \frac{eD_n n_{p0}}{L_n}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] = e\sqrt{\frac{D_n}{\tau_{n0}}} \cdot \frac{n_i^2}{N_a}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

$$20 = (1.6 \times 10^{-19})\sqrt{\frac{25}{5 \times 10^{-7}}} \cdot \frac{(1.5 \times 10^{10})^2}{N_a}\left[\exp\left(\frac{0.65}{0.0259}\right) - 1\right]$$

$$\boxed{N_a = 1.01 \times 10^{15} \text{ cm}^{-3}}$$

$$J_p = \frac{eD_p p_{n0}}{L_p}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] = e\sqrt{\frac{D_p}{\tau_{p0}}} \cdot \frac{n_i^2}{N_d}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

$$5 = (1.6 \times 10^{-19})\sqrt{\frac{10}{5 \times 10^{-7}}} \cdot \frac{(1.5 \times 10^{10})^2}{N_d}\left[\exp\left(\frac{0.65}{0.0259}\right) - 1\right]$$

$$\boxed{N_d = 2.55 \times 10^{15} \text{ cm}^{-3}}$$

Ideal Current/Voltage Relationship

For $x > x_n$:

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

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

For $x < -x_p$:

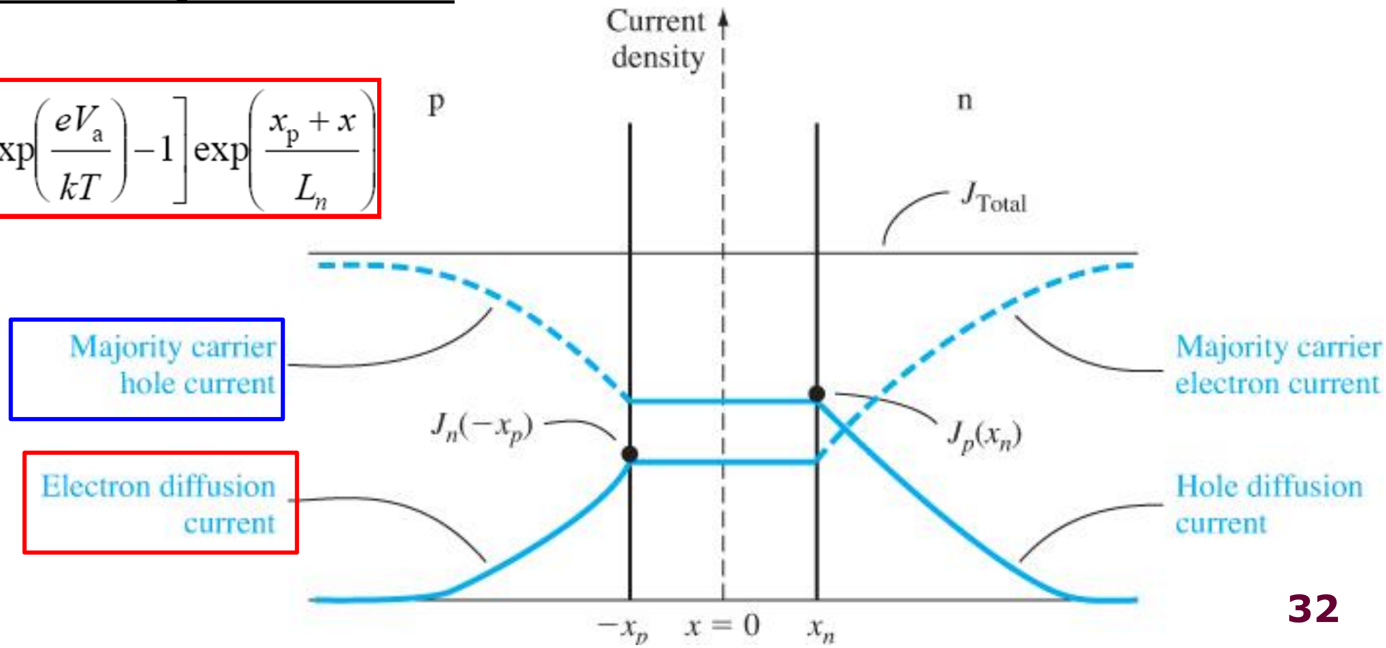
$$\delta n_p(x) = n_p(x) - n_{p0} = n_{p0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\exp\left(\frac{x_p + x}{L_n}\right)$$

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

Ideal Current/Voltage Relationship

- The minority carrier diffusion current density decreases with distance away from the junction. Since the total current density is constant, the majority carrier current density must increase.
- The drift of the majority hole in p-type towards the junction is to supply the carriers that are being injected across the space charge region and also to supply the carriers that are lost by recombination with the excess minority electrons.

