Semiconductor Devices

Chapter 8
The pn Junction Diode

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Ideal PN Junction Diode Analysis: Assumption

1. Non-degenerately doped step junction, depletion approximation, neutral other than depletion region
2. Boltzmann approximation
3. Low-level injection condition
4. Total current is constant within PN junction diode.
   Electron and Hole current are continuous.
   Recombination and Generation are negligible in depletion region.
   Steady-state condition

<u>Continuity Equation</u>

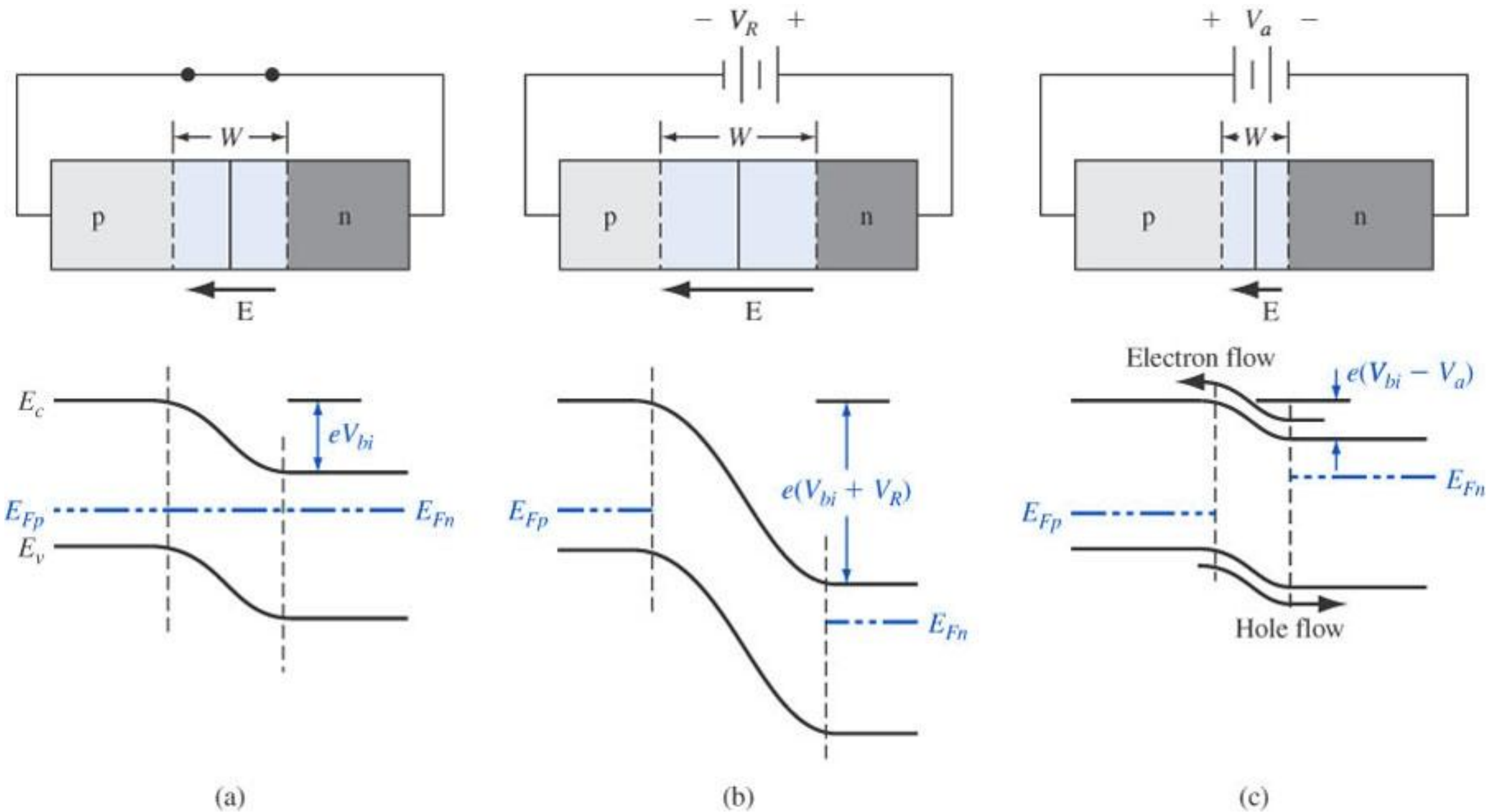
$$\frac{\partial p(t,x)}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} + g_p{}' - R_p{}' \qquad R_p{}' = \frac{\delta p}{\tau_p}$$

$$\frac{\partial n(t,x)}{\partial t} = +\frac{1}{q}\frac{\partial J_n}{\partial x} + g_n{}' - R_n{}' \qquad R_n{}' = \frac{\delta n}{\tau_n}$$

