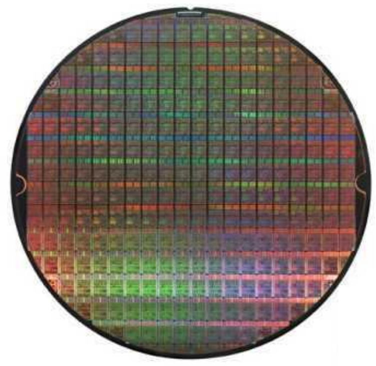
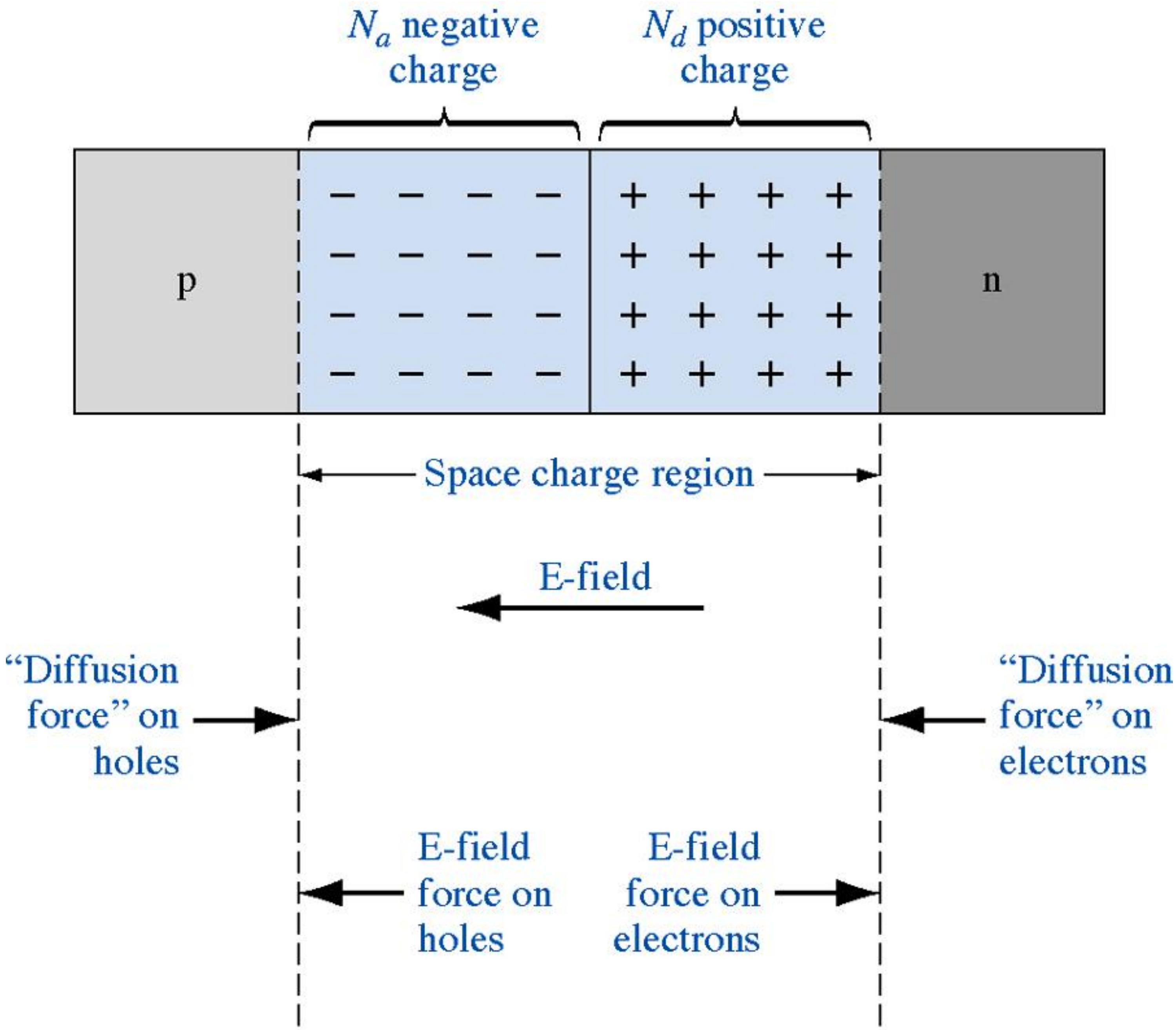