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



Example

❖ Consider a silicon pn junction at T = 300 K with the following parameters and an applied forward-bias voltage V_a = 0.65 V: Calculate the electric field in a neutral region to produce a given majority carrier drift current density

$N_a = N_d = 10^{16}$ cm^{-3}, $n_i = 1.5 \times 10^{10}$ cm^{-3},
$D_n = 25$ cm^2/s, $\tau_{p0} = \tau_{n0} = 5 \times 10^{-7}$ s,
$D_p = 10$ cm^2/s, $\varepsilon_r = 11.7$, $\mu_n = 1350$ cm^2/(V·s).

$$J_s = e n_i^2 \left[\frac{1}{N_a}\sqrt{\frac{D_n}{\tau_{n0}}} + \frac{1}{N_d}\sqrt{\frac{D_p}{\tau_{p0}}} \right] = 4.16 \times 10^{-11}\,\text{A/cm}^2$$

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

$$J = \left(4.16 \times 10^{-11}\right)\left[\exp\left(\frac{0.65}{0.0259}\right) - 1\right] = 3.30\,\text{A/cm}^2$$

$$J_n \cong e\mu_n N_d E$$

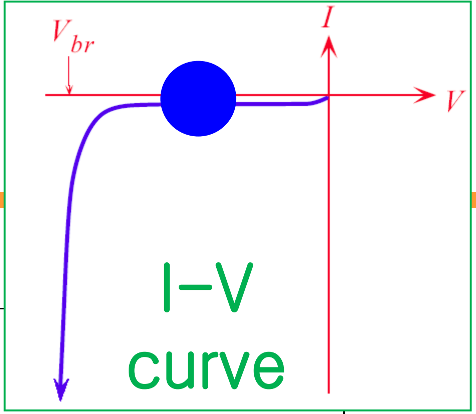
$$E = \frac{J_n}{e\mu_n N_d} = \frac{3.30}{\left(1.6 \times 10^{-19}\right)(1350)\left(10^{16}\right)} = 1.53\,\text{V/cm}$$

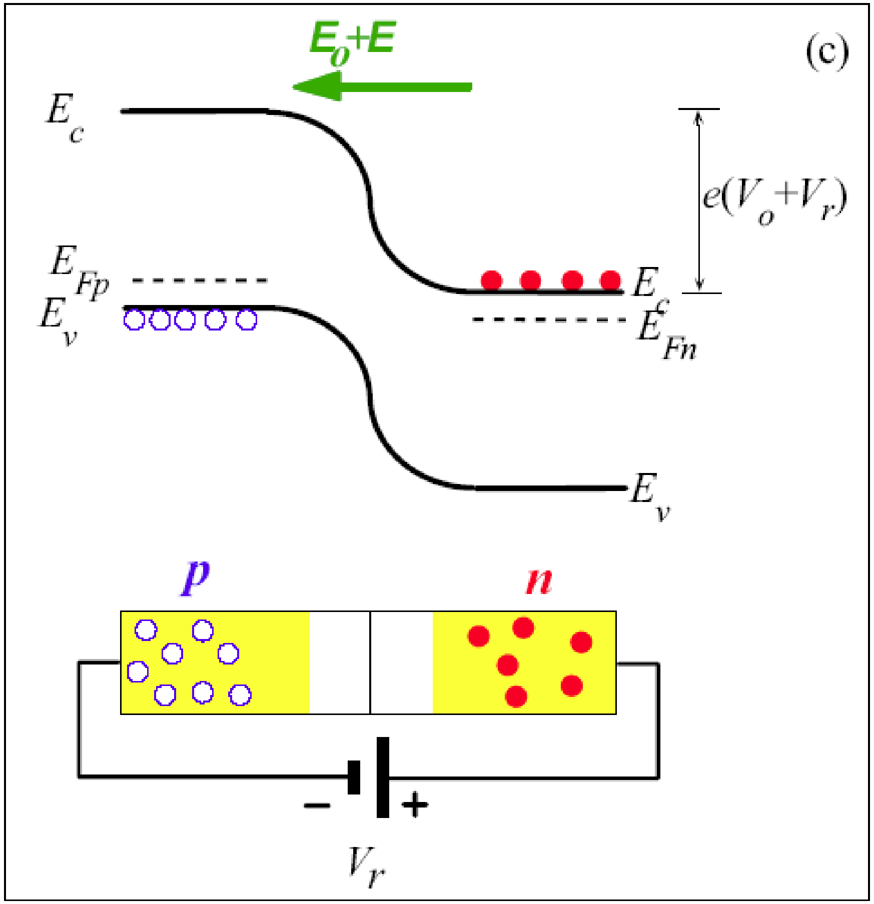
The electric field in the neutral region is very small. Therefore the approximation of zero electric field in the bulk p- and n-regions is very good.