$$J_p(t,x) = qp(t,x)\mu_p E(x) - qD_p\frac{\partial p(t,x)}{\partial x}$$

$$J_n(t,x) = qn(t,x)\mu_n E(x) + qD_n\frac{\partial n(t,x)}{\partial x}$$

PN Junction and Energy Band Diagram under Voltage Bias



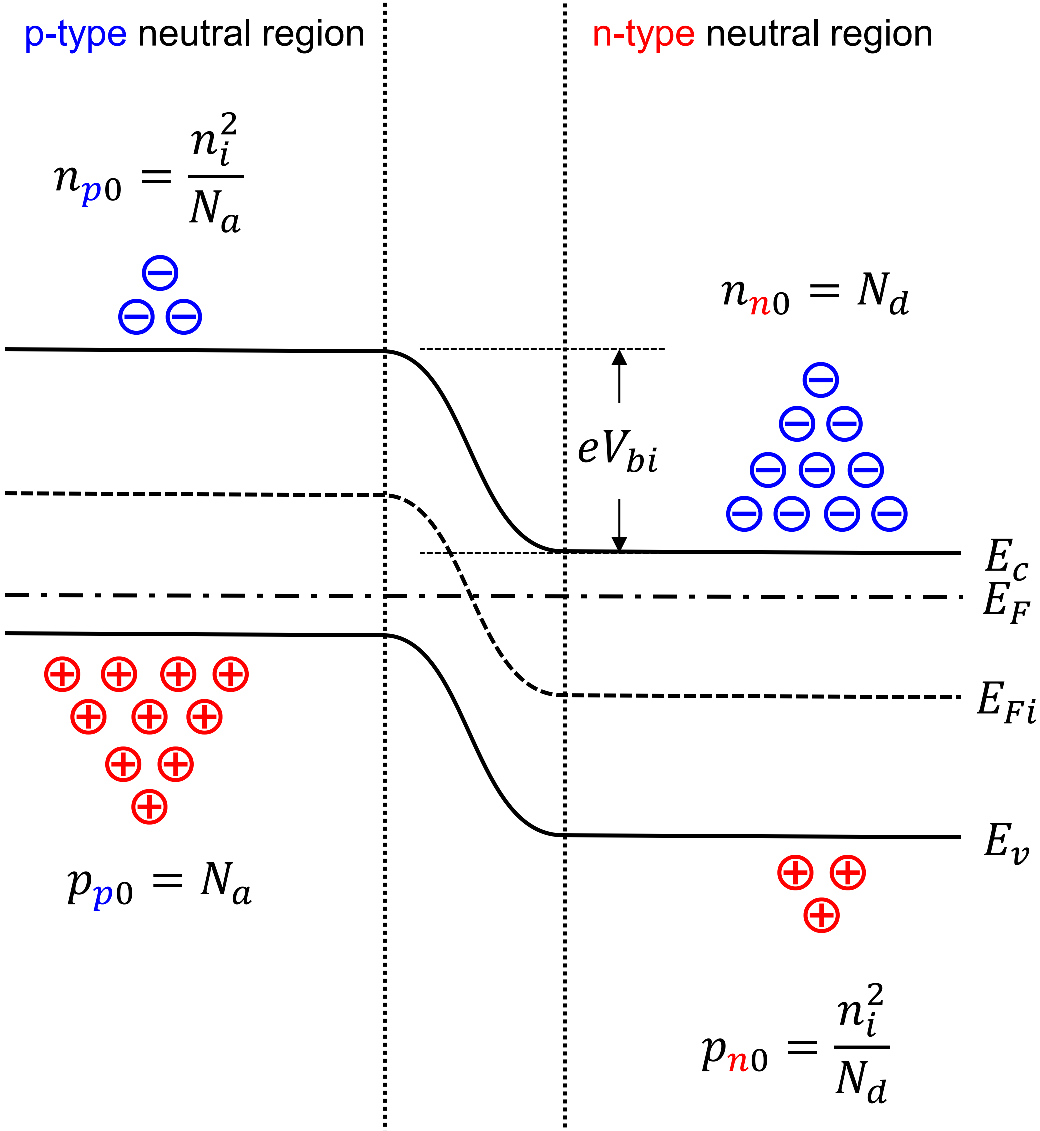
Terms and Notation for PN Junction

Table 8.1 | Commonly used terms and notation for this chapter

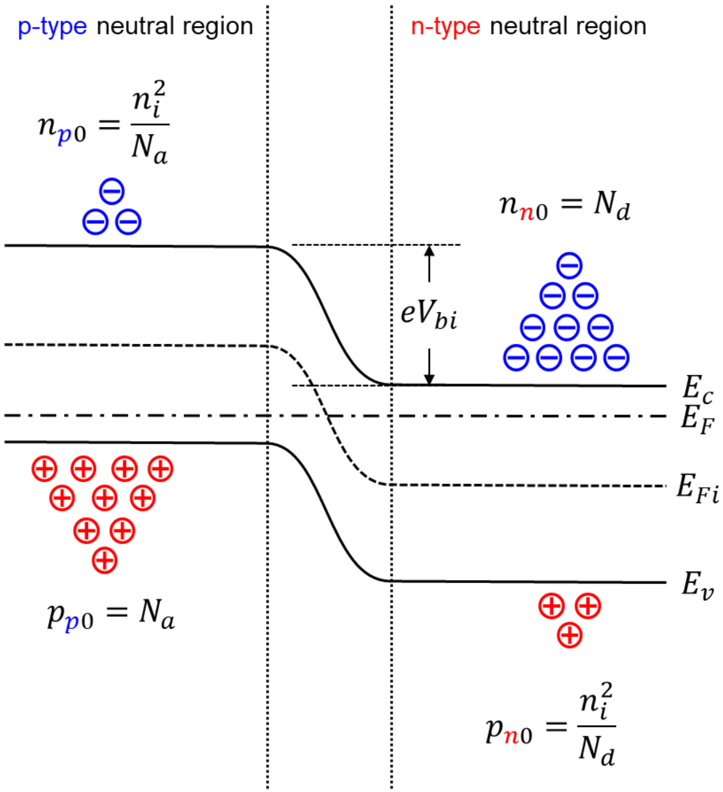
Term	Meaning
N_a	Acceptor concentration in the p region of the pn junction
N_d	Donor concentration in the n region of the pn junction
$n_{n0} = N_d$	Thermal equilibrium majority carrier electron concentration in the n region
$p_{p0} = N_a$	Thermal equilibrium majority carrier hole concentration in the 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

Terms and Notation for PN Junction under Thermal Equilibrium (Zero Bias)

- Assume steady state



Zero Bias (Steady State)



Built-in potential barrier

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

⇩

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

⇩

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

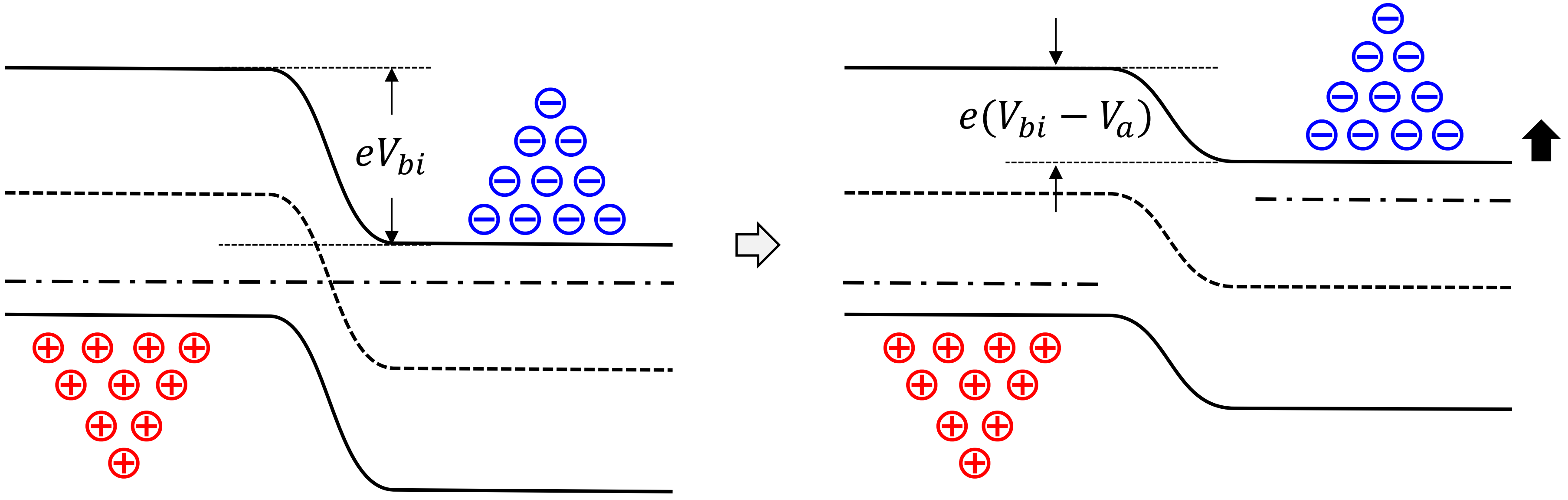
⇩

$$n_{p0} = \frac{n_i^2}{N_a} \qquad n_{n0} = N_d$$

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

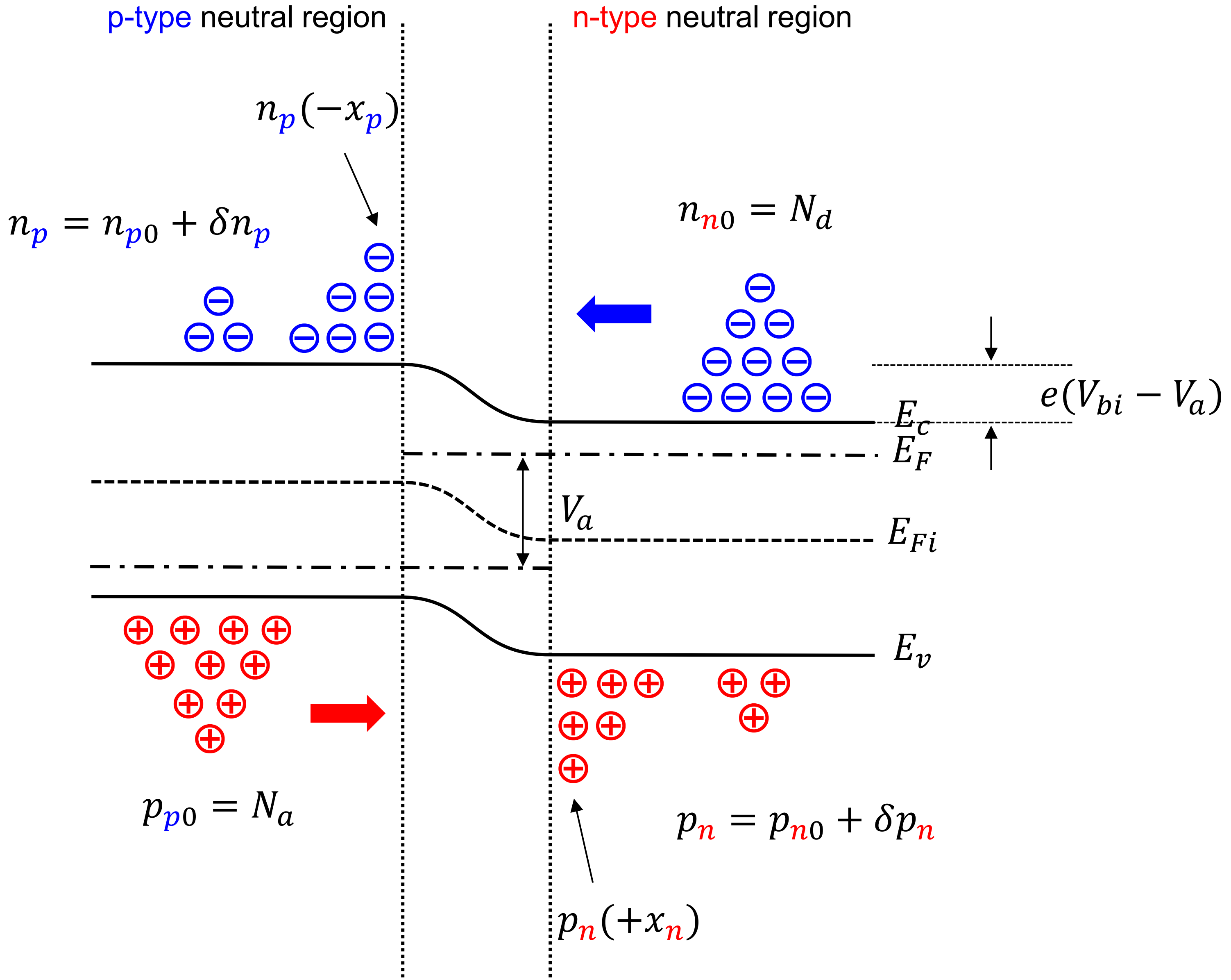
$$p_{n0} = p_{p0} \exp\left(-\frac{eV_{bi}}{kT}\right) = N_a \exp\left(-\frac{eV_{bi}}{kT}\right)$$