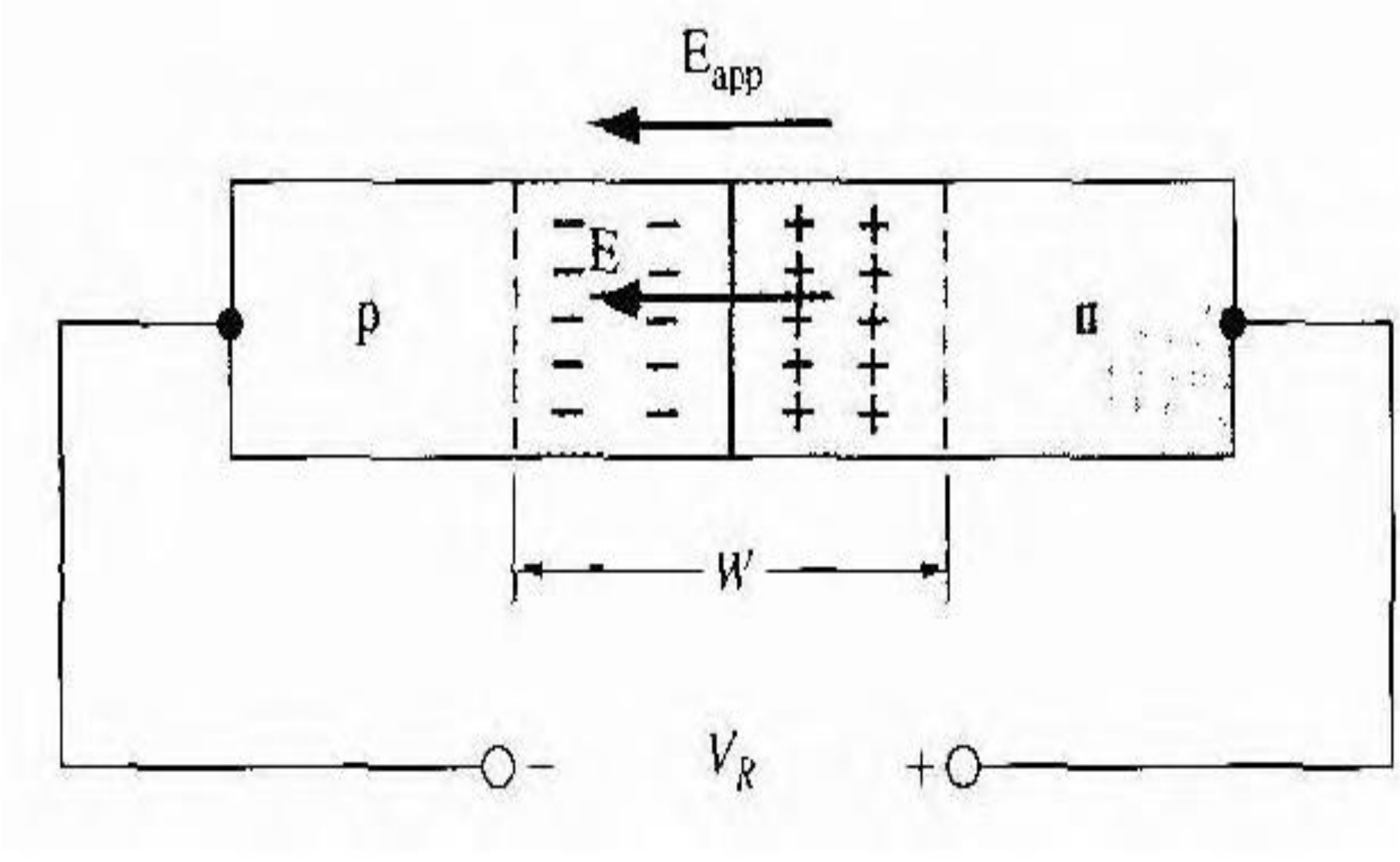
Physics of Semiconductor Devices

Module – II.4

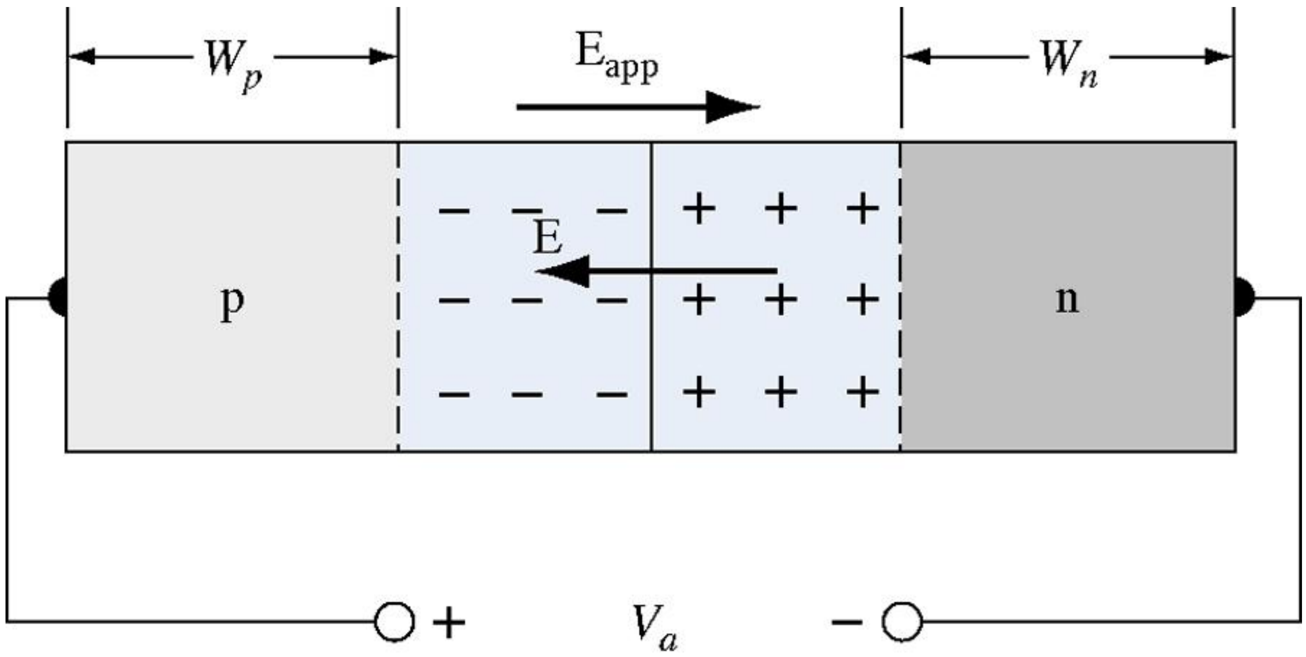


N_a negative charge
N_d positive charge
p
n
Space charge region
E-field
"Diffusion force" on holes
"Diffusion force" on electrons
E-field force on holes
E-field force on electrons

