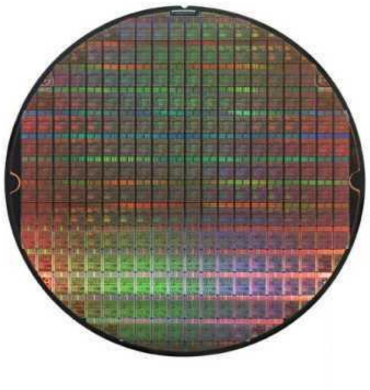
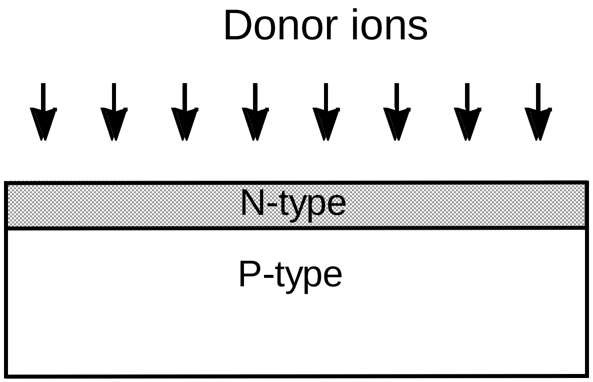
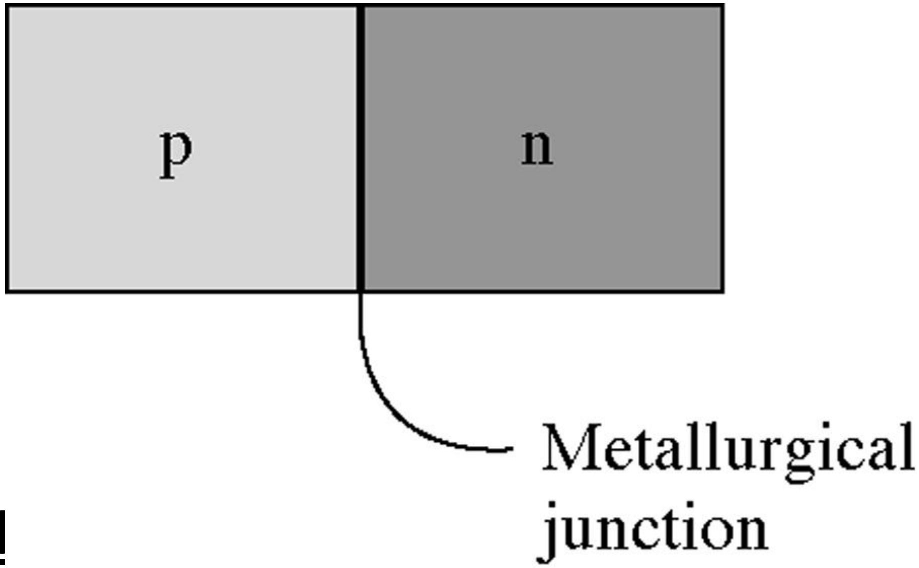


Physics of Semiconductor Devices

Module – II.3

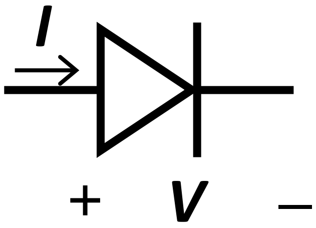
P-N Junction



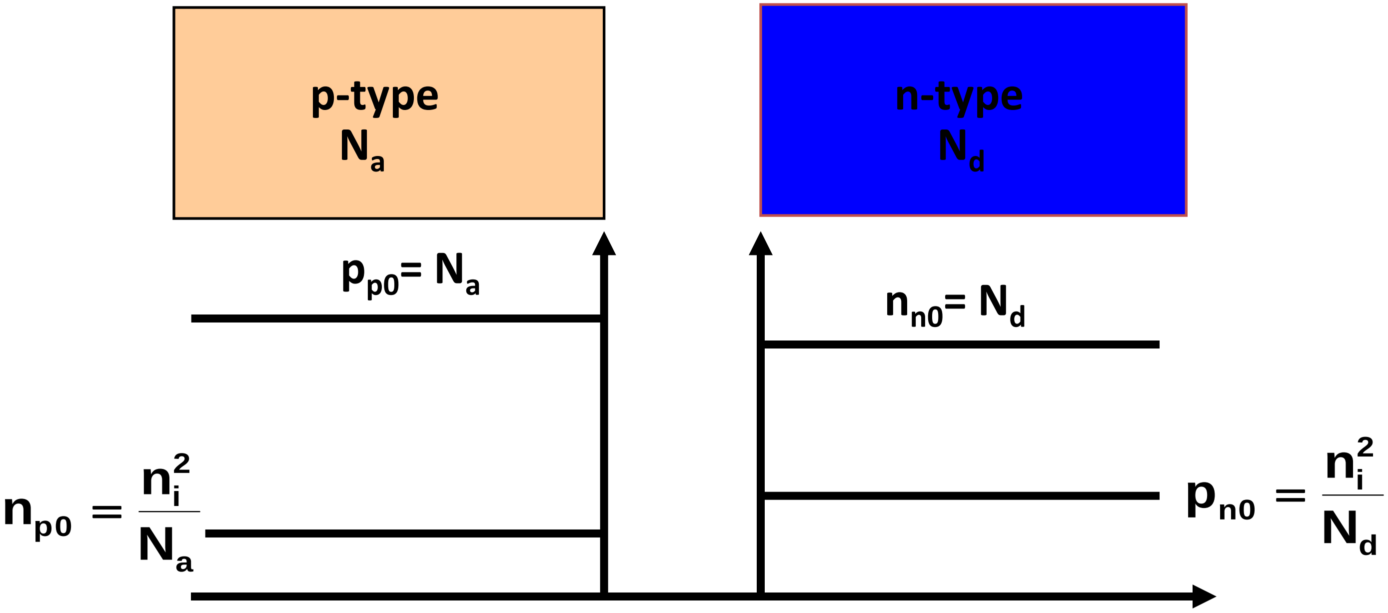


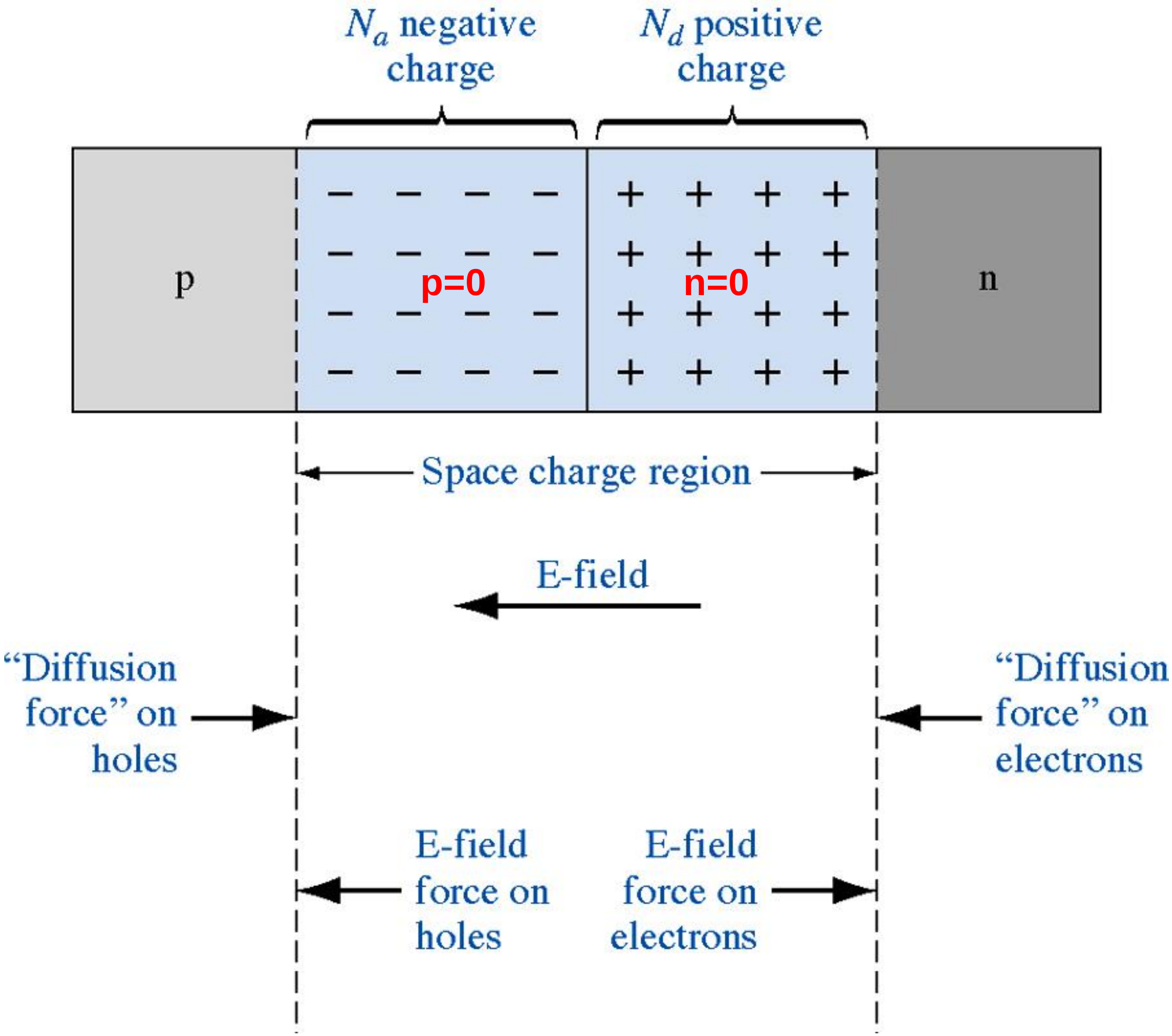
(a)