Zero Bias and Forward Bias (Steady State)

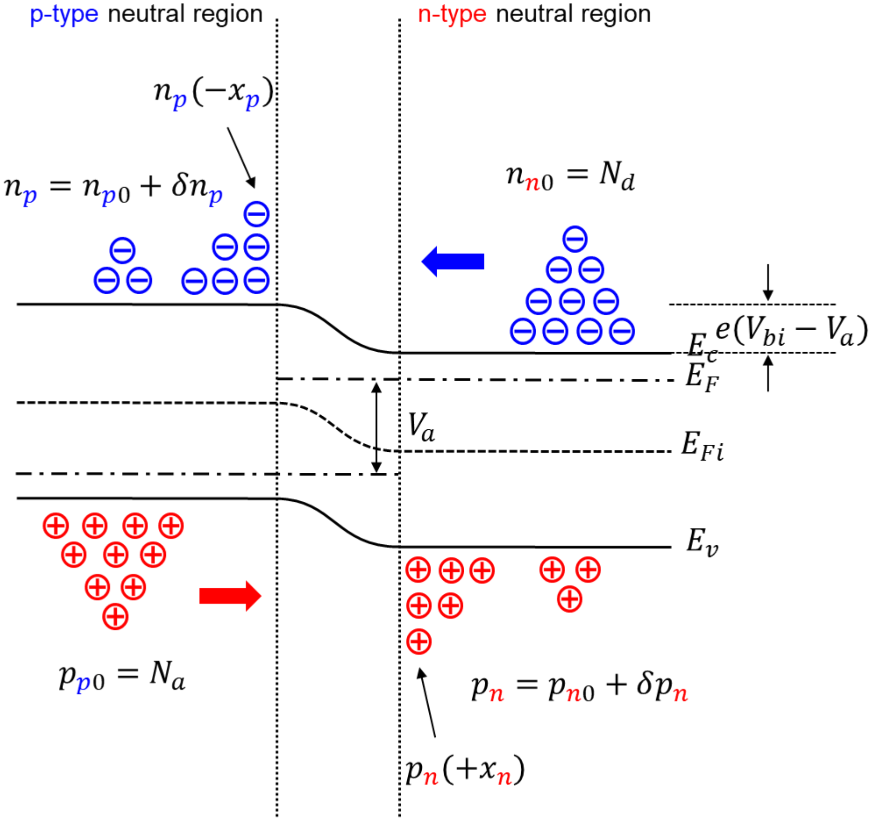


Terms and Notation for PN Junction under Forward Bias

- Assume steady state



Forward Bias (Steady State)



For thermal equilibrium

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

Under application of **Forward** bias

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

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

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

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

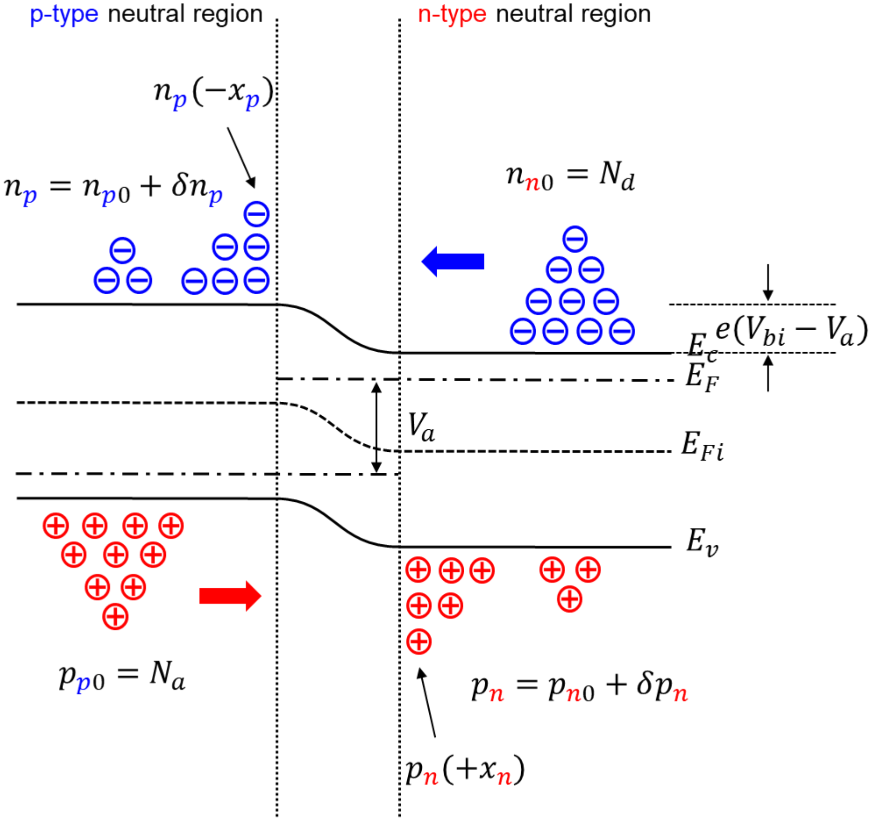
$$p_n = p_{n0} \exp\left(\frac{eV_a}{kT}\right)$$

⇨

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

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

Forward Bias (Steady State)



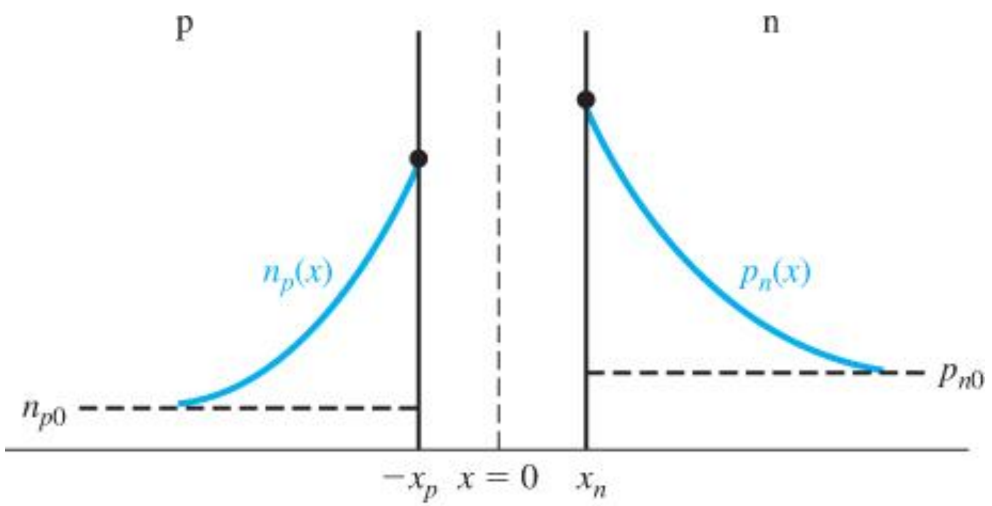


Figure 8.5 | Steady-state minority carrier concentrations in a pn junction under forward bias.