REVERSE BIAS PN JUNCTION

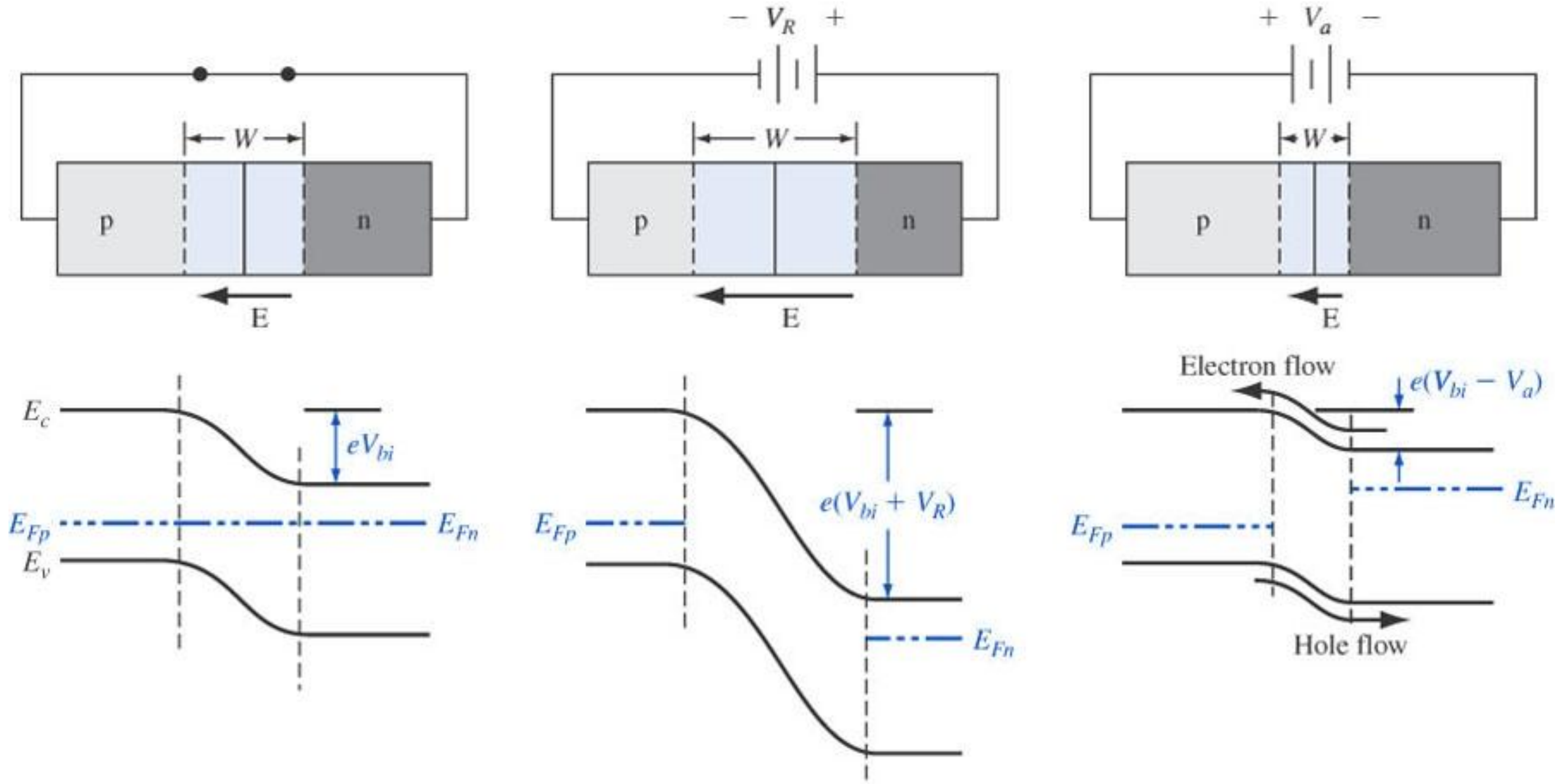


FORWARD BIAS PN JUNCTION



(a)

JUNCTION BIASING



(a) (b) (c)

Assumptions in forward biasing

The ideal current-voltage relationship of a pn junction is derived on the basis of four assumptions.

1. The space charge regions have abrupt boundaries and the semiconductor is neutral outside of the depletion layer

2. The Maxwell-Boltzmann approximation applies to carrier statistics.

3. The concept of low injection applies.

4. The total current is a constant throughout the entire pn structure.

The individual electron and hole currents are continuous functions through the pn junction

The individual electron and hole currents are constant throughout the depletion region.

Boundary Conditions:-

In zero biased pn junction, the built-in-potential maintains the thermal equilibrium and prevents the majority carriers to flow across the junction

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

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

Thermal equilibrium majority carrier electron concentration in the n region=n_{n0}= N_d

assuming complete ionization,

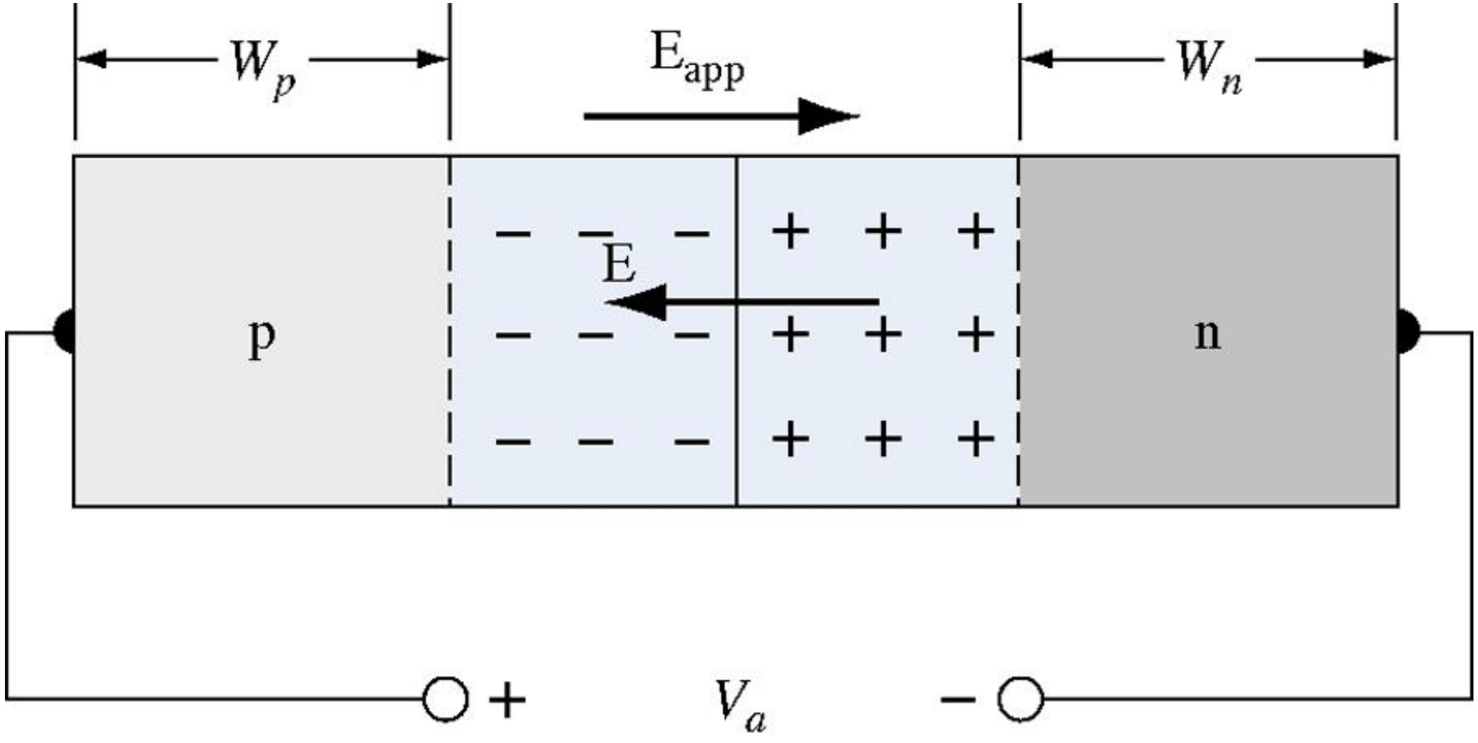
$$n_{n0} \approx N_d$$

Thermal equilibrium minority carrier electron concentration in the p region= $n_{p0} = n_i^2 / N_a$

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

Is the relation between minority carrier electron conc.on the p side & the majority carrier electron conc.on the n side of the junction in thermal eqbm.

FORWARD BIAS PN JUNCTION



(a)

❖Injection of holes into the n region means these holes are minority carriers there.
❖Injection of electrons into the p-region means these electrons are minority carriers there.
❖The behavior of these minority carriers is described by the ambipolar transport equations.

Forward Biasing

- The applied forward biasing potential $\mathbf{V_a}$ reduces the depletion layer potential to $\mathbf{(V_{bi}-V_a)}$.