Circuit syml



Step Junction





N_a negative charge

N_d positive charge

p

p=0

n=0

n

Space charge region

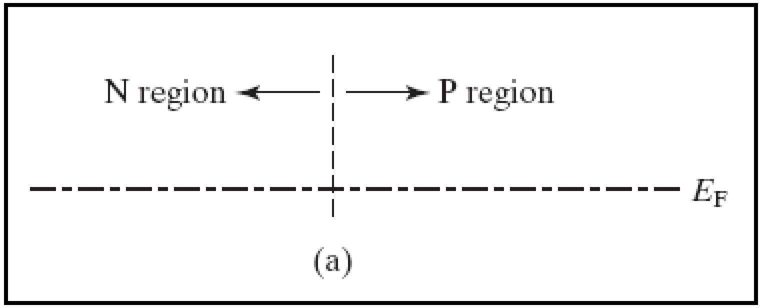
E-field

"Diffusion force" on holes

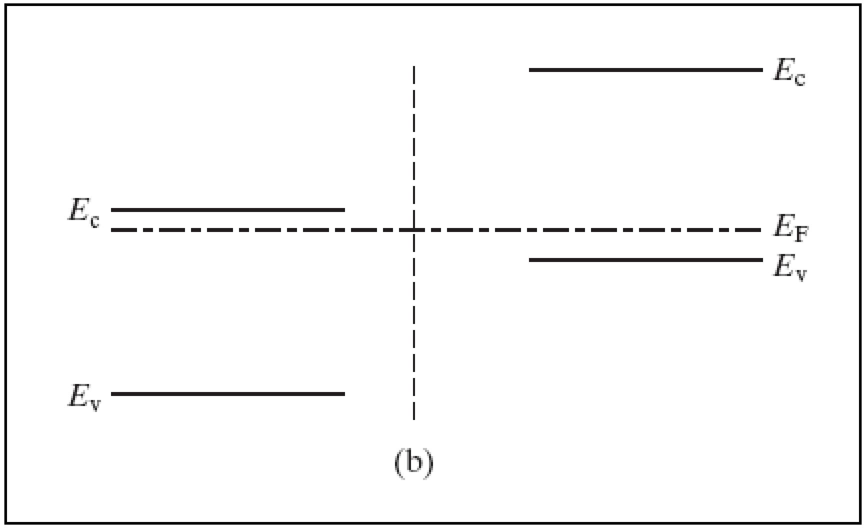
"Diffusion force" on electrons

E-field force on holes

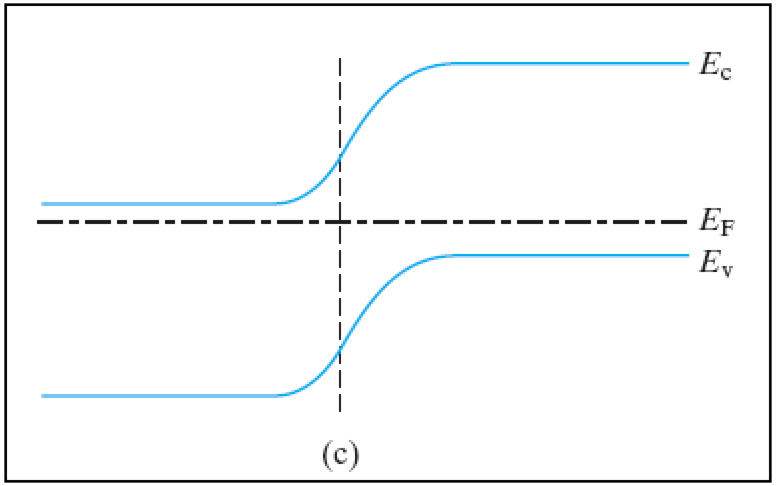
E-field force on electrons


N region
P region
E_F

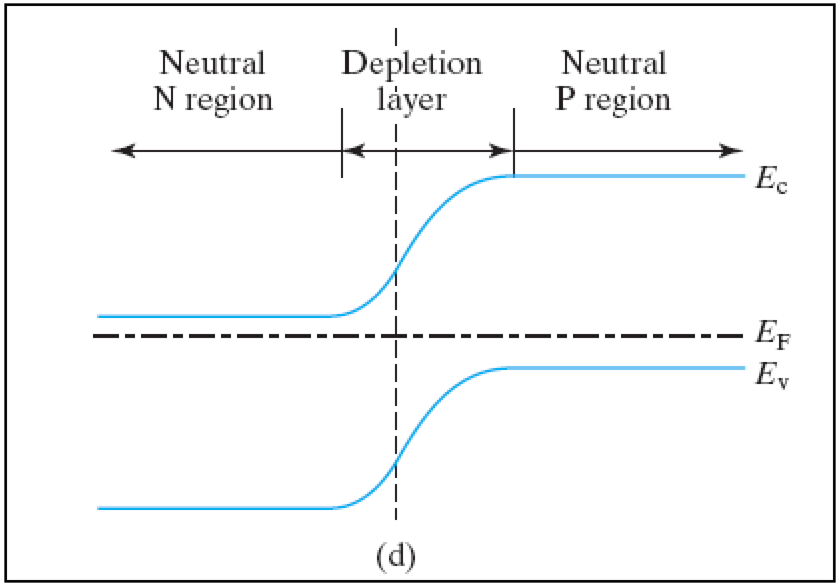
(a)


E_c
E_c
E_F
E_v
E_v

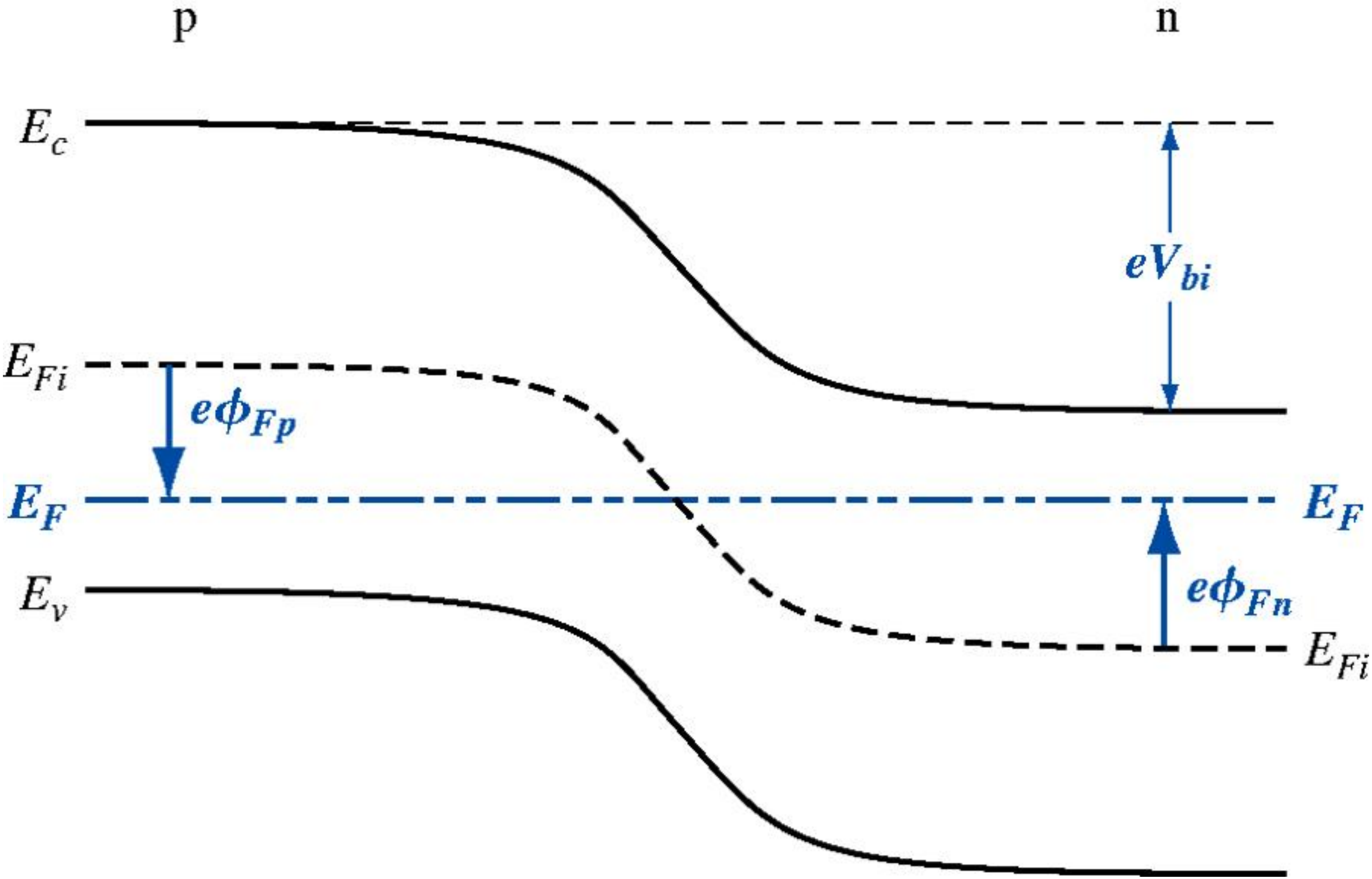
(b)