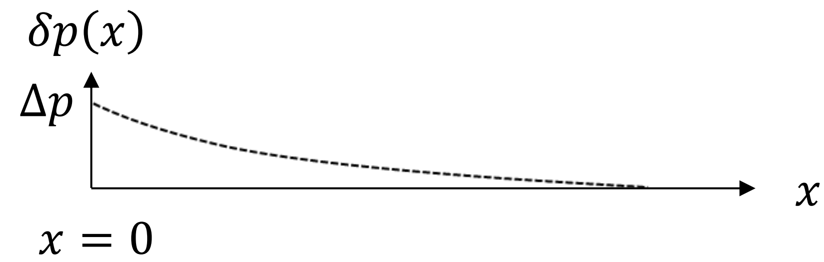
$$n_p = n_{p0} \exp\left(\frac{eV_a}{kT}\right) \qquad \Rightarrow \qquad n_p(-x_p) = n_{p0} \exp\left(\frac{eV_a}{kT}\right)$$

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

Ambipolar Transport (Example)

Additional assumptions

- No excess carrier generation
- No external (applied) E-field
- Steady-state condition



<u>For n-type</u>

$$\frac{d^2 \delta N(x)}{dx^2} = \frac{\delta N(x)}{D_p \tau} \qquad L_p = \sqrt{D_p \tau_p} \quad \Rightarrow \quad \delta p(x) = A e^{+\frac{x}{L}} + B e^{-\frac{x}{L}}$$

<u>Boundary condition</u>

$$x \to \infty, \qquad \delta p(x) \to 0 \quad \Rightarrow \quad A = 0$$

$$x = 0, \qquad \delta p(0) = \Delta p \quad \Rightarrow \quad B = \Delta p$$

$\Rightarrow$

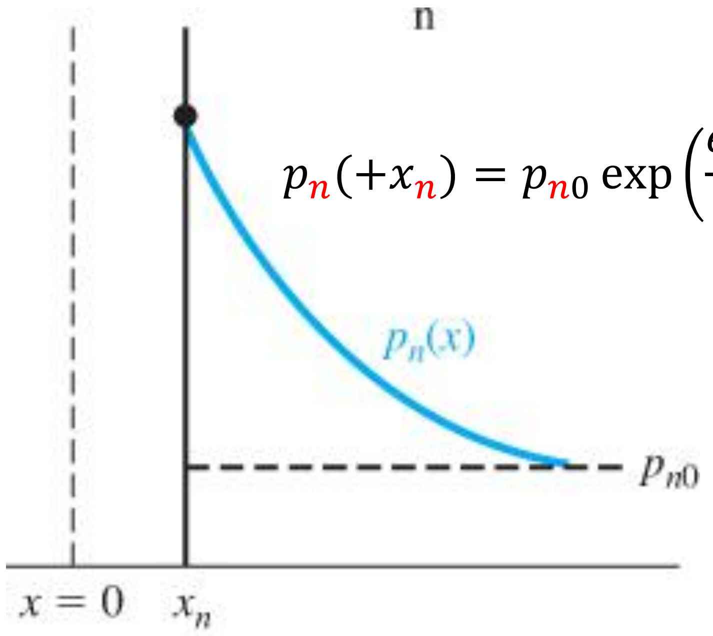
<u>Excess carrier concentration</u>

$$\delta p(x) = \Delta p e^{-\frac{x}{L_p}}$$

<u>Current density</u>

$$J_p(x) = J_{p|diff} = -qD_p \frac{dp(x)}{dx} = -qD_p \frac{d\delta p(x)}{dx} = \frac{qD_p \Delta p}{L_p} e^{-\frac{x}{L_p}} = q \frac{D_p}{L_p} \delta p(x)$$

Forward Bias (Steady State) for n-type Region



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

<u>Boundary conditions</u>

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

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

$$= p_{n0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

$x \to \infty$ ⇨ $p_n(x \to \infty) = p_{n0}$

$$\delta p_n(x \to \infty) = 0$$

$(x \geq +x_n)$

$(x \to x - x_n)$

$$\delta p_n(x) = A \exp\left(+\frac{x}{L_p}\right) + B \exp\left(-\frac{x}{L_p}\right) \Rightarrow \delta p_n(x) = A \exp\left(+\frac{x - x_n}{L_p}\right) + B \exp\left(-\frac{x - x_n}{L_p}\right)$$

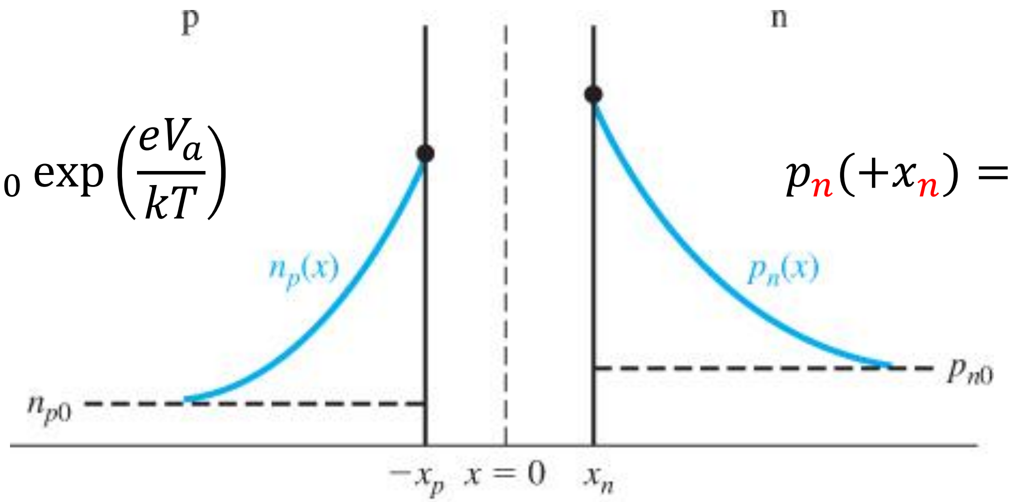
$x \to \infty$ ⇨ $\delta p_n(x \to \infty) = 0, \qquad A = 0$

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

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

Forward Bias (Steady State)

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



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

For n-type region

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

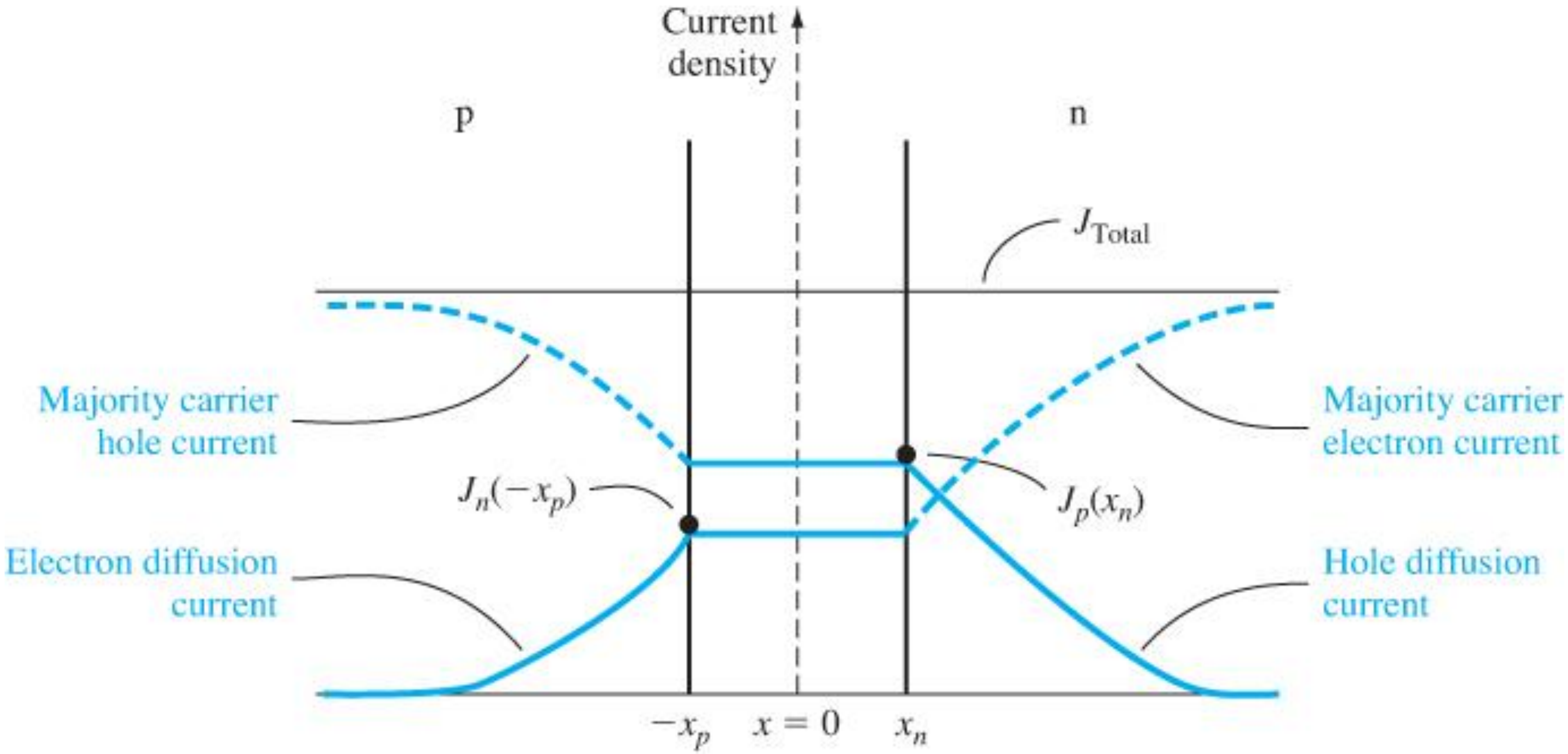
$$= p_{n0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\exp\left(\frac{x_n - x}{L_p}\right) \qquad (x \geq +x_n)$$