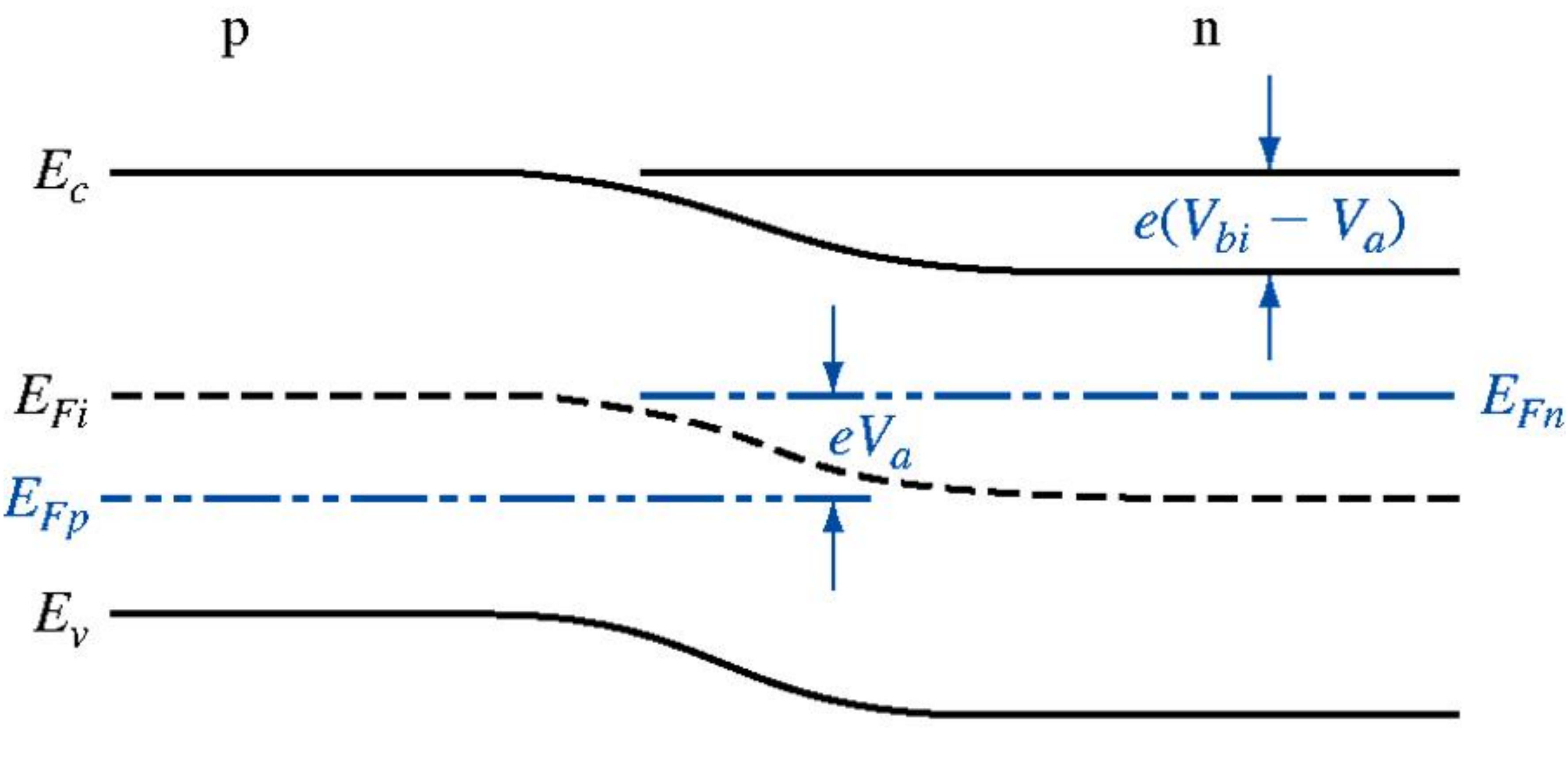
- Since the applied field is in the opposite direction now the net EF is reduced , so thermal eqbm. is also disturbed.

- The electric field force that prevented majority carriers from crossing the space charge region is reduced.

- Majority carrier electrons from the n side are now injected across the depletion region into the p material, and majority carrier holes from the p side are injected across the depletion region .

- As long as the bias V_a is applied, the injection of carriers across the space charge region continues and a current is created in the pn junction

ENERGY BAND DIAGRAM IN FORWARD BIASING



(b)

total minority carrier electron concentration in the p region $=n_p$

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

- Assuming **low injection**, the majority carrier electron concentration n_{n0}, does not change significantly.

- However, the minority carrier concentration, n_p can deviate from its thermal-equilibrium value n_{p0} by orders of magnitude

$\Rightarrow$

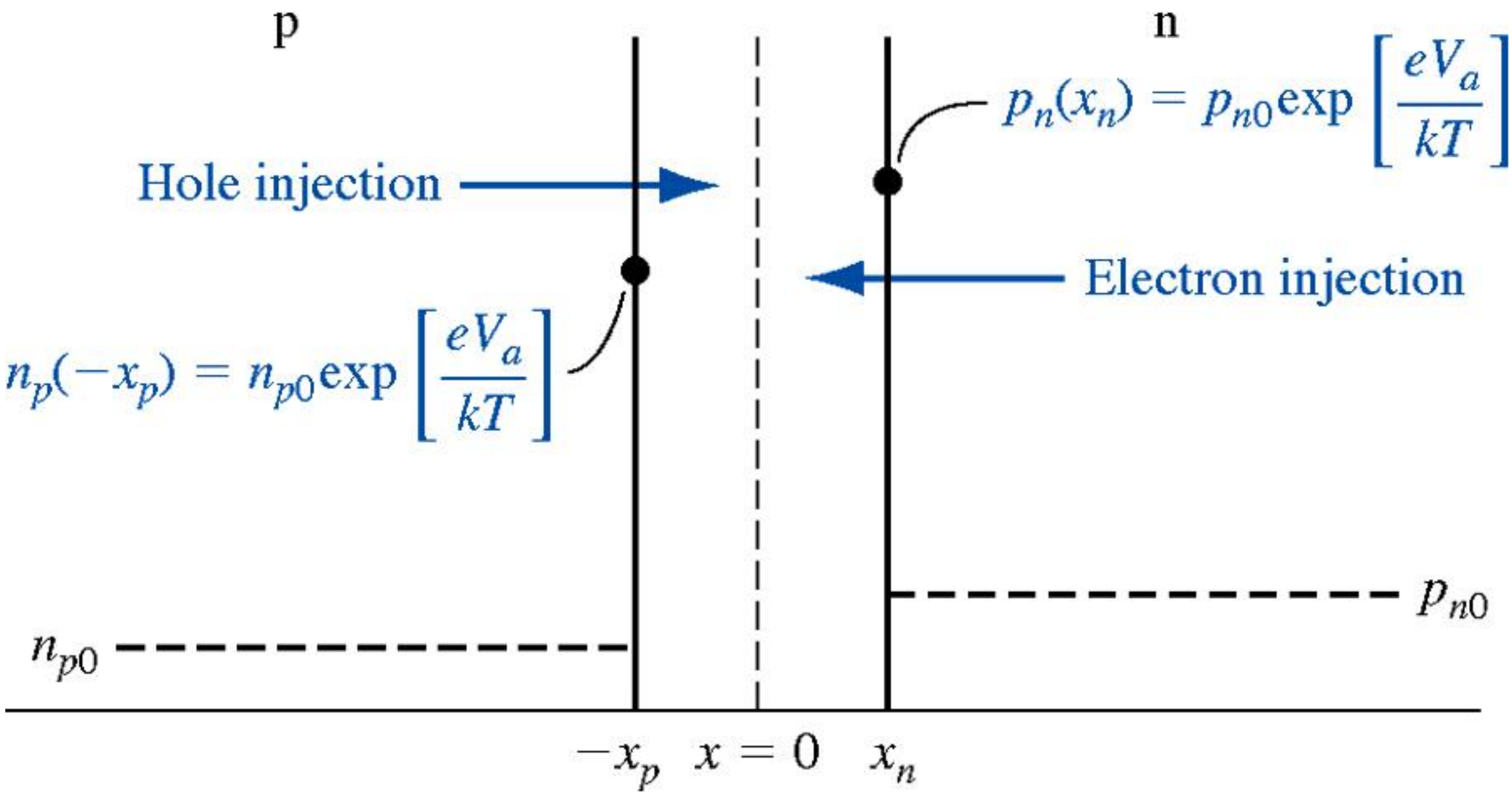
$$n_p = n_{p0} \exp\left(\frac{eV_a}{kT}\right)$$