E_c
E_F
E_v

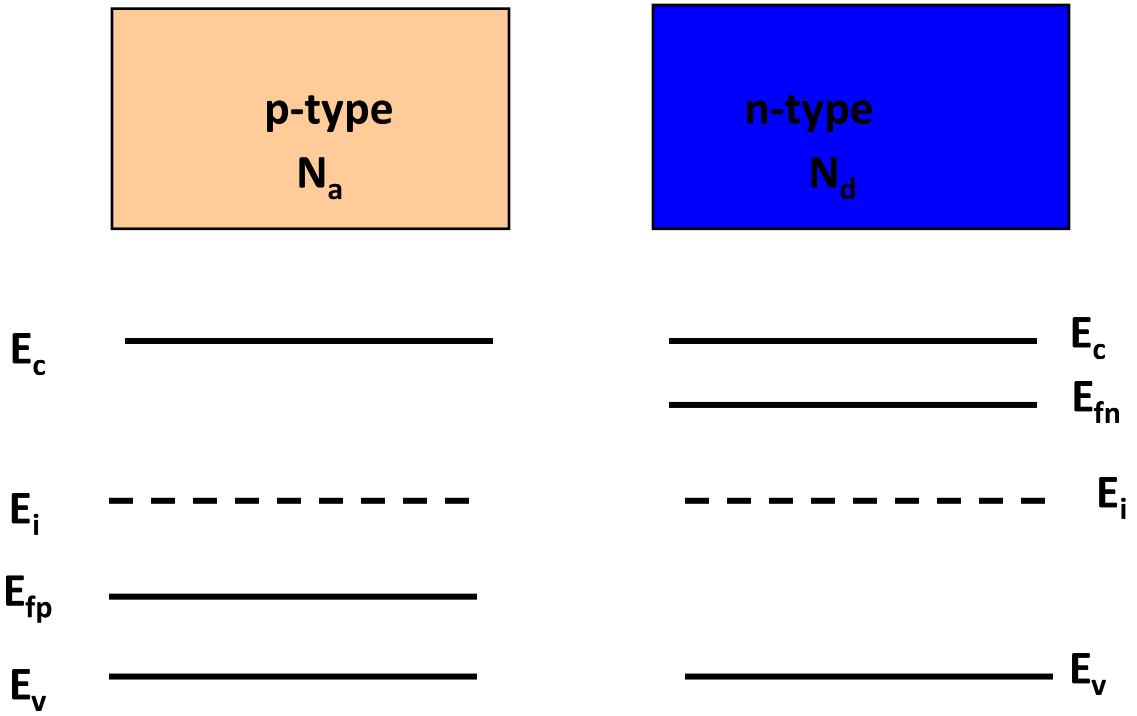
(c)


Neutral N region
Depletion layer
Neutral P region
E_c
E_F
E_v

(d)


p
n
E_c
eV_{bi}
E_{Fi}
$e\phi_{Fp}$
E_F
E_F
$e\phi_{Fn}$
E_v
E_{Fi}

P-N Junction & Thermal Equilibrium



p-type

N_a

n-type

N_d

E_c

E_i

E_{fp}

E_v

E_c

E_{fn}

E_i

E_v

Built- in – potential at the P-N junction is given by ,

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

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

⟹ $$e\phi_{Fn} = E_{Fi} - E_F$$

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

setting $n_0 = N_d$. ⟶ $$\phi_{Fn} = \frac{-kT}{e} \ln\left(\frac{N_d}{n_i}\right)$$

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

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

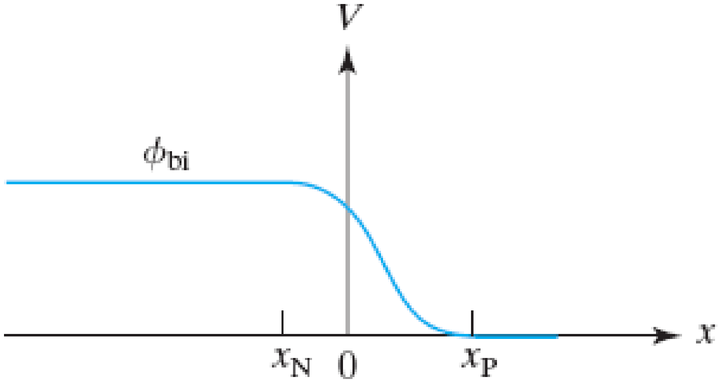
$$\phi_{Fp} = +\frac{kT}{e}\ln\left(\frac{N_a}{n_i}\right)$$

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

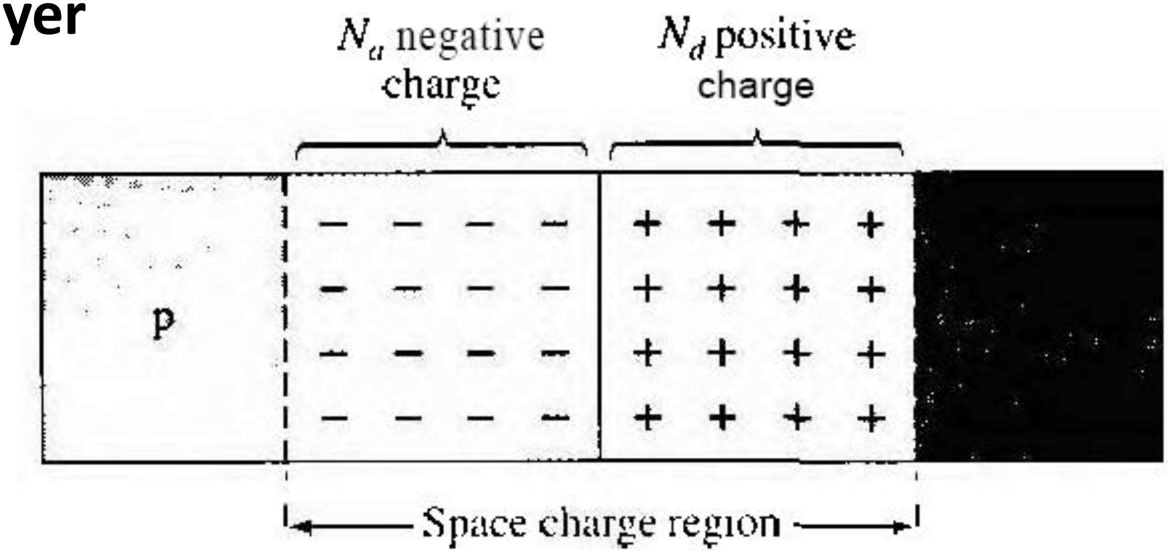
larger the N_d *or* N_a *, larger the* V_{bi} *.*
it is ~ 0.9 V for a silicon PN junction.