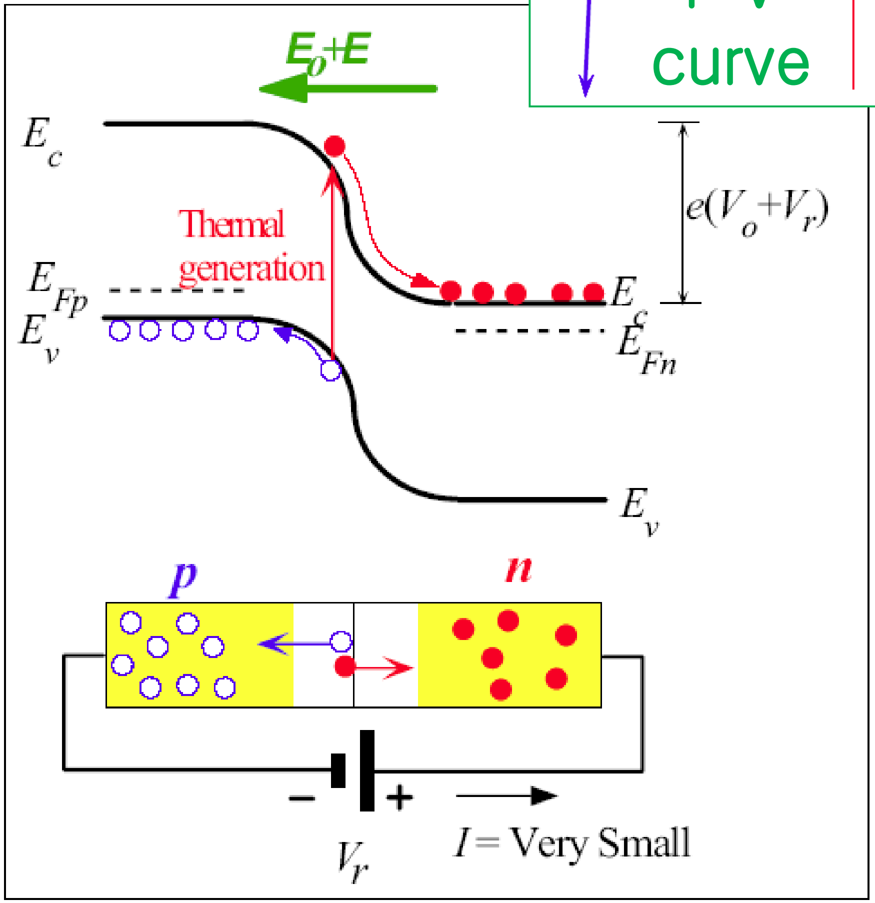
Outline

- Ideal Current-Voltage Relationship
- Minority Carrier Distribution
- Ideal pn Junction Current
- **Reverse-Bias Generation Current**
- Forward-Bias Recombination Current