- When a forward-bias voltage is applied, thermal equilibrium is disturbed. Total minority carrier electron conc. in the p region, becomes greater than the thermal eqbm. value.
- The forward-bias voltage lowers the potential barrier so that majority carrier electrons from the n region are injected across the junction into the p region, increasing the minority carrier electron conc.
- So excess minority carrier electrons are produced in the p region.
- When the electrons are injected into the p region, these excess carriers undergo diffusion and recombination processes.
- Expression for the minority carrier electron concentration in the p region is,

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

Similarly, for excess minority carrier holes In n-region is

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


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

Minority Carrier Distribution

Ambipolar transport equation for excess minority carrier holes in an n region

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

$\delta p_n = p_n - p_{n0}$ is the excess minority carrier hole concentration :- is the difference between the total and thermal equilibrium minority carrier concentrations

Assuming E=0 and g' =0 in the neutral n and p regions ($x > x_n$ & $x < -x_p$) at steady state

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

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

excess minority carrier electron concentration in the p region is determined from

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

The boundary conditions for the total minority carrier concentrations are

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

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

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

$$n_p(x \to -\infty) = n_{p0}$$

For long pn junction, the general solutions are;

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

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

Applying the boundary conditions, A and D found to be zero and coefficients B and C are;-

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

&

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

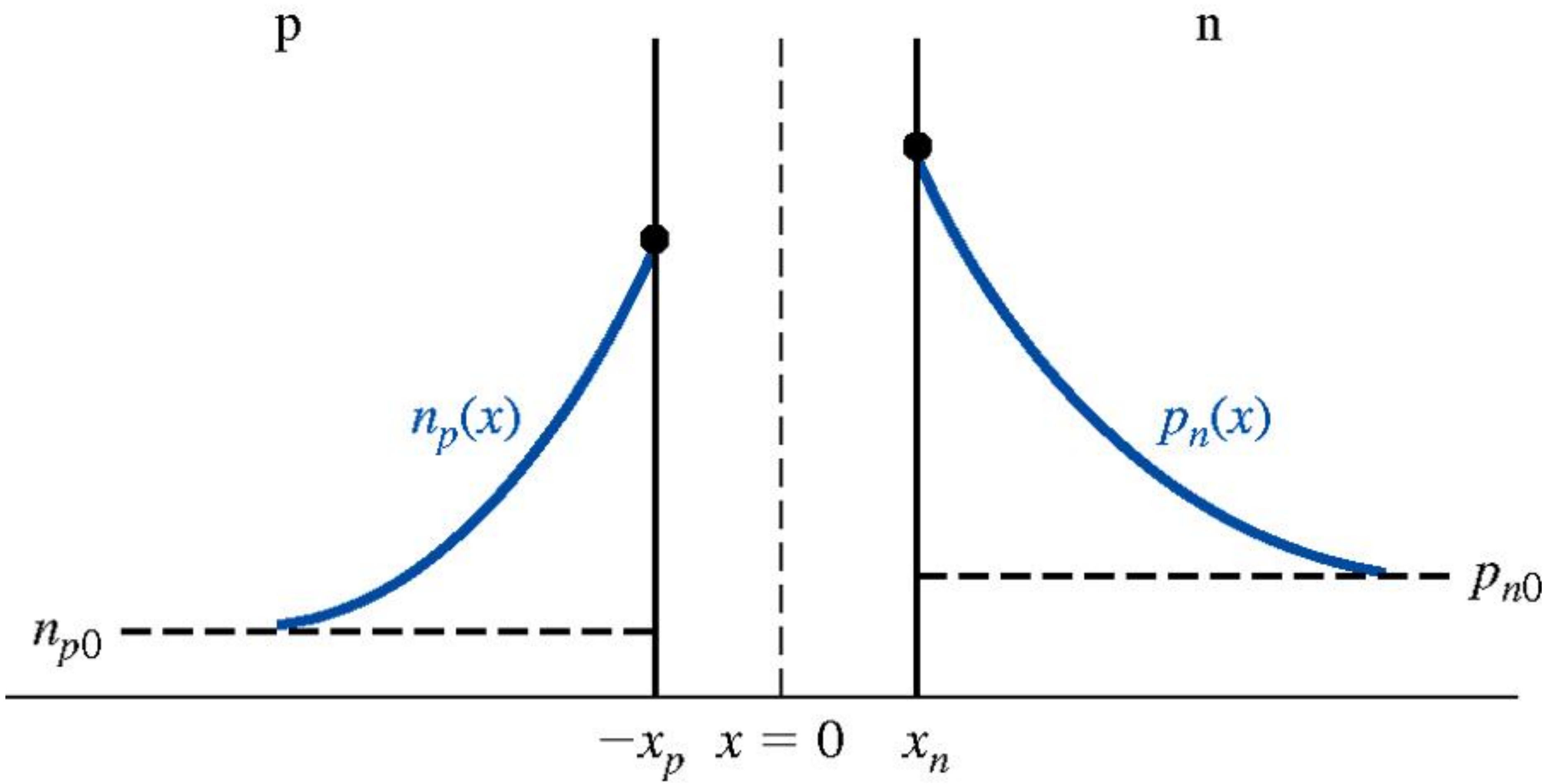
$$so, \quad \delta p_n(x) = p_n(x) - p_{n0}$$

$$= p_{n0}\left(e^{\frac{eV_a}{kT}} - 1\right) e^{\frac{x_n - x}{L_p}} \qquad (x \geq x_n)$$

$$\&, \quad \delta n_p(x) = n_p(x) - n_{p0}$$

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

The minority carrier concentrations decay exponentially with distance away from the junction to their thermal-equilibrium values