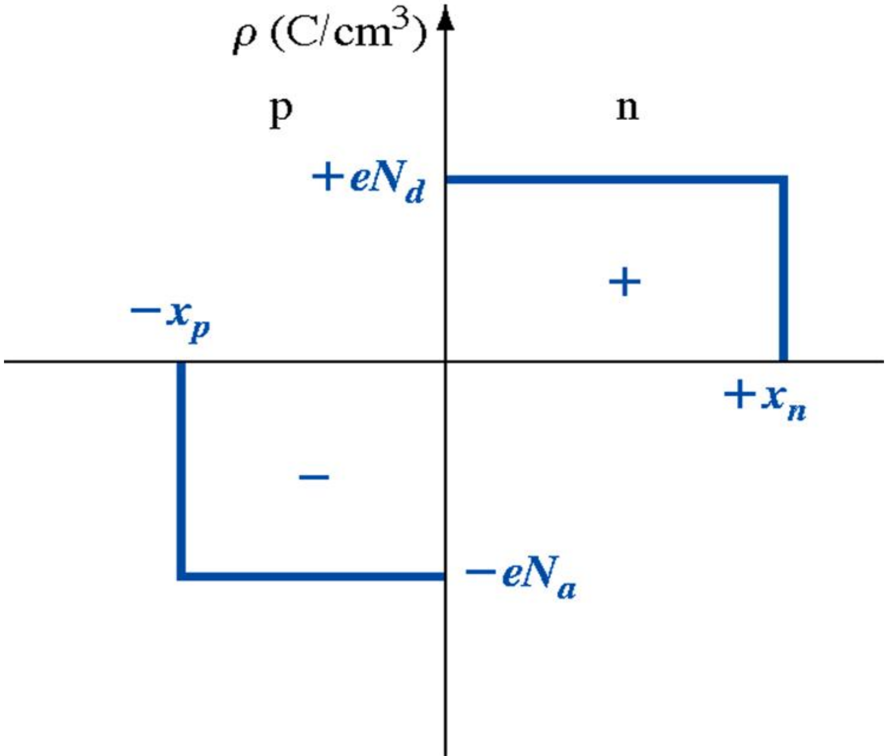
N_d and N_a will denote the net donor and acceptor concentrations in the individual n and p regions, respectively

As lower Ec means a higher voltage, the N side is at a higher voltage or electrical potential than the P side.



Theory of Depletion layer





$$\frac{d^2\phi(x)}{dx^2} = \frac{-\rho(x)}{\epsilon_s} = -\frac{d\mathrm{E}(x)}{dx} \qquad \text{Poisson's equation}$$

where ϕ(x) is the electric potential, E(x) is the electric field, ρ(x) is the volume charge density, and ε_s is the permittivity of the semiconducting material.

In the p region, the charge density $\rho(x) = -eN_a \qquad -x_p < x < 0$

In the n region, the charge density $\rho(x) = eN_d \qquad 0 < x < x_n$

ELECTRIC FIELD in the Depletion layer

In the n region, the electric field is

$$\mathrm{E} = \int \frac{(eN_d)}{\epsilon_s}\,dx = \frac{eN_d}{\epsilon_s}x + C_2$$

In the PN junction the surface charge density is zero, so electric field must be continuous, but in the neutral **N** region $\mathbf{x \geq x_n}$ and neutral **P**-region $\mathbf{x \leq x_p}$, EF $\mathbf{E = 0}$

Putting the boundary condition E= 0 at x= x_n

Value of C2 can be found out, so EF in N-region is

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

Similarly in the P-region

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

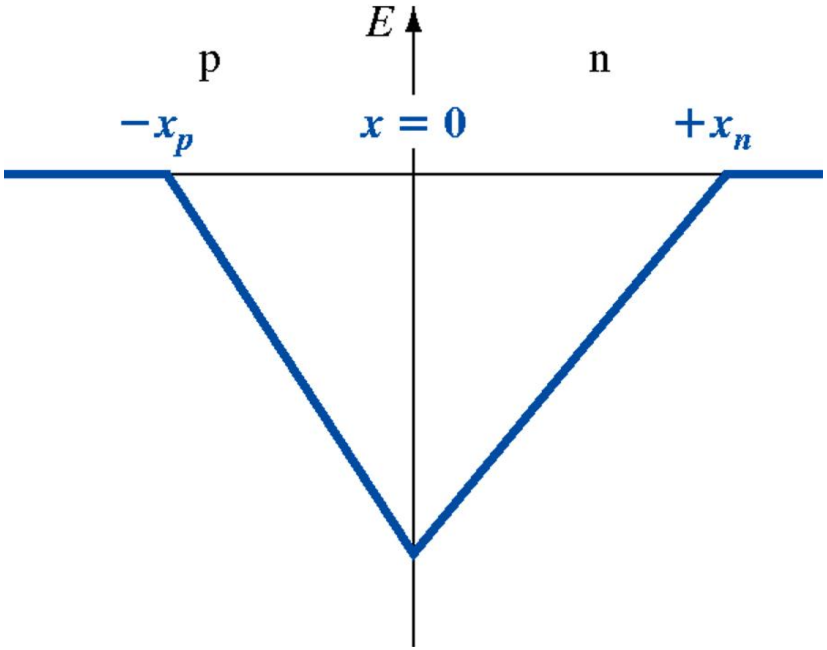
The constant of integration is determined by setting E = 0 at x = -x_p. Hence electric field in the p-region is given by

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

electric field is also continuous at the metallurgical junction, at **x = 0.**

$$N_a x_p = N_d x_n$$

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. For the uniformly doped PN junction, the E-field is a linear function of distance through the junction, and the maximum (magnitude) electric field occurs at the metallurgical junction. An electric field exists in the depletion region even when no voltage is applied between the P-and N- regions directed from N side to P-side.



POTENTIAL in the depletion layer

potential in the junction is found by integrating the electric field.
In the N-region

$$\phi(x) = \int \frac{eN_d}{\epsilon_s}(x_n - x)\,dx$$

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

In the P-region,

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

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

arbitrarily set the potential equal to zero at $\mathbf{x} = -x_p$.

$$C_1' = \frac{eN_a}{2\epsilon_s} x_p^2$$

so that the potential in the P- region

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

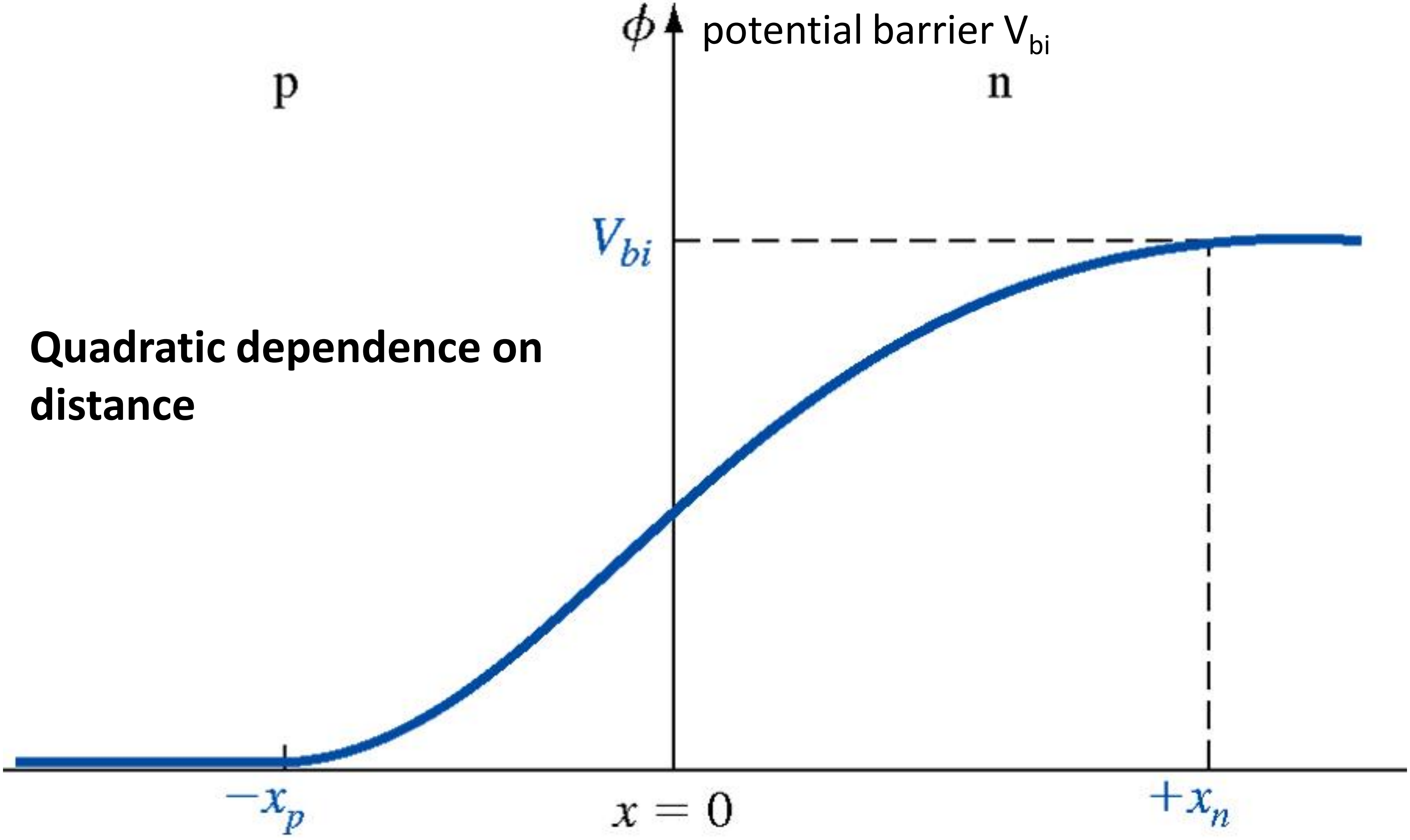
As potential is a continuous function, potential on N-side will be equal to potential on P-side at the metallurgical junction x=0, which gives,

$$C_2' = \frac{eN_a}{2\epsilon_s} x_p^2$$

so that the potential in the N- region

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

at $x = x_n$,
potential is equal to the built-in potential barrier V_{bi}



Quadratic dependence on distance

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

The potential (**ϕ)** and the potential energy (**-eϕ)** of an electron varies as a quadratic function of distance through the space charge region.