Reverse-Bias Generation Current





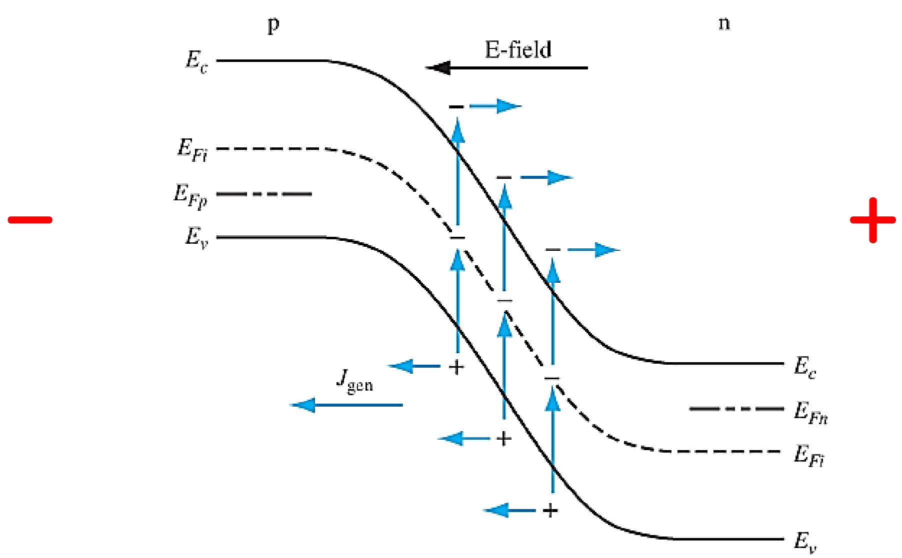


(c) Reverse bias conditions.

(d) Thermal generation of electron hole pairs in the depletion region results in a small reverse current, J_{gen}

Reverse-Bias Generation Current

- The flow of charge is in the direction of a reverse-bias current. This **reverse bias generation current** is additional to the **ideal reverse-bias saturation current**
- J_s is independent of the reverse bias voltage. J_{gen} depends on the depletion width and thus is a function of the reverse-bias voltage.



$$\boxed{J_{gen} = \frac{e n_i W}{2\tau_0}}$$

$$J_R = J_s + J_{gen}$$

Example-1/2

❖ Consider a silicon pn junction under reverse bias at T = 300 K with the following parameters: $N_a = N_d = 10^{16}$ cm^{-3}, n_i = 1.5x10^{10} cm^{-3}, D_n=25 cm^2/sec, D_p=10 cm^2/sec, $\tau_0 = \tau_{p0} = \tau_{n0}$ = 5 x10^{-7} sec, ε_r = 11.7, $V_{bi} + V_R$ = 5V. Determine the ideal reverse saturation current density and the generation current density.

$$\boxed{J_{so} = \left[\left(\frac{eD_h}{L_h N_d}\right) + \left(\frac{eD_e}{L_e N_a}\right)\right] n_i^2}$$

$$J_s = e n_i^2 \left[\frac{1}{N_a} \sqrt{\frac{D_n}{\tau_{n0}}} + \frac{1}{N_d} \sqrt{\frac{D_p}{\tau_{p0}}} \right] = 4.16 \times 10^{-11} \text{A/cm}^2$$

$$V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right) = (0.0259) \ln\left[\frac{(10^{16})(10^{16})}{(1.5 \times 10^{10})^2}\right] = 0.695 \text{ V}$$

Example-2/2

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

$$= \left\{ \frac{2(11.7)(8.85 \times 10^{-14})(0.695 + 5)}{1.6 \times 10^{-19}} \left[\frac{10^{16} + 10^{16}}{(10^{16})(10^{16})} \right] \right\}^{1/2}$$

$$= 1.214 \times 10^{-4} \text{ cm}$$

$$J_{\text{gen}} = \frac{e n_i W}{2\tau_0} = \frac{(1.6 \times 10^{-19})(1.5 \times 10^{10})(1.214 \times 10^{-4})}{2(5 \times 10^{-7})}$$

$$J_{\text{gen}} = 2.914 \times 10^{-7} \text{ A/cm}^2$$

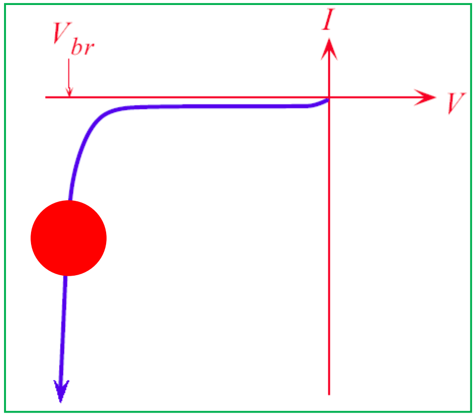
$$\frac{J_{\text{gen}}}{J_s} = \frac{2.914 \times 10^{-7}}{4.155 \times 10^{-11}} \cong 7 \times 10^3$$

The generation current density is the dominant reverse-biased current in a Si pn junction diode.