For p-type region

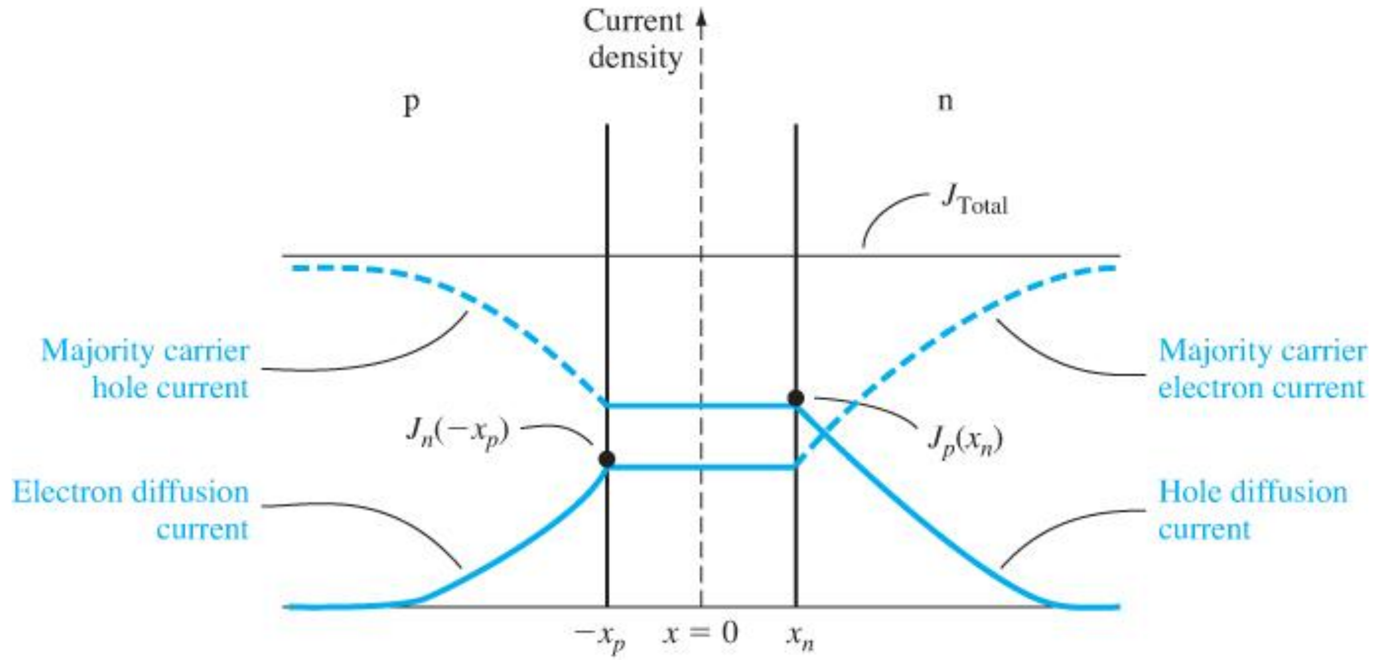
$$\delta n_p(x) = n_{p0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\exp\left(-\frac{-(x + x_p)}{L_n}\right)$$

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

Ideal PN Junction Current under Forward Bias



Ideal PN Junction Current under Forward Bias



For n-type region

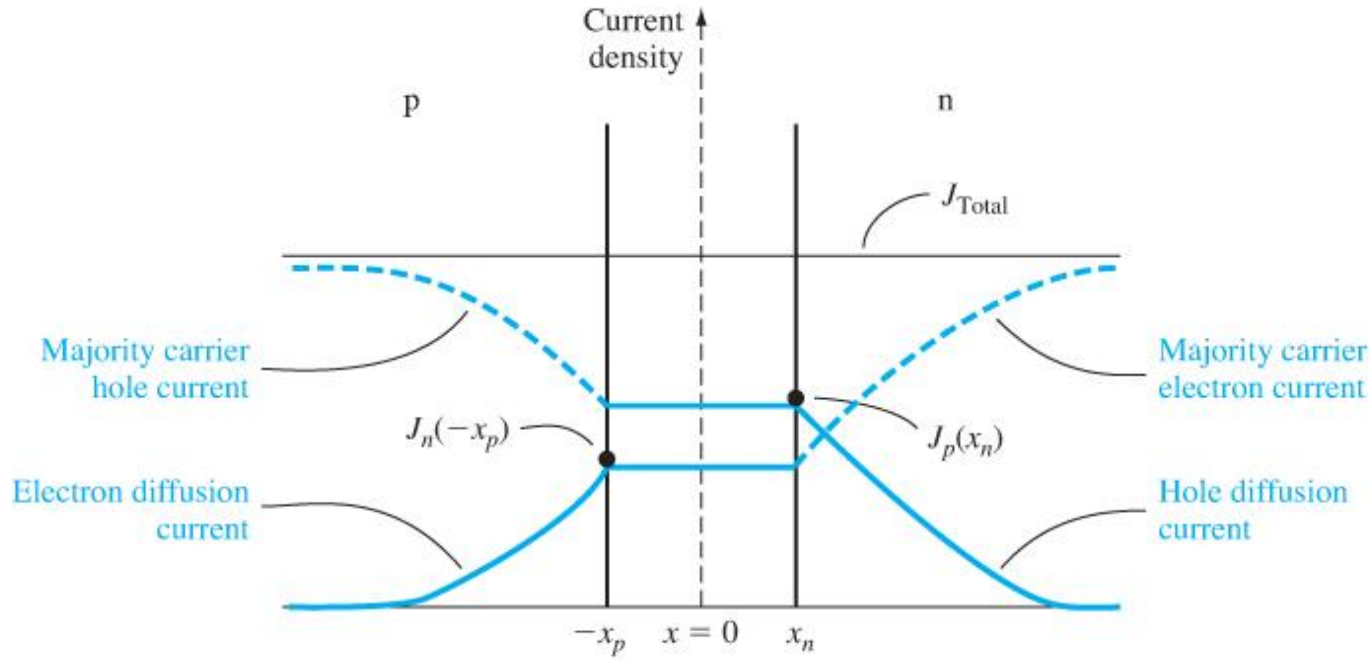
$$J_p(x) = J_{p|diff} = -qD_p \frac{dp_n(x)}{dx} = -eD_p \frac{d\delta p_n(x)}{dx}$$