WIDTH of the depletion layer

The depletion layer exten $N_a x_p = N_d x_n$ N regions from the metallurgical junction which is given as ,

$$W = x_n + x_p$$

We have ,

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

&

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

So,

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

&

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

Or,

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

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

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

&

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

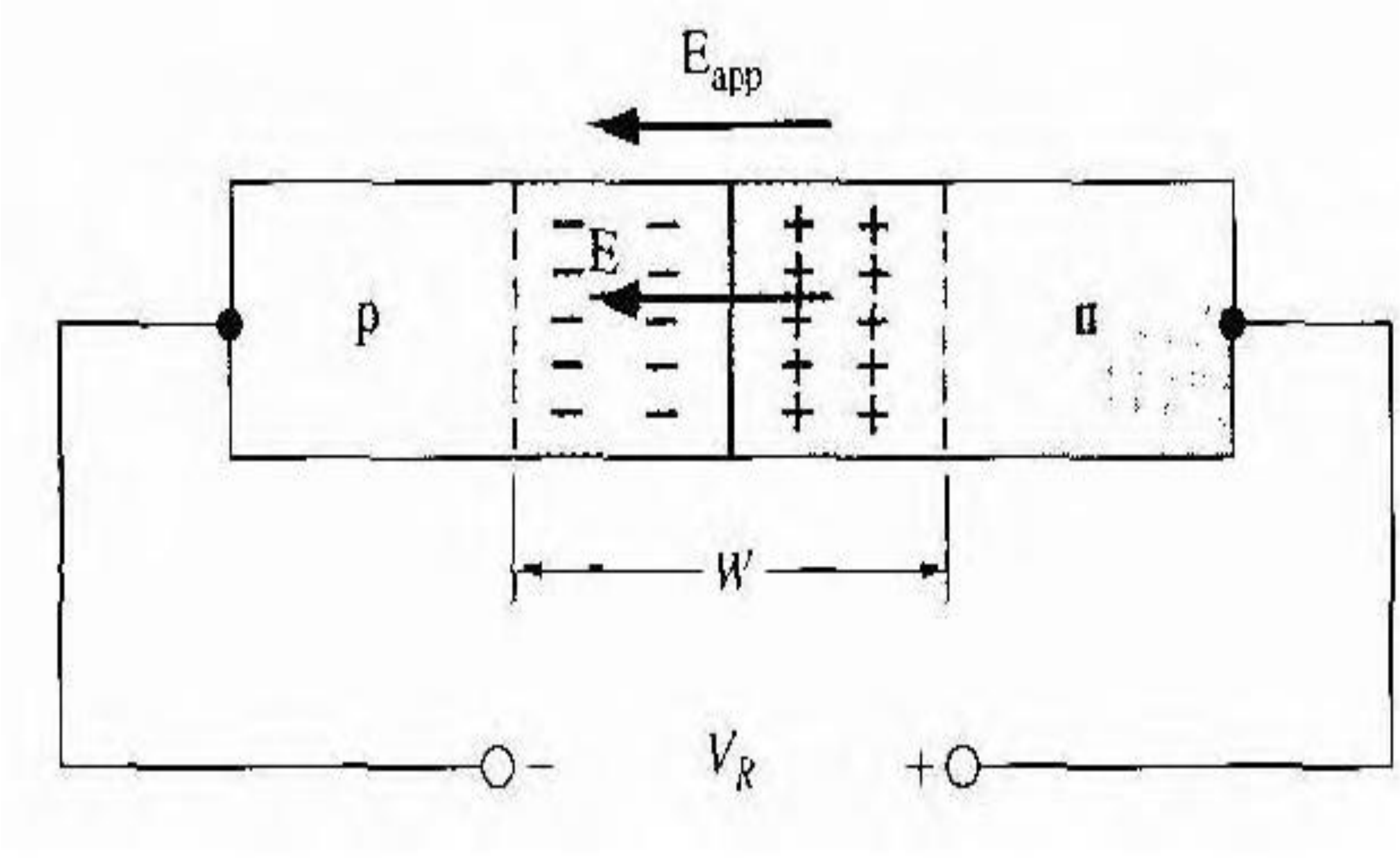
$$E_{\mathbf{max}} = -\left\{\frac{2eV_{bi}}{\varepsilon_s}\left(\frac{N_a N_d}{N_a + N_d}\right)\right\}^{\frac{1}{2}}$$

Since,

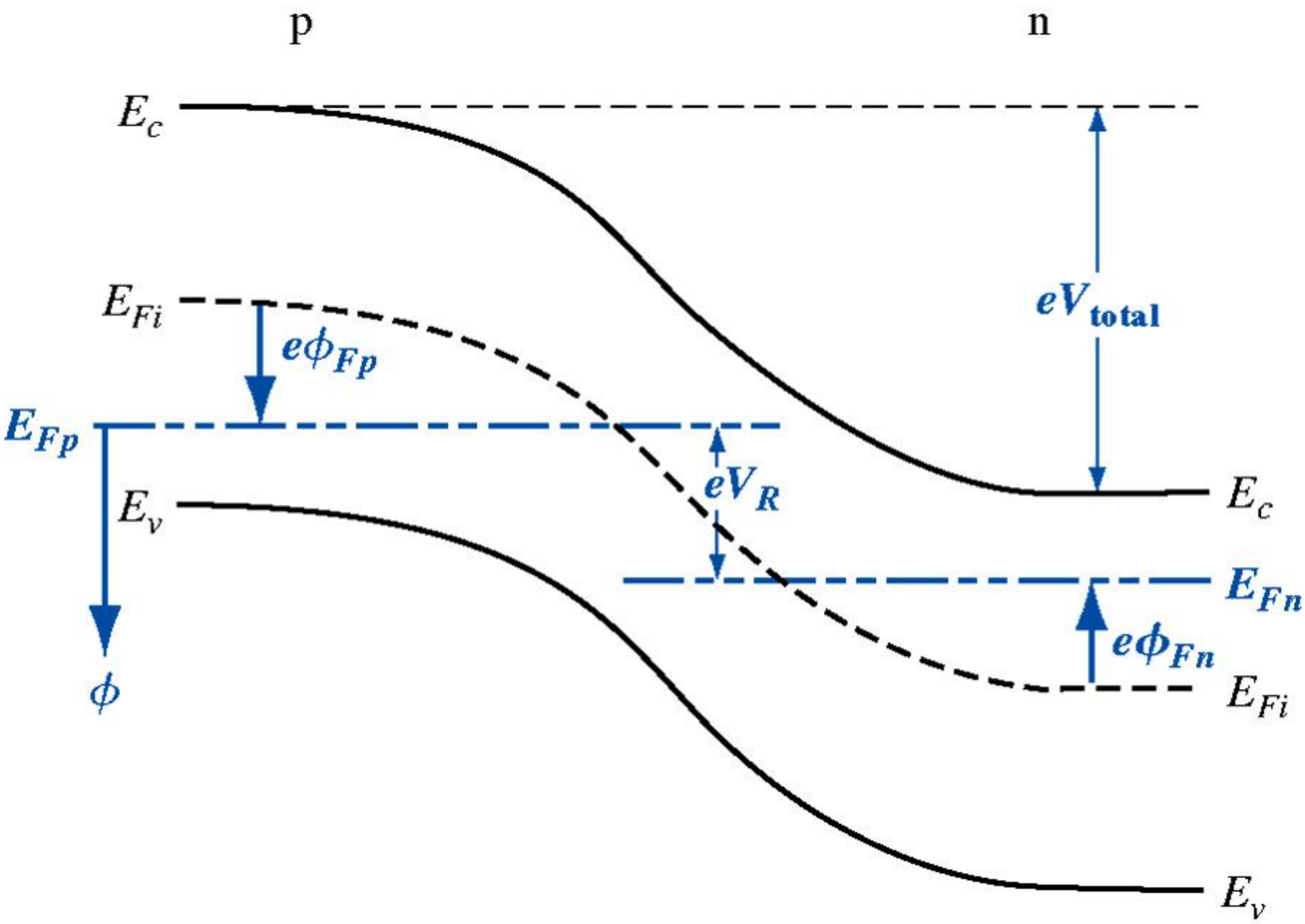
$$W = \left\{\frac{2\epsilon_s V_{bi}}{e}\left[\frac{N_a + N_d}{N_a N_d}\right]\right\}^{1/2}$$