Junction Breakdown

- The reverse-bias voltage applied on pn junctions cannot increase without limit. Up to a certain threshold, the reverse-bias current will increase rapidly.
- The applied voltage at this point is called the **breakdown voltage**.
- There are two mechanisms causing the reverse-bias breakdown in a pn junction:
  1. Zener Breakdown
  2. Avalanche Breakdown

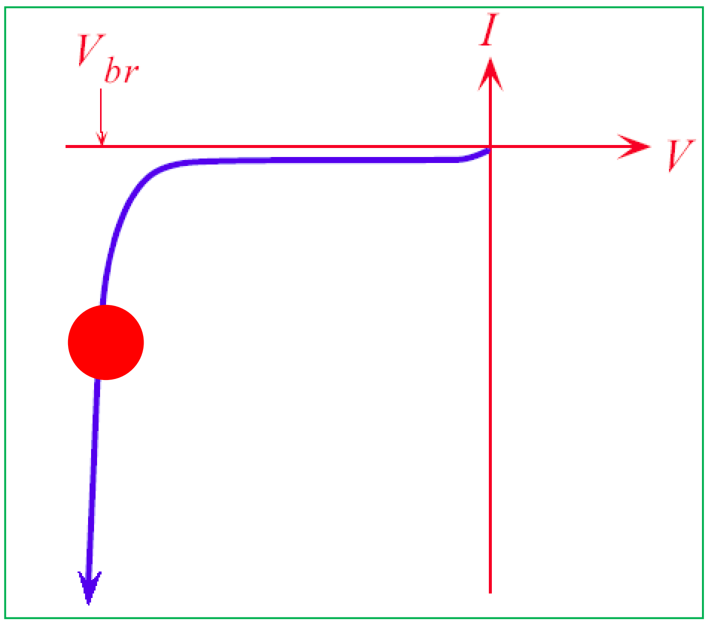
I–V curve

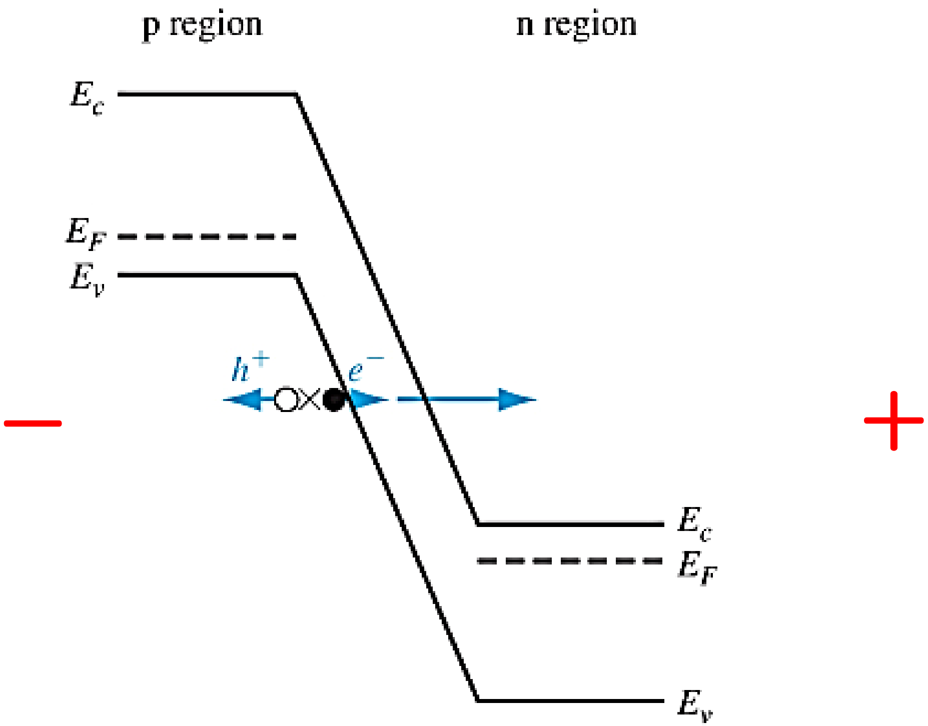


1. Zener Breakdown

- In highly doped pn junctions through a **tunneling** mechanism. The conduction and valence bands on the opposite sides of highly doped pn junctions are very close under reverse bias so that electrons may tunnel directly from the VB on the p-side into the CB on the n-side.