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

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

$(x = +x_n)$

Ideal PN Junction Current under Forward Bias



For p-type region

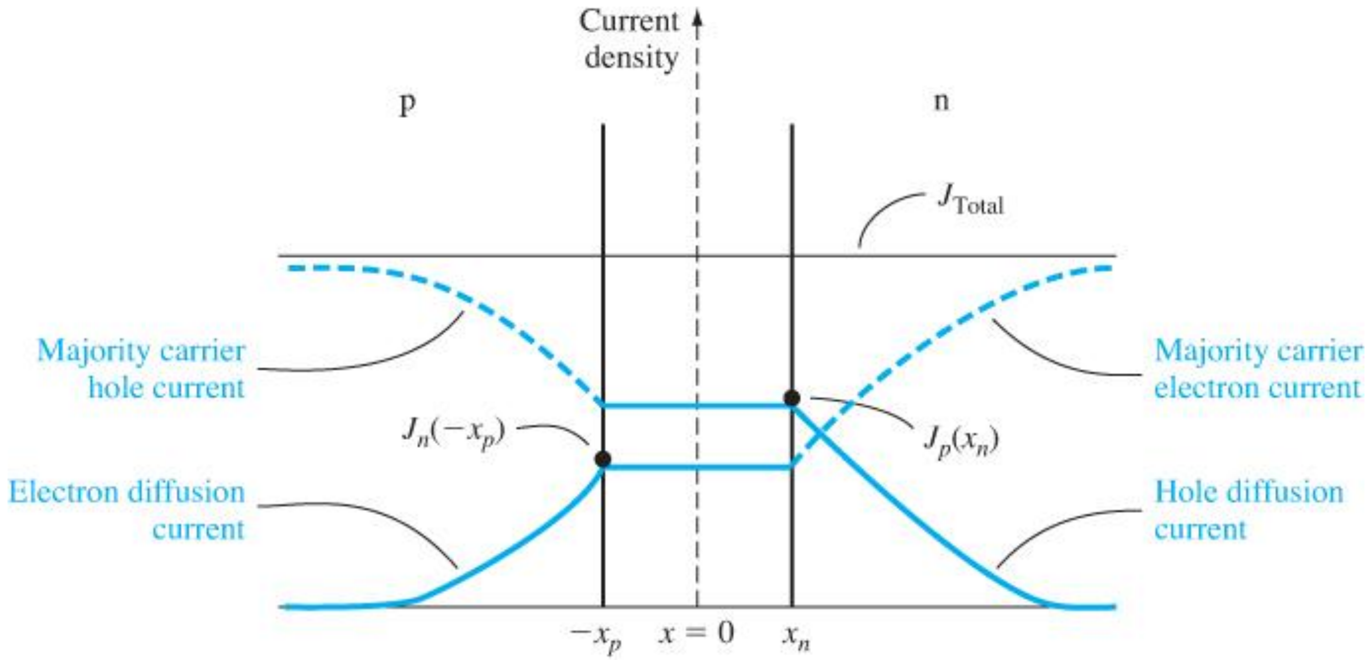
$$J_n(x) = J_{n|diff} = +qD_n \frac{dn_p(x)}{dx} = +eD_n \frac{d\delta n_p(x)}{dx}$$

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

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

$$(x = -x_p)$$

Ideal PN Junction Current under Forward Bias



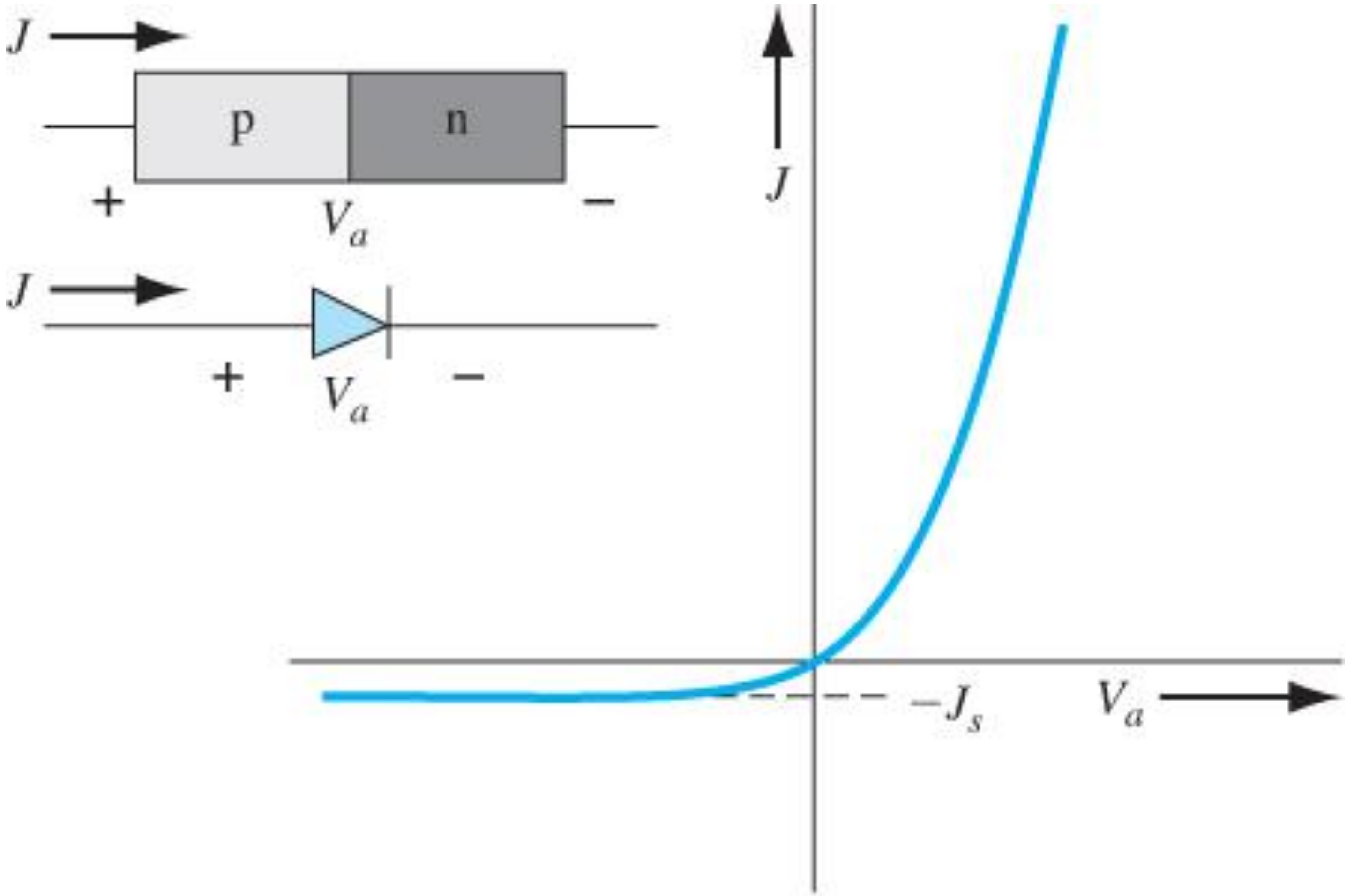
$$J_n(-x_p) = \frac{eD_n}{L_n} n_{p0} \left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] \qquad J_p(x_n) = \frac{eD_p}{L_p} p_{n0} \left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

Depletion region total current density = Total current density

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

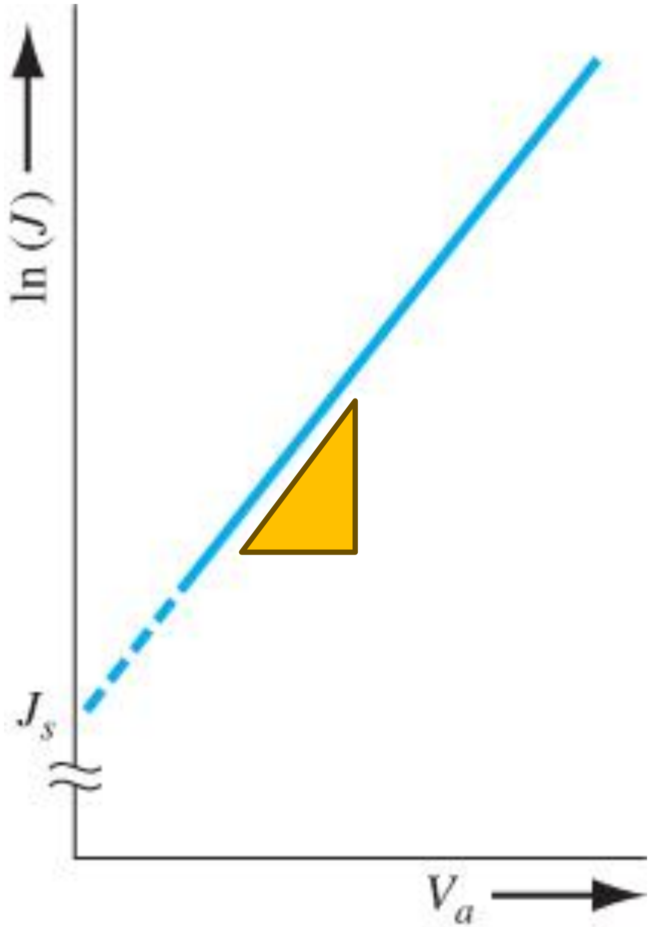
$$= J_s \left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

Ideal I-V (Current-Voltage) Characteristics of a PN Junction Diode (Linear Plot)



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

Ideal I-V (Current-Voltage) Characteristics of a PN Junction Diode (Semilog Plot)



$$if \ \exp\left(\frac{eV_a}{kT}\right) \gg 1$$

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

⇩

$$\log(J_{Total}) \cong \log\left(\exp\left(\frac{eV_a}{kT}\right)\right) + \log J_s$$

$$= \frac{\ln\left(\exp\left(\frac{eV_a}{kT}\right)\right)}{\ln 10} + \log J_s = \frac{\frac{eV_a}{kT}}{\ln 10} + \log J_s$$

⇩

$$Slope = \frac{d\log(J_{Total})}{dV_a} = \frac{\frac{e}{kT}}{\ln 10} \cong 16.76$$