$$E_{\mathbf{max}} = \frac{-2V_{bi}}{W}$$

REVERSE BIAS PN JUNCTION



BAND diagram of REVERSE BIAS PN JUNCTION



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

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

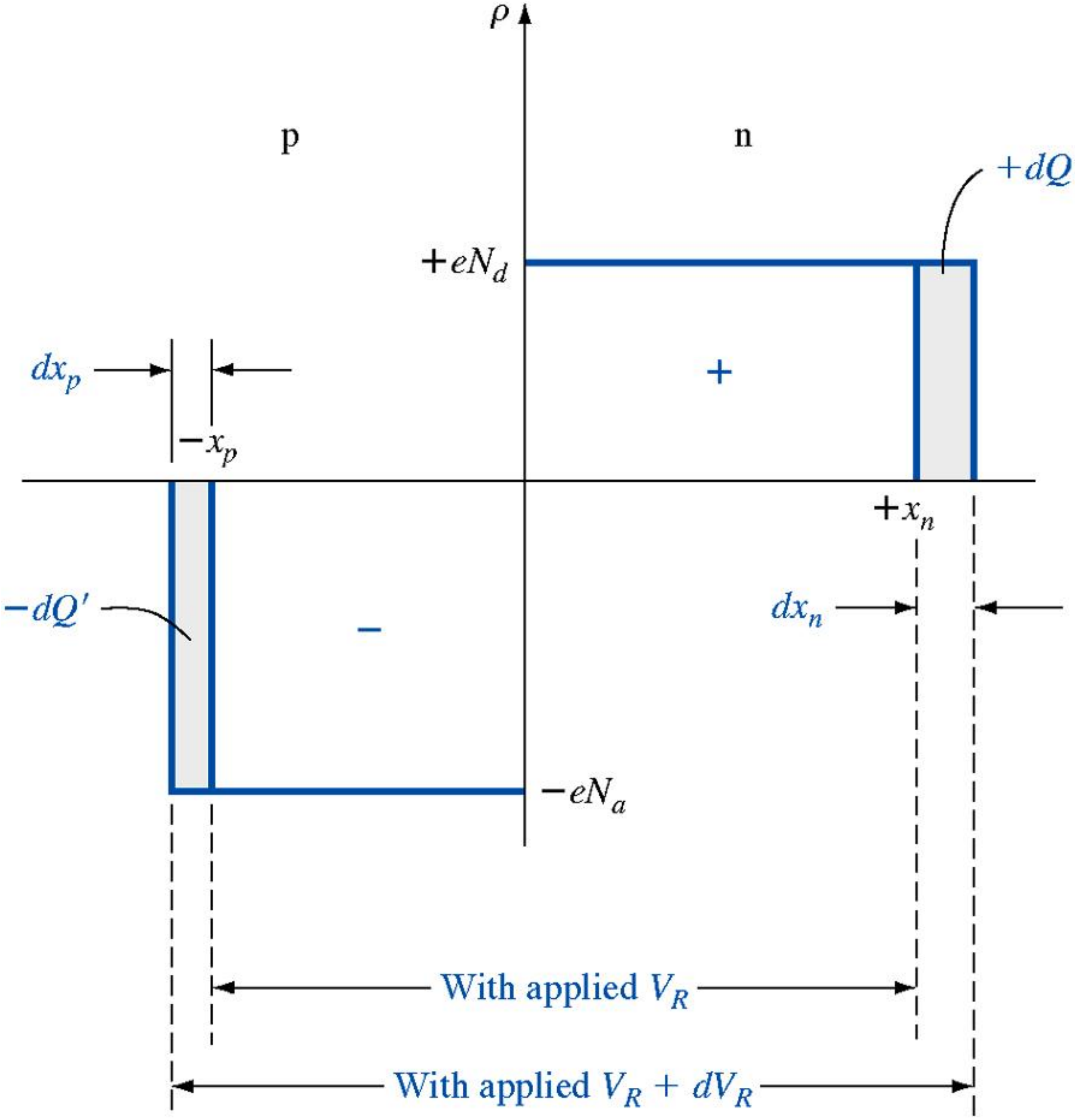
Space charge width

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

Max. Electric field

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

$$\boxed{\mathrm{E}_{\max} = \frac{-2(V_{bi} + V_R)}{W}}$$



ρ
p
n
$+dQ'$
$+eN_d$
dx_p
+
$-x_p$
$+x_n$
$-dQ'$
−
dx_n
$-eN_a$
With applied V_R
With applied $V_R + dV_R$

JUNCTION CAPACITANCE

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

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

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

$$C' = \frac{dQ'}{dV_R} = eN_d\frac{dx_n}{dV_R} \qquad (\mathrm{F/cm^2})$$

Depletion layer capacitance=

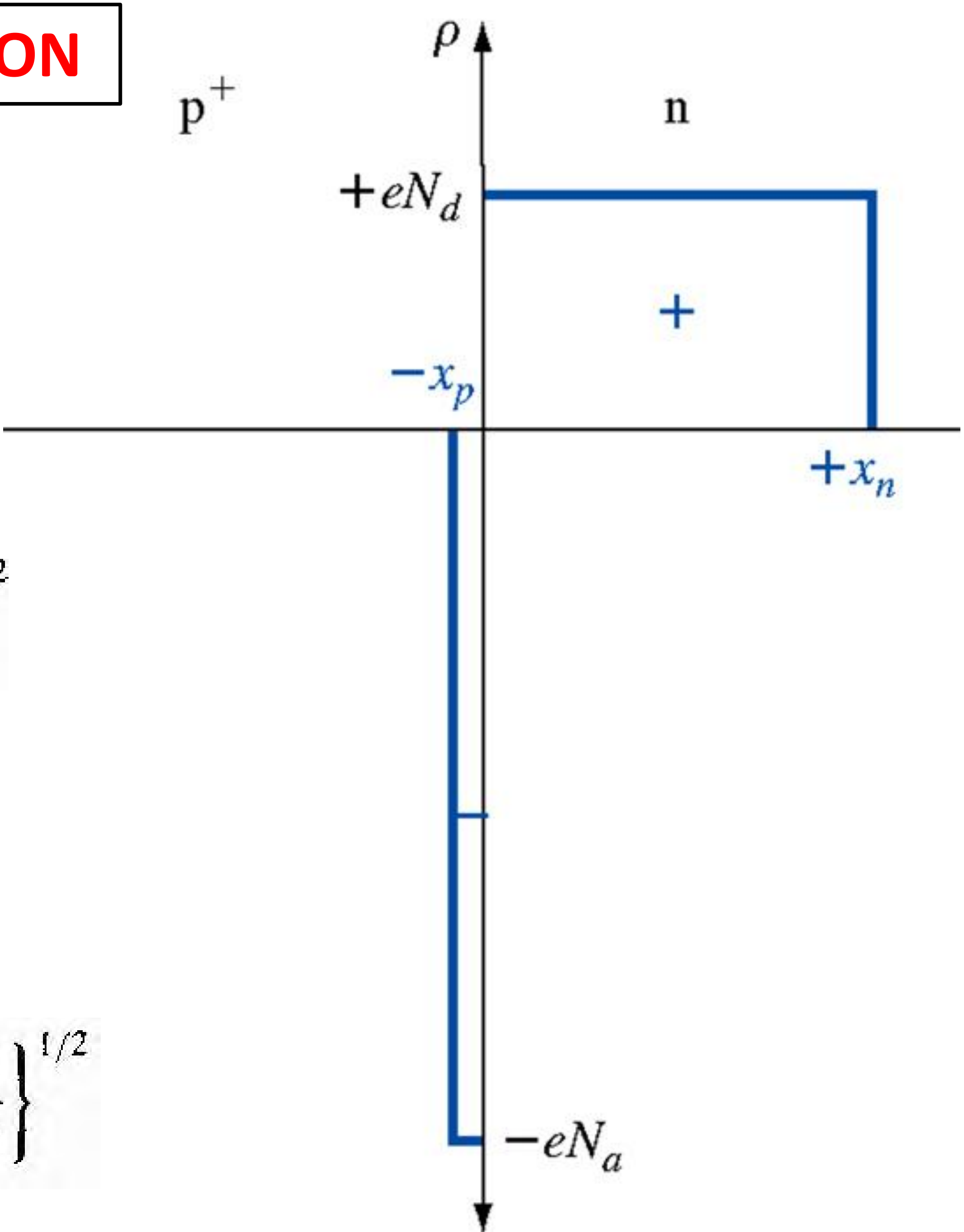
$$\boxed{C' = \left\{\frac{e\epsilon_s N_a N_d}{2(V_{bi}+V_R)(N_a+N_d)}\right\}^{1/2}}$$