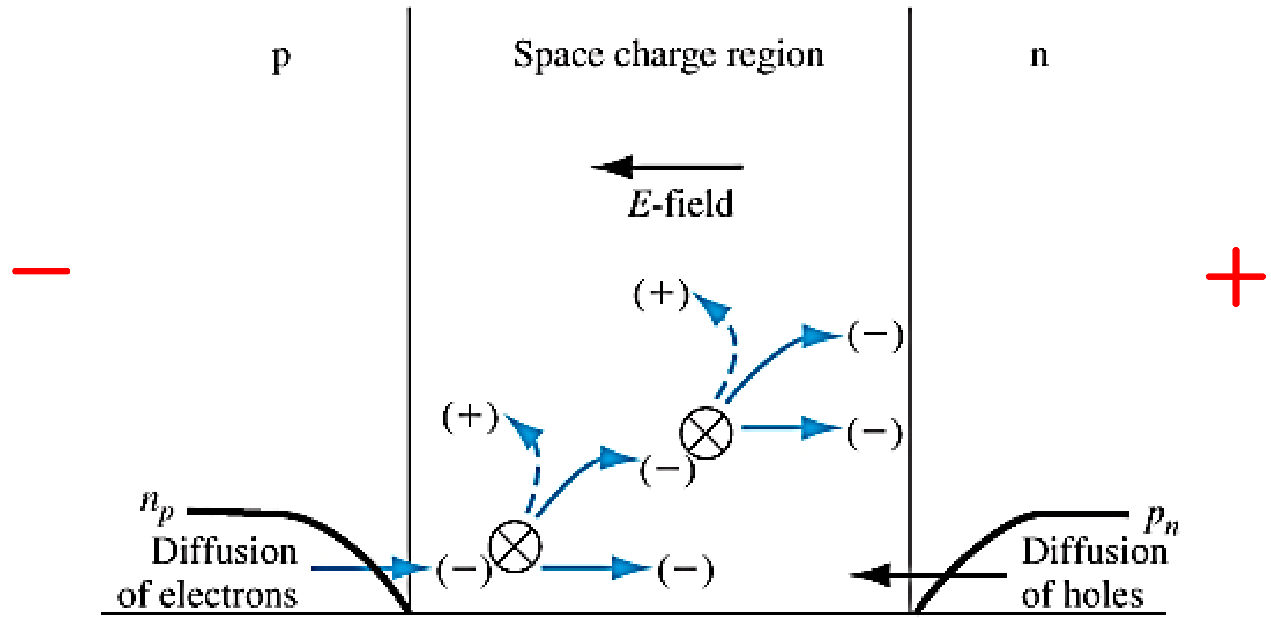
I–V curve





2. Avalanche Breakdown

- Electrons/holes moving through the space charge region acquire sufficient energy from the electric field (V_R) to **create electron–hole pairs by colliding with atoms**. The newly created electrons/holes move in opposite directions due to the electric field and thus contribute to the **reverse-bias current**. In addition, the newly generated electrons/holes may acquire sufficient energy to ionize other atoms, leading to the avalanche process.