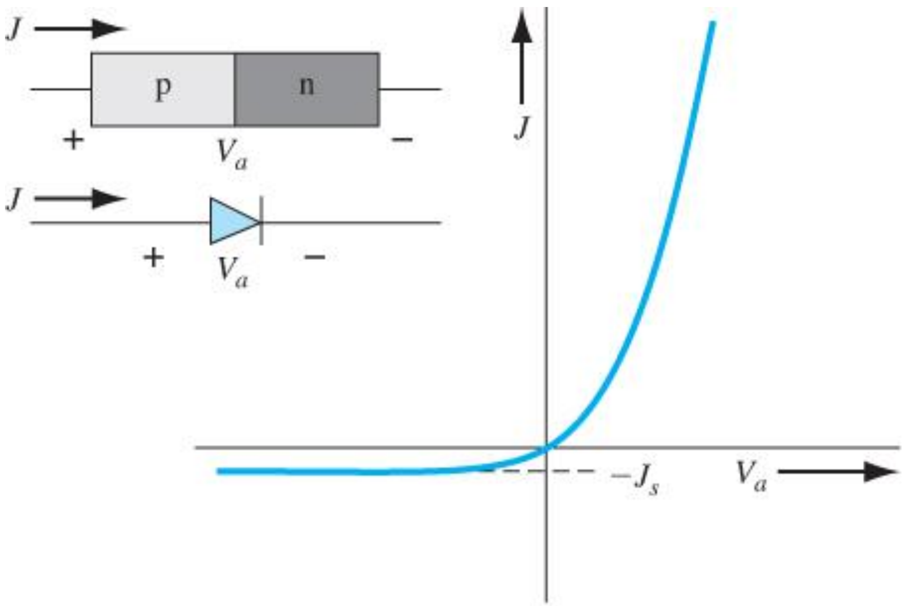
$$\frac{1}{Slope} = \frac{dV_a}{d\log(J_{Total})} \cong \frac{1}{16.76} = 0.060[\mathrm{V/dec}] = 60[\mathrm{mV/dec}]$$

Temperature Effects

Depletion region total current density = Total current density

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

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



For reverse bias

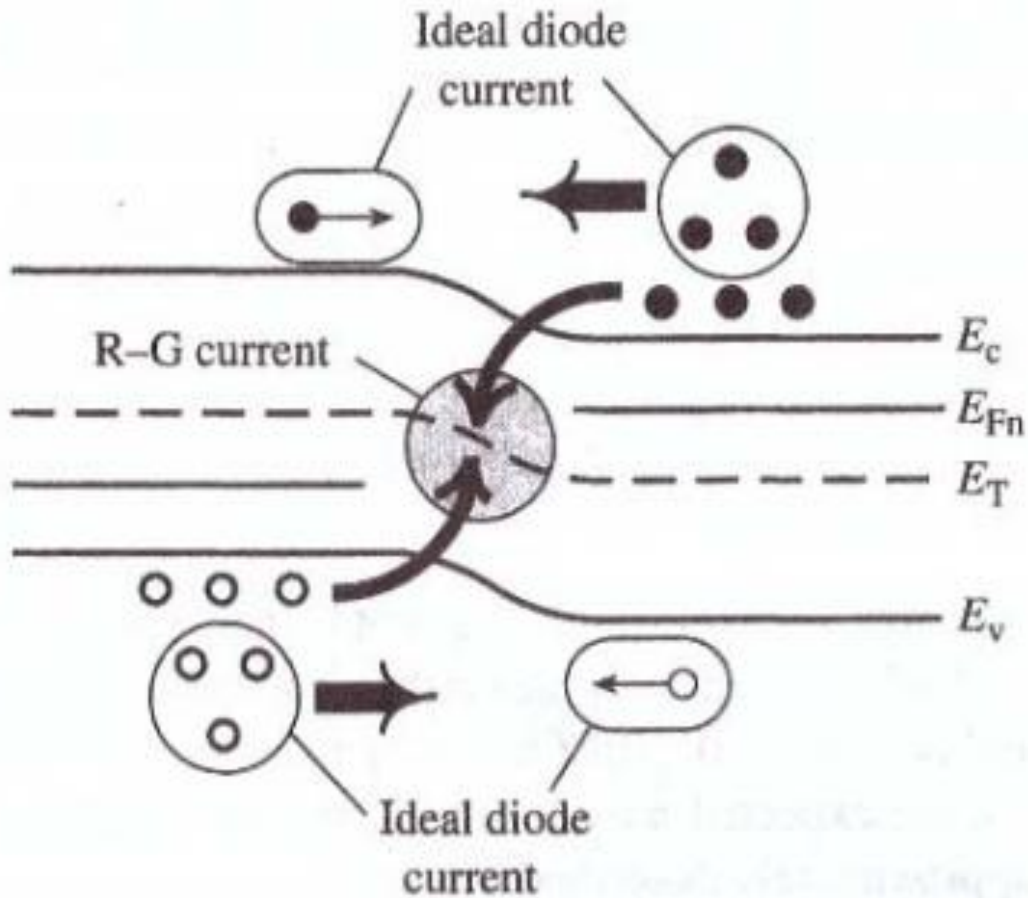
$$J_{Total} \cong \left[\frac{eD_n}{L_n} n_{p0} + \frac{eD_p}{L_p} p_{n0}\right] \cong J_s$$

$$n_{p0} = \frac{n_i^2}{N_a} \qquad p_{n0} = \frac{n_i^2}{N_d}$$

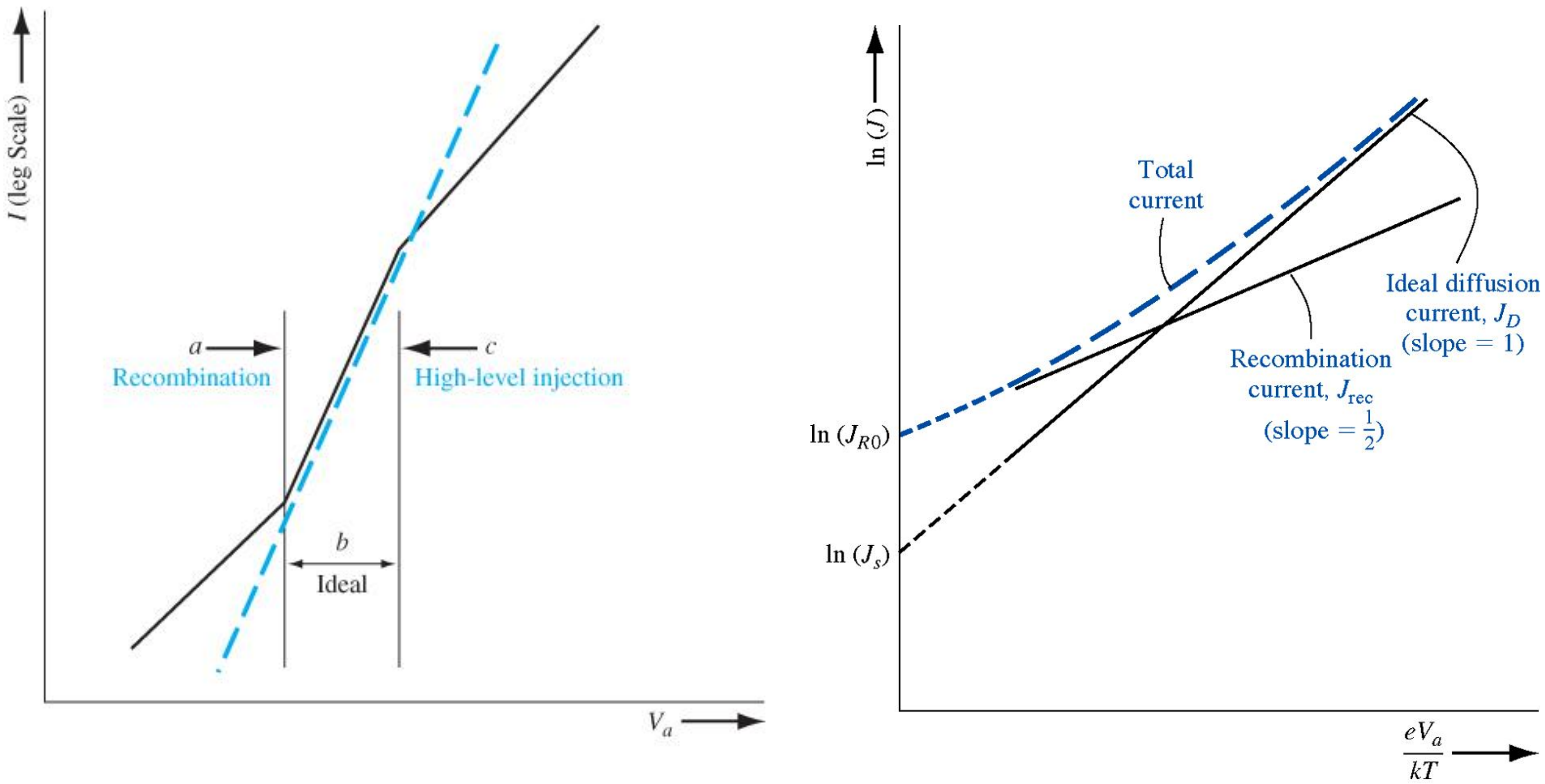
For forward bias

$$J_{Total} \cong J_s \exp\left(\frac{eV_a}{kT}\right)$$

Generation-Recombination Currents (Recombination effects, Forward Bias)