$$\boxed{C' = \frac{\epsilon_s}{W}}$$

ONE SIDED JUNCTION

$N_d >> N_a$:- N^+P junction

$N_a >> N_d$:- P^+N junction

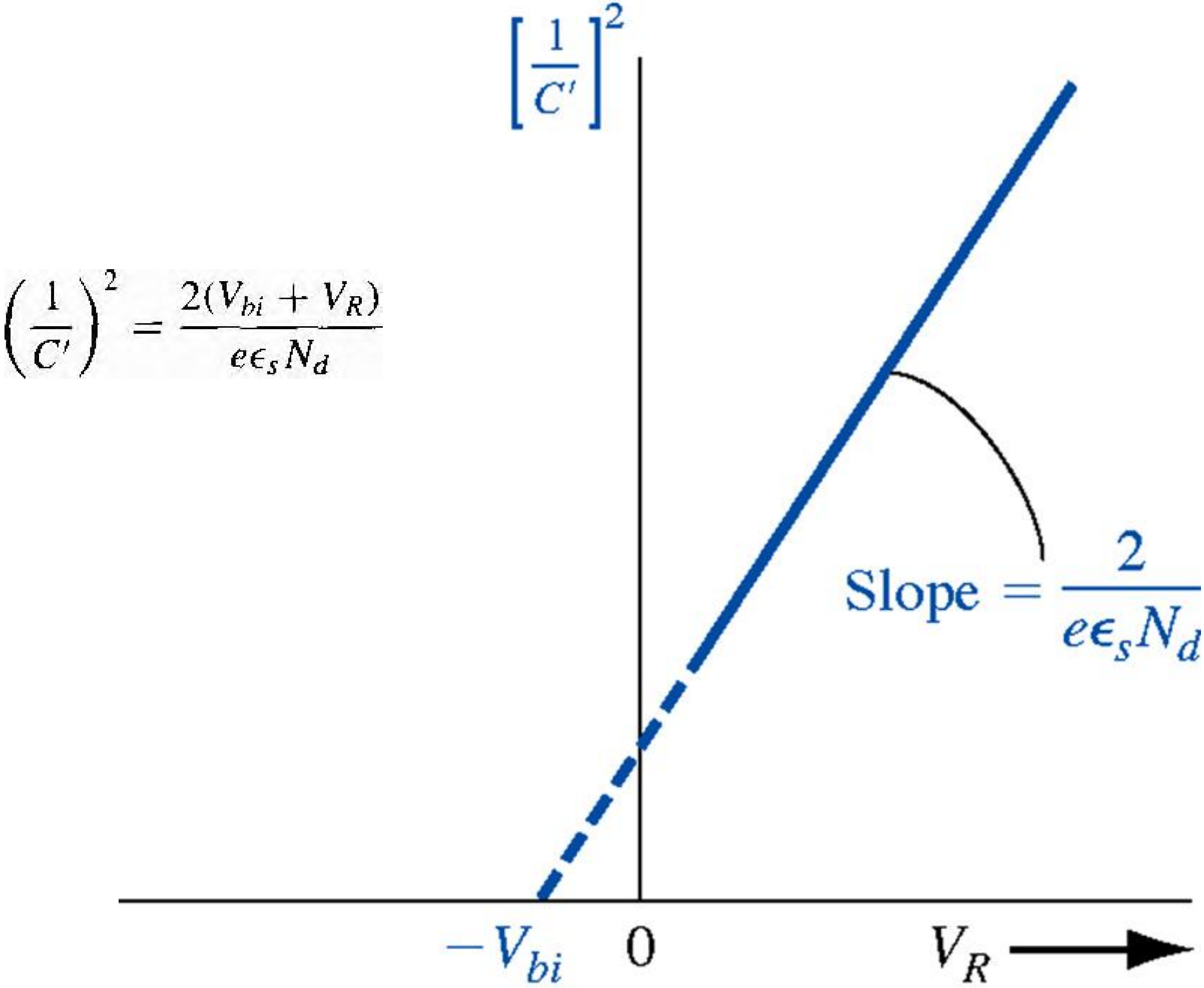


$$W \approx \left\{\frac{2\epsilon_s(V_{bi}+V_R)}{eN_d}\right\}^{1/2}$$

$$x_p \ll x_n$$

$$W \approx x_n$$

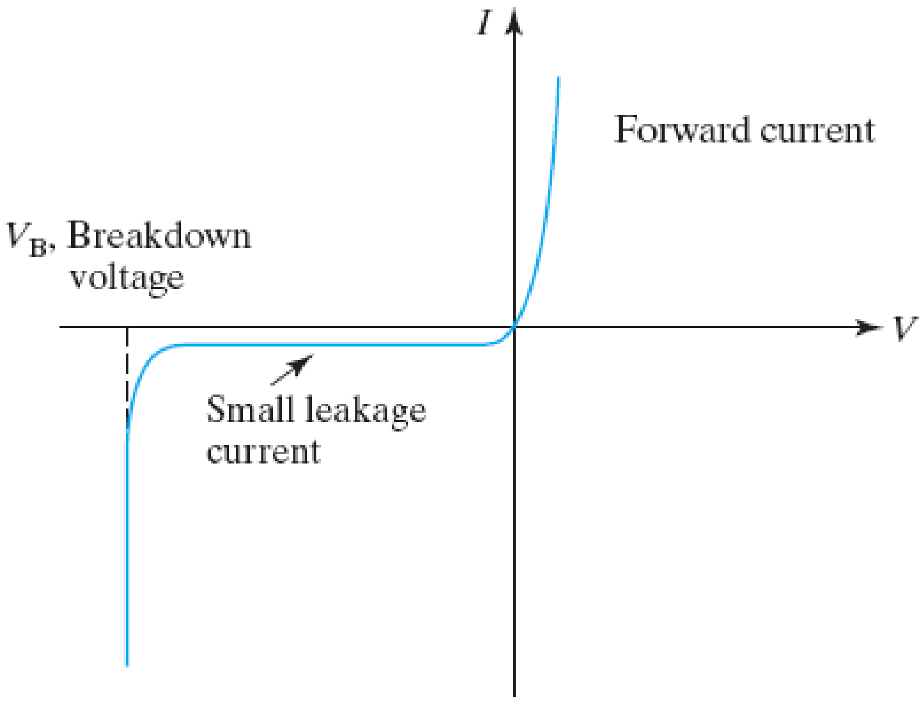
$$C' \approx \left\{\frac{e\epsilon_s N_d}{2(V_{bi}+V_R)}\right\}^{1/2}$$



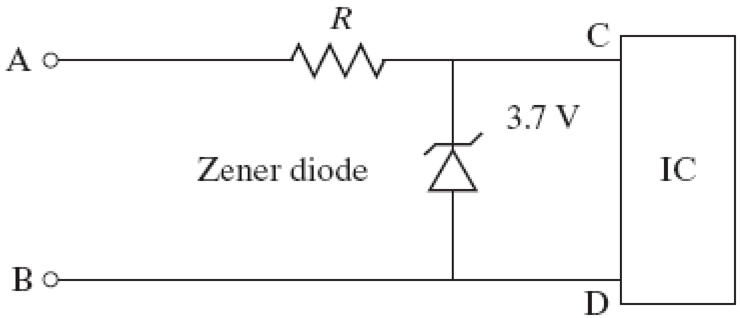
$$\left(\frac{1}{C'}\right)^2 = \frac{2(V_{bi} + V_R)}{e\epsilon_s N_d}$$

JUNCTION BREAKDOWN

As the reverse voltage is made more negative, EF inside SCR increases causing a breakdown beyond breakdown voltage, $V_{B.}$



(a)



(b)

A Zener diode is designed to operate in the breakdown mode.

Breakdown Mechanism:

Breakdown occurs by two mechanisms.

- **Avalanche Breakdown**
  Energetic carriers ionize host atoms and there is carrier multiplication leading to breakdown.
- **Zener Breakdown**
  Electrons from p-region can tunnel to the conduction band in the n-region causing breakdown.