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

IDEAL PN JUNCTION CURRENT

As the electron and hole currents are continuous through the pn junction, the total pn junction current will be the minority carrier hole diffusion current at $x = x_n$, plus the minority carrier electron diffusion current at $x = -x_p$

As electric field to be zero at the space charge edges, minority carrier drift current may be neglected and due to the conc. gradient , diffusion current is produced

minority carrier hole diffusion current density at $x = x_n$

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

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

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

The hole current density for this forward-bias condition is in the +x direction, which is from the p to the n region.

the electron diffusion current density at x = **$-x_p$**

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

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

electron current density is also in the +x direction.

total current density in the pn junction is

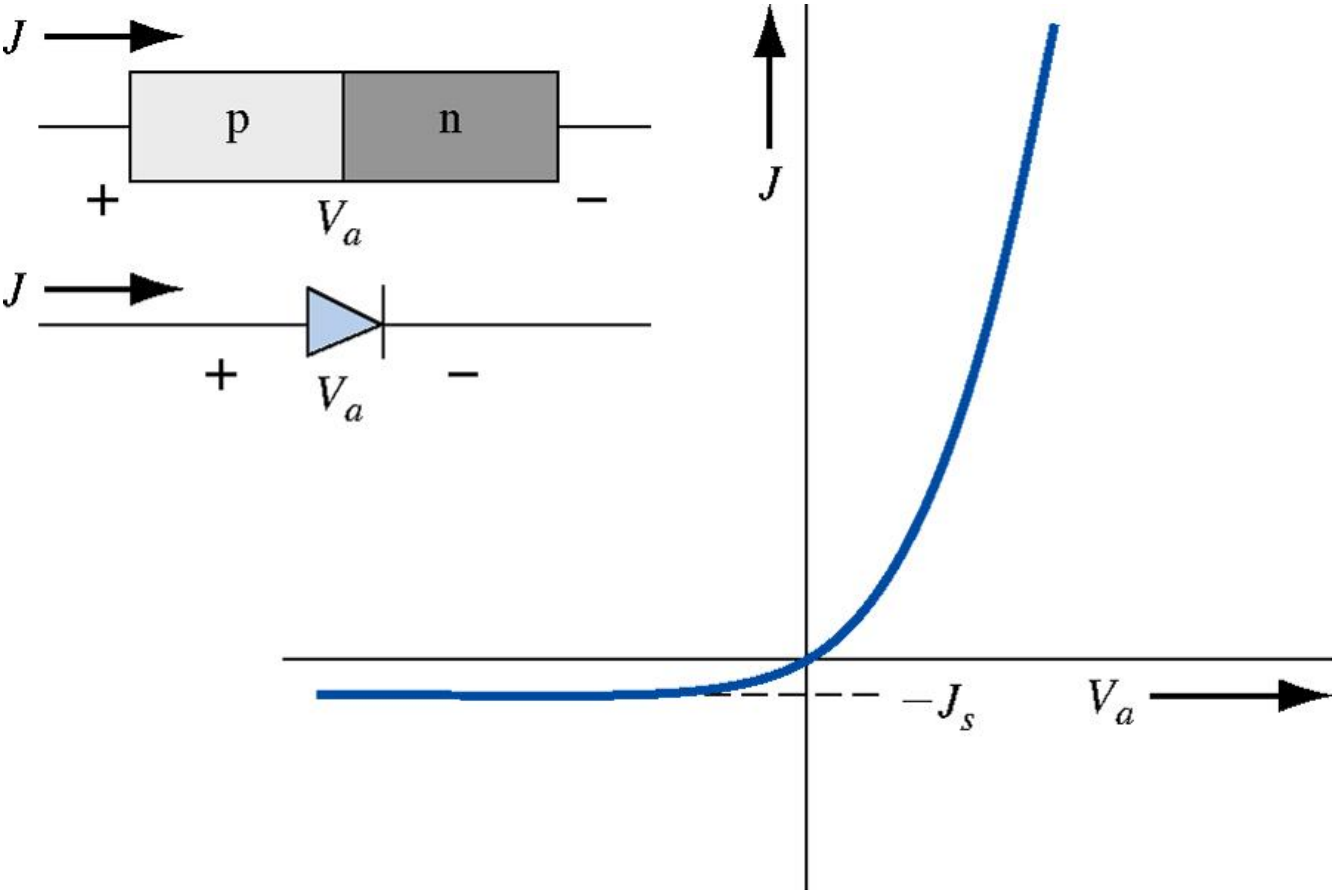
$$J = J_p(x_n) + J_n(-x_p)$$

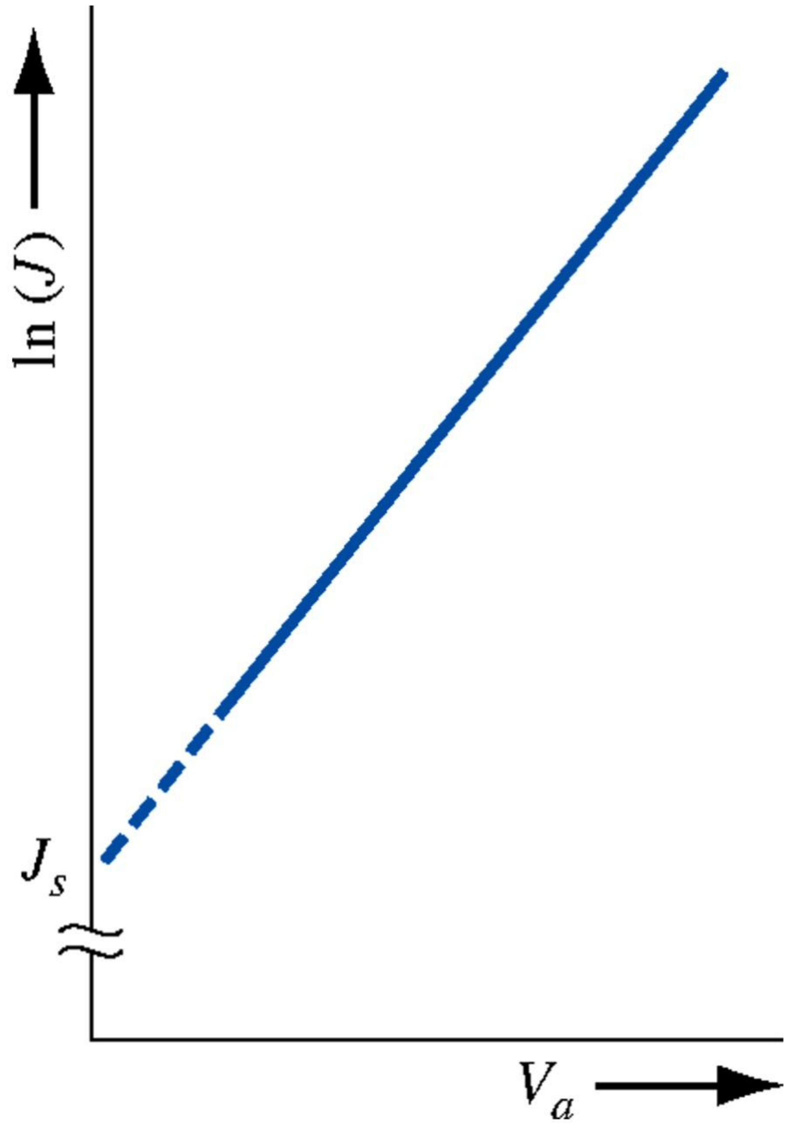
$$\frac{eD_p p_{n0}}{L_p}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] + \frac{eD_n n_{p0}}{L_n}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