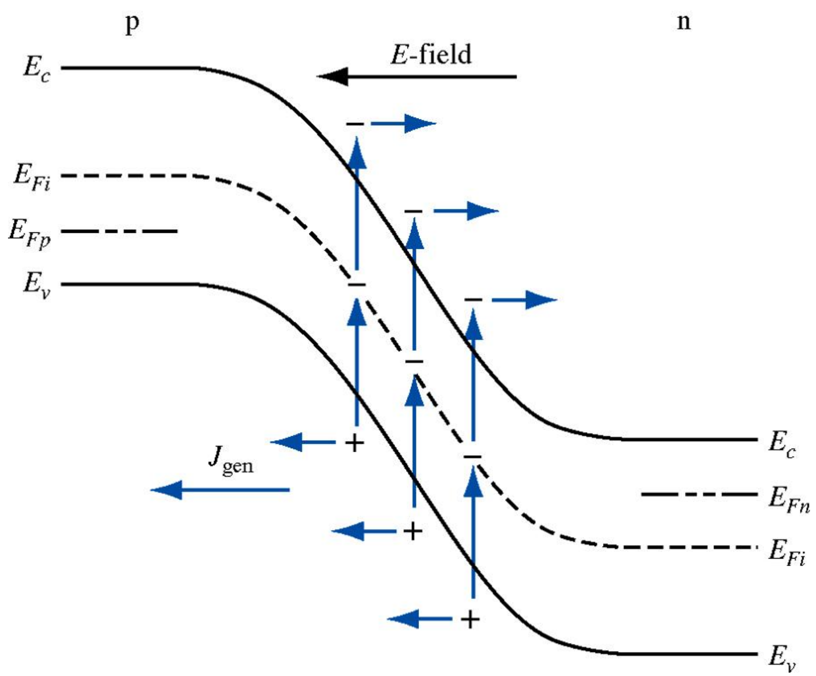
Generation-Recombination Currents (Recombination effects)

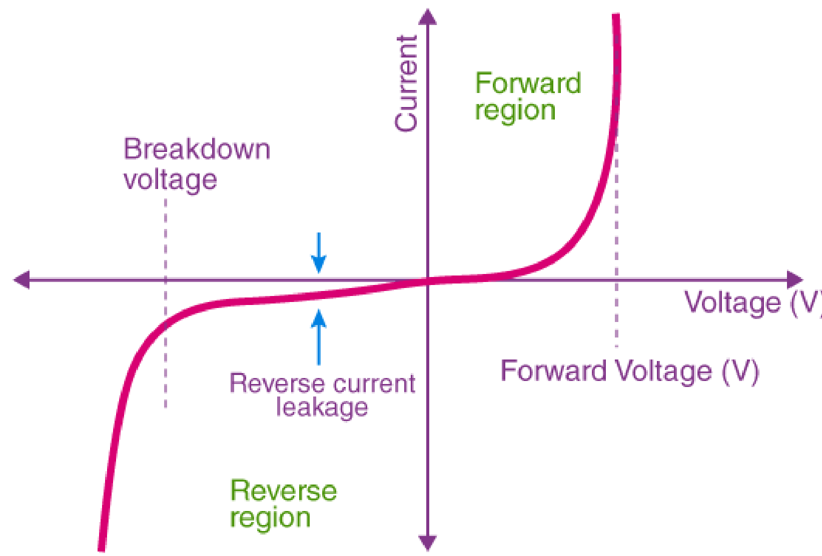


At low bias region with recombination

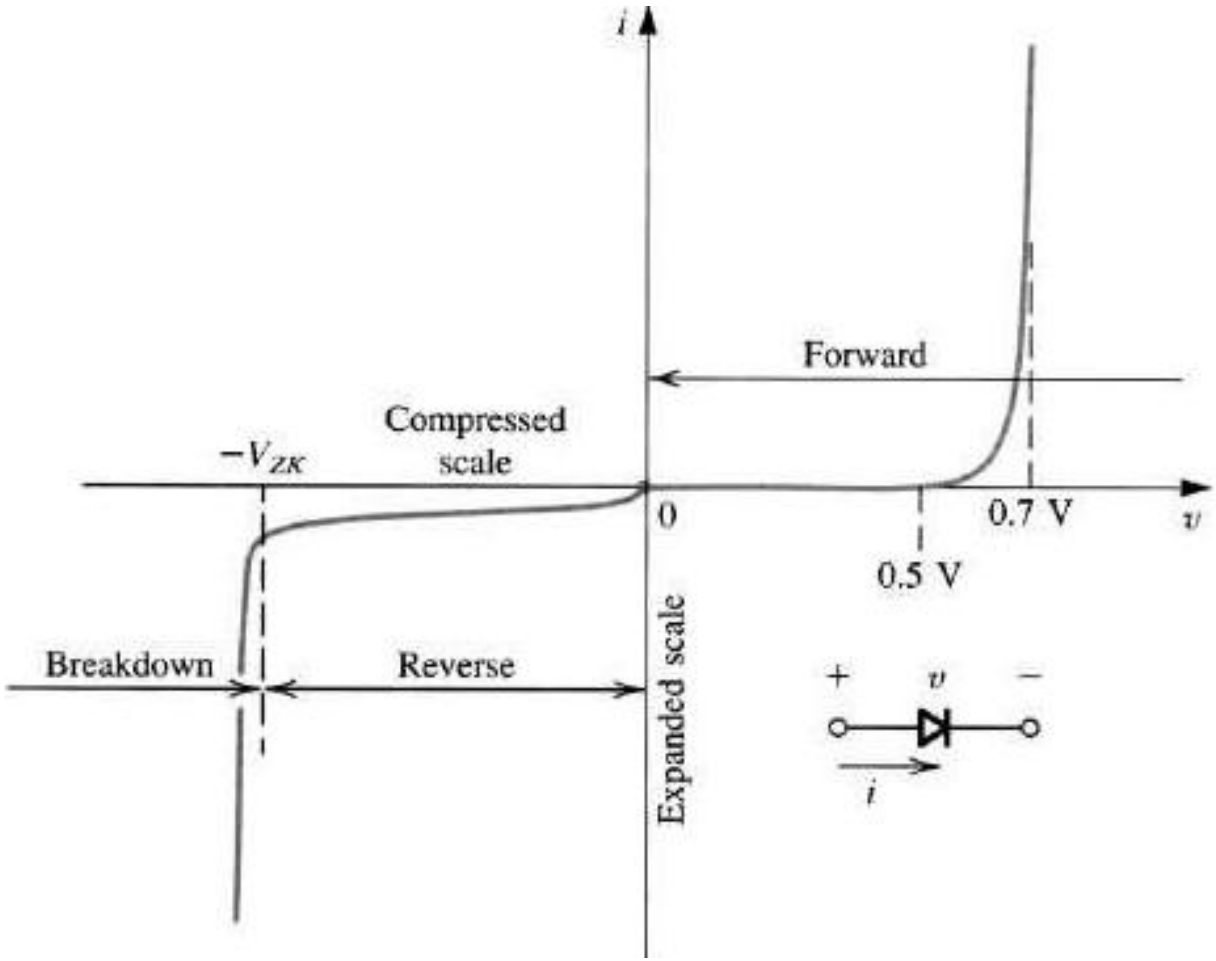
$$J_{Total} = J_s \exp\left(\frac{eV_a}{kT}\right) \quad \Rightarrow \quad J_{Total} = J_s \exp\left(\frac{eV_a}{2kT}\right)$$

Generation-Recombination Currents (Generation effects, Reverse Bias)





I-V Characteristics of a PN Junction Diode Summary



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