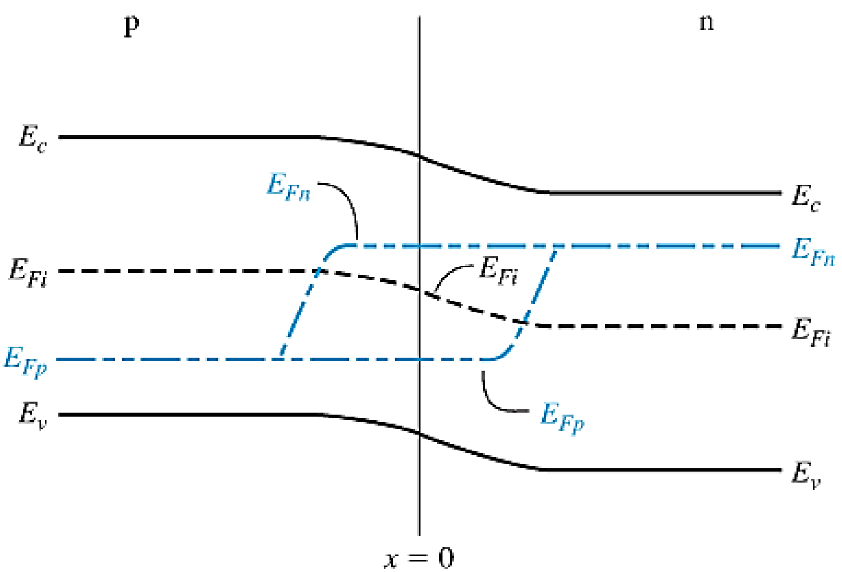


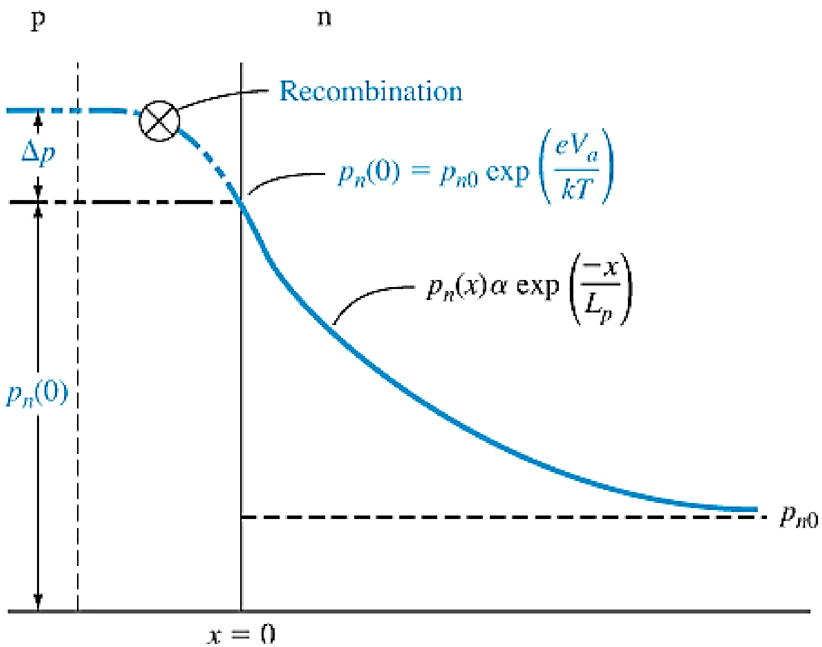
Outline

- Ideal Current-Voltage Relationship
- Minority Carrier Distribution
- Ideal pn Junction Current
- Reverse-Bias Generation Current
- **Forward-Bias Recombination Current**

Forward-Bias Recombination Current

❖ Under forward bias, it is possible that some injected electrons and holes will recombine within the space charge region and not become part of the minority carrier distribution.





$$(E_{Fn} - E_{Fi}) + (E_{Fi} - E_{Fp}) = eV_a$$

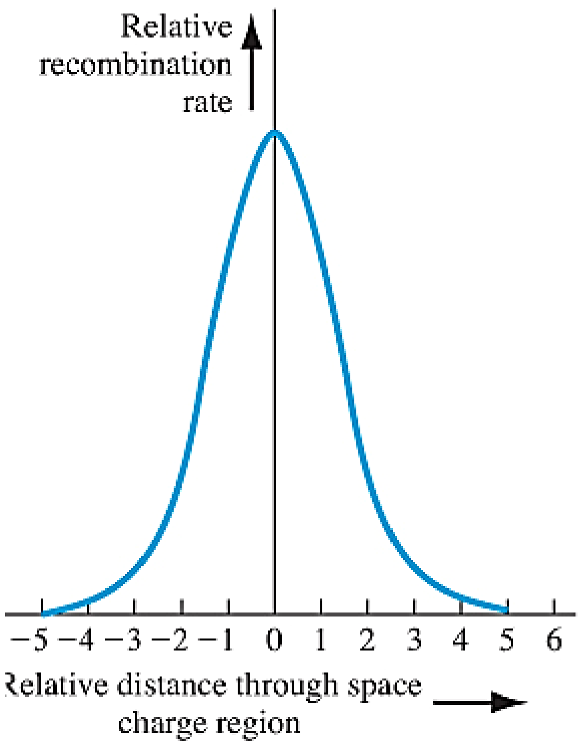
Forward-Bias Recombination Current

- The maximum recombination rate occurs at the metallurgical junction since

$$E_{Fn} - E_{Fi} = E_{Fi} - E_{Fp} = \frac{eV_a}{2}$$

- The max recombination rate is:

$$R_{\max} = \frac{n_i}{2\tau_0} \exp\left(\frac{eV_a}{2kT}\right)$$



- The recombination current density is:

$$J_{\text{rec}} = \int_0^W eR\, dx$$

$$\boxed{J_{\text{rec}} = \frac{eWn_i}{2\tau_0} \exp\left(\frac{eV_a}{2kT}\right) = J_{r0} \exp\left(\frac{eV_a}{2kT}\right)}$$