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

$$J \approx J_s \left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$ Where, $$J_s = \frac{eD_n n_{p0}}{L_n} + \frac{eD_p p_{n0}}{L_p}$$

- A plot between J and V_a will give the **I~V** characteristic for forward biasing PN junction
- **If the voltage V_a, becomes negative (reverse bias) by a few (k T / e) V, then the reverse-bias current density becomes independent of the reverse-bias voltage.**
- The parameter J_s is referred to as the **reverse saturation current density**


J
p
n
+
V_a
−
J
+
V_a
−
J
$-J_s$
V_a



Ideal ***I-V*** characteristic of ***a*** pn junction diode (current plotted on a log scale.)

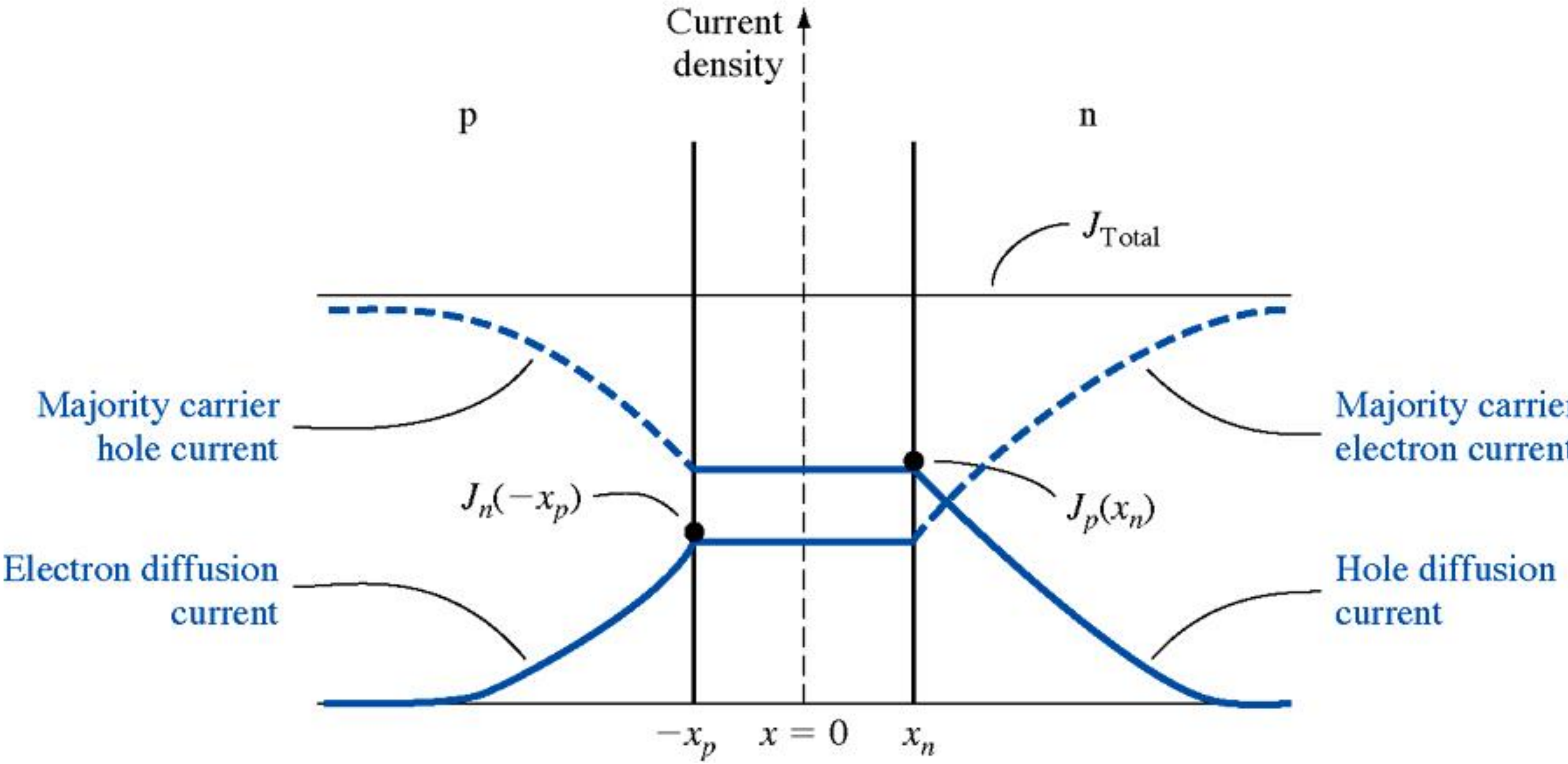
minority carrier diffusion current densities as a function of distance p- and n-regions, are

$$J_p(x) = \frac{eD_p p_{n0}}{L_p}\left[e^{\left(\frac{eV_a}{kT}\right)} - 1\right] e\left(\frac{x_n - x}{L_p}\right) \quad ; \quad (x \geq x_n)$$

$$J_n(x) = \frac{eD_n n_{p0}}{L_n}\left[e^{\left(\frac{eV_a}{kT}\right)} - 1\right] e\left(\frac{x_p + x}{L_n}\right) \quad ; \quad (x \leq -x_p)$$

minority carrier diffusion current densities decay exponentially in each region.

Various current components through the pn junction



- Minority carrier diffusion current densities decay exponentially in each region.
- Total current through the pn junction is constant.
- The difference between total current and minority carrier diffusion current is majority carrier current.
- The drift of majority carrier holes in the p region far from the junction supply holes that are being injected across the space charge region into the n region and also to supply holes that are lost by recombination with excess minority carrier electrons.

Effect of temperature

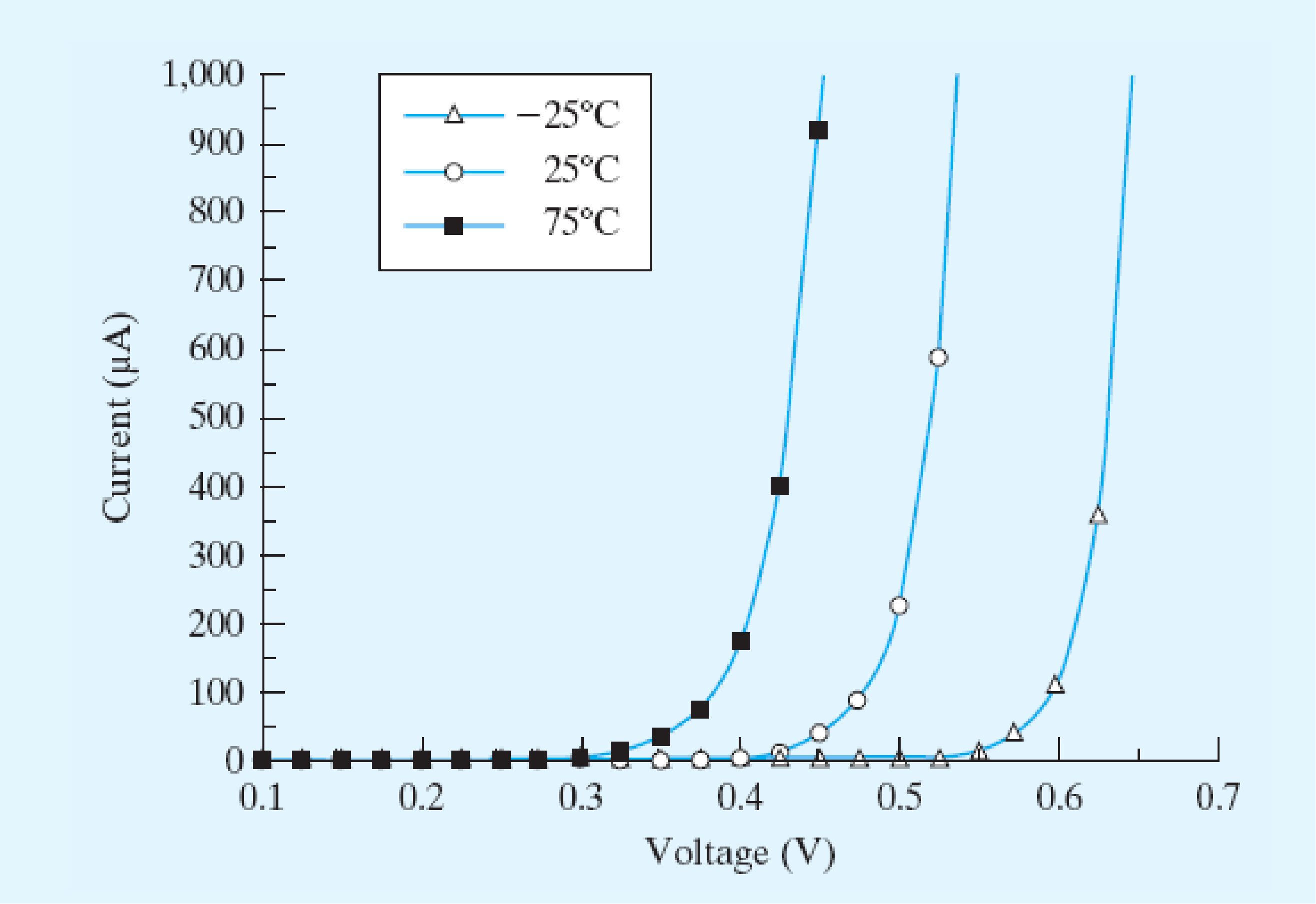
$$J \simeq J_s \left[\exp\left(\frac{eV_a}{kT} \right) - 1 \right] \qquad J_s = \frac{eD_n n_{p0}}{L_n} + \frac{eD_p p_{n0}}{L_p}$$

- Ideal reverse saturation current density Js , is a function of the thermal-equilibrium minority carrier concentrations n_{p0} and p_{n0} , which are proportional to n_i, which is a very strong function of temperature.

- Forward-bias current-voltage relation has Js and $\exp(eV_a/kT)$

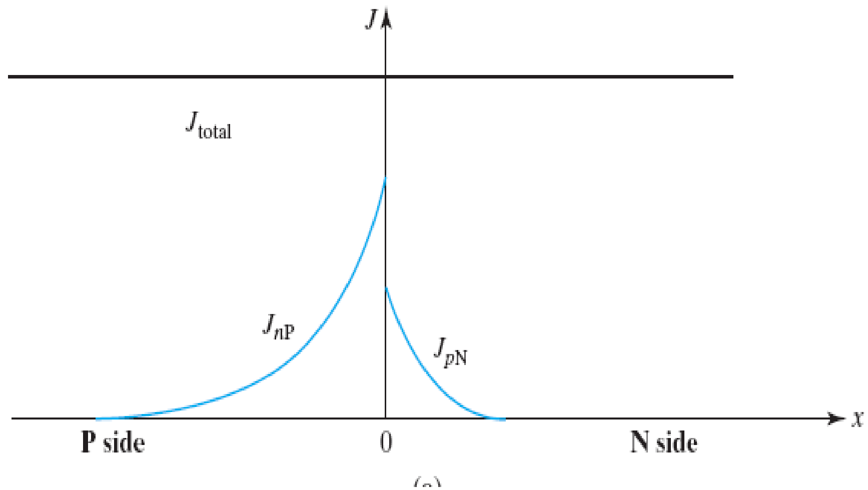
- Which makes the forward-bias current-voltage relation a function of temperature

- As temperature increases, less forward-bias voltage is required to obtain the same diode current.
- If the voltage is constant, the diode current will increase as temperature increases



The *IV curves of the silicon PN diode shift to lower voltages with increasing temperature*

CHARGE STORAGE in PN JUNCTION



Excess electrons and holes are present in a PN diode when it is forward biased.

This phenomenon is called **charge storage*.***

The stored **charge is proportional to δn(0) and δp(0) or e*V_a/kT – 1).***

stored charge, Q (Coul.), is proportional to I

I is the rate of minority charge injection into the diode.

In steady state, this rate must be equal to the rate of charge recombination, which is Q/τs.

Where, τ*s is called the* ***charge-storage time,*** is an average of the recombination lifetimes on the N side and the P side.

$$I = Q/\tau_s$$

$$Q = I\tau_s$$