Forward-Bias Recombination Current

❖ The total forward-bias current density is the sum of the recombination and the ideal diffusion current densities:

$$J = J_{\text{rec}} + J_{\text{D}} = J_{\text{r0}} \exp\left(\frac{eV_{\text{a}}}{2kT}\right) + J_{\text{s}} \exp\left(\frac{eV_{\text{a}}}{kT}\right)$$

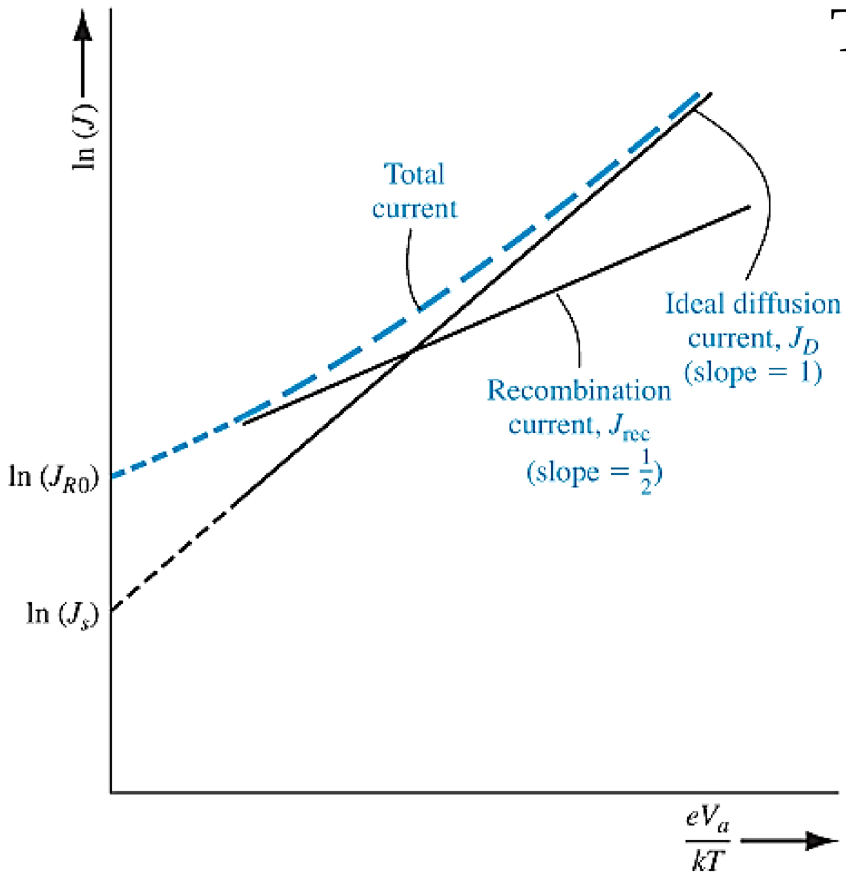
❖ In general, the diode current-voltage relationship can be described as:

$$\boxed{I = I_s\left[\exp\left(\frac{eV_a}{nkT}\right) - 1\right]}$$

❖ n is ideality factor

Forward-Bias Recombination Current

❖ At a low current density, the recombination current dominates, and at a high current density, the diffusion current dominates.



Take the log of both current densities:

$$\ln J_{\rm rec} = \ln J_{r0} + \frac{eV_a}{2kT} = \ln J_{r0} + \frac{V_a}{2V_t}$$

$$\ln J_D = \ln J_s + \frac{eV_a}{kT} = \ln J_s + \frac{V_a}{V_t}$$

$$\boxed{I = I_s\left[\exp\left(\frac{eV_a}{nkT}\right) - 1\right]}$$

n = 1: diffusion dominates

n = 2: recombination dominates

References

- Principles of Electronic Materials and Devices, Third Edition, S. O. Kasap, McGraw-Hill, 2006
- D. A. Neamen, “Semiconductor Physics and Devices: Basic Principles”, Fourth Edition, McGraw-Hill, 2011
- Source form Department of Microelectronics and Computer Engineering, TU Delft.
- Source form http://www.phy.cuhk.edu.hk/~jfwang/PDF/Chapter%205%20pn%20junction%20I.pdf