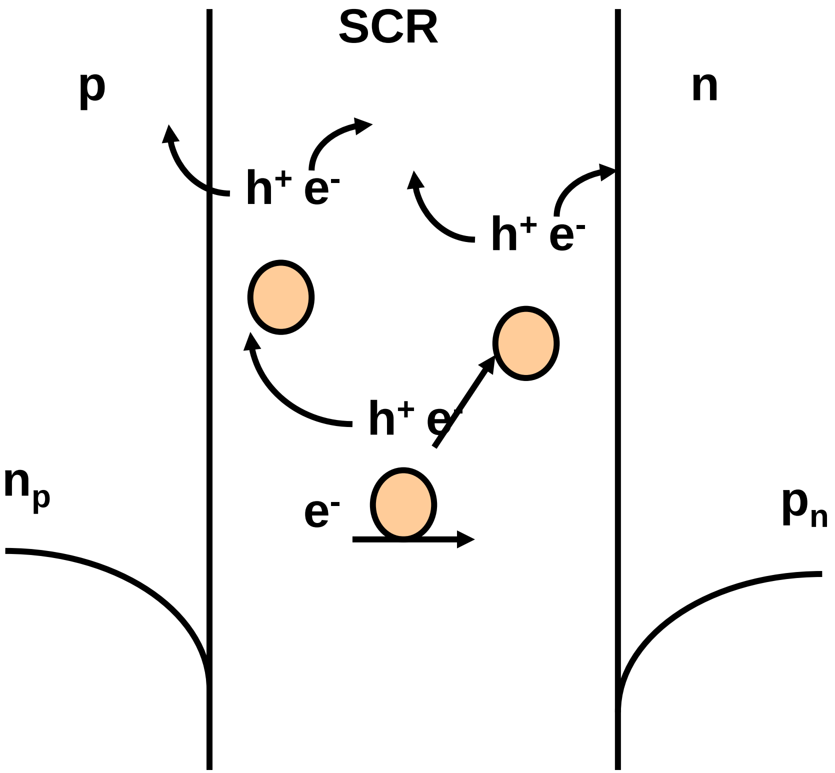
$$If\ \ V_B < 4\frac{E_g}{q}, breakdown is\ Zener.$$

$$If\ \ V_B > 6\frac{E_g}{q}, breakdown is\ Avalanche.$$

$$If\ \ 4\frac{E_g}{q} < V_B < 6\frac{E_g}{q}, breakdown is\ Mixed.$$

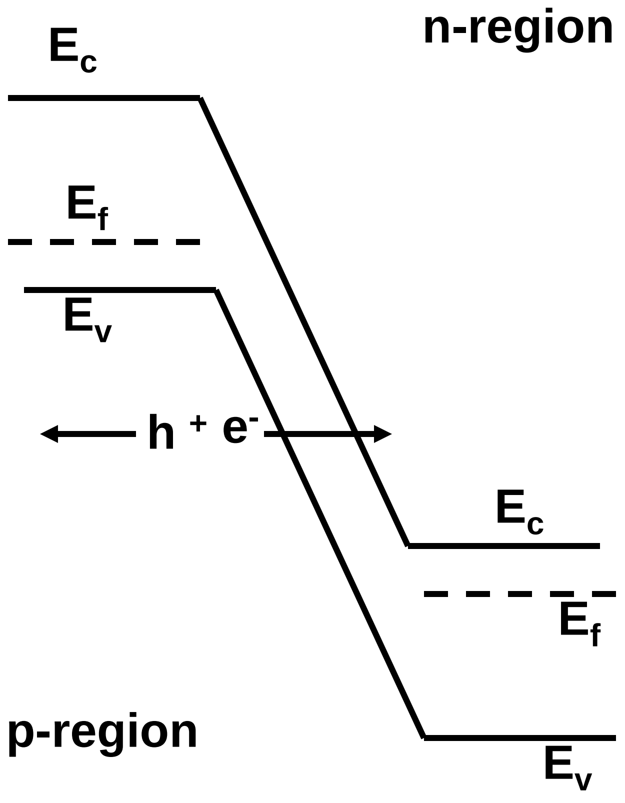
Avalanche Breakdown : in high electric field

- Electrons or holes traveling inside the SCR attain high velocity when reverse bias is high.
- High velocity electrons collide with atoms dislodging an electron from the atom and causing an electron-hole pair to form.
- Each pair will then get accelerated and generate more electron-hole pairs increasing the electron and hole concentration to large values. This is known as **Avalanche multiplication**
- This results in a large reverse bias current leading to breakdown due to creation of carriers by avalanche multiplication.



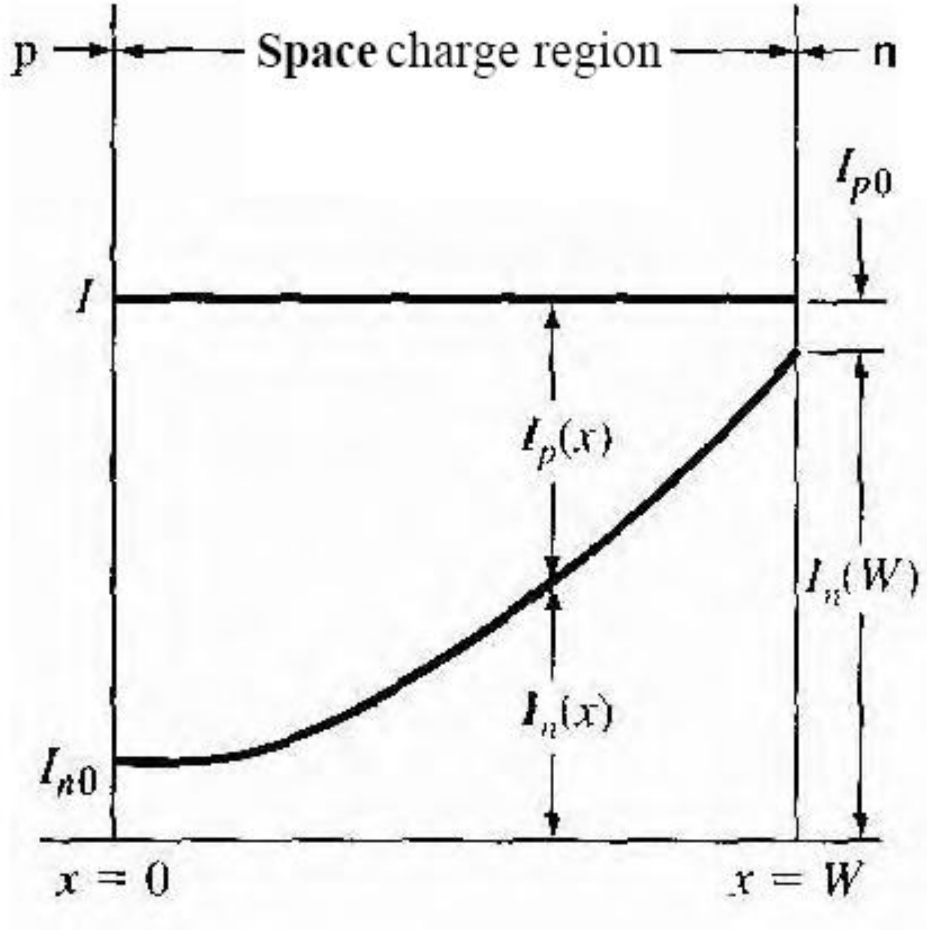
Zener Breakdown : Heavily doped junction

- At high reverse bias the valence band edge of p-region will be at a higher potential than the conduction band edge of the n-region as shown on right.
- Breakdown occurs due to electron tunneling between the valence band of the p-region and conduction band of the n-region. A large reverse current flows. This is known as **Zener Breakdown.**
- Such tunneling is appreciable when the width of the SCR is small. This happens if the p and n regions are heavily doped and there is large electric field present.
- Zener breakdown occurs in highly doped p-n junction.



During reverse biasing hole current is from **n to p** and electron current from **p to n**

Let, $\mathbf{I_{n0}}$ electron current entering from p side at **x=0**
$\mathbf{I_n(W)}$ electron current at **x= W** due to avalanche process



So,

$I_n(W) = M_n I_{n0}$ where M_n is the multification factor

Similarly, hole current enters into the SCR from n side at x=W and is maxm. At x=0

At steady state, total current in the depletion layer is a const.

At any intermediate point in the SCR the electron current

$$dI_n(x) = I_n(x)\alpha_n \, dx + I_p(x)\alpha_p \, dx$$

Where, α‘ are the ionisation rates per length of the carriers

$$\frac{dI_n(x)}{dx} = I_n(x)\alpha_n + I_p(x)\alpha_p$$

As, total Current $I = I_n(x) + I_p(x)$ Then, $\frac{dI_n(x)}{dx} + (\alpha_p - \alpha_n) I_n(x) = \alpha_p I$

Let $\alpha_p = \alpha_n = \alpha$

x varies from 0 to W

So, In (W) – In (0) = I ∫ α dx

$$\frac{M_n I_{n0} - I_n(0)}{I} = \int_0^W \alpha \, dx$$

Since $M_n I_{n0} \approx$ I and since $I_n(0) = I_{n0}$

$$1 - \frac{1}{M_n} = \int_0^W \alpha \, dx$$

Avalanche condition :- $V = V_B$, $M_n = \infty$

The avalanche breakdown condition is then given by $\int_0^W \alpha \, dx = 1$

$$For\ p^{+}n\ junction,\ N_a >> N_d$$

$$\left|E_{\mathbf{max}}\right| = \frac{eN_d x_n}{\varepsilon_s} \quad as\, V_{bi} << V_R,$$

$$= \frac{eN_d}{\varepsilon_s}\left\{\frac{2\varepsilon_s V_R}{e}\frac{1}{N_d}\right\}^{\frac{1}{2}}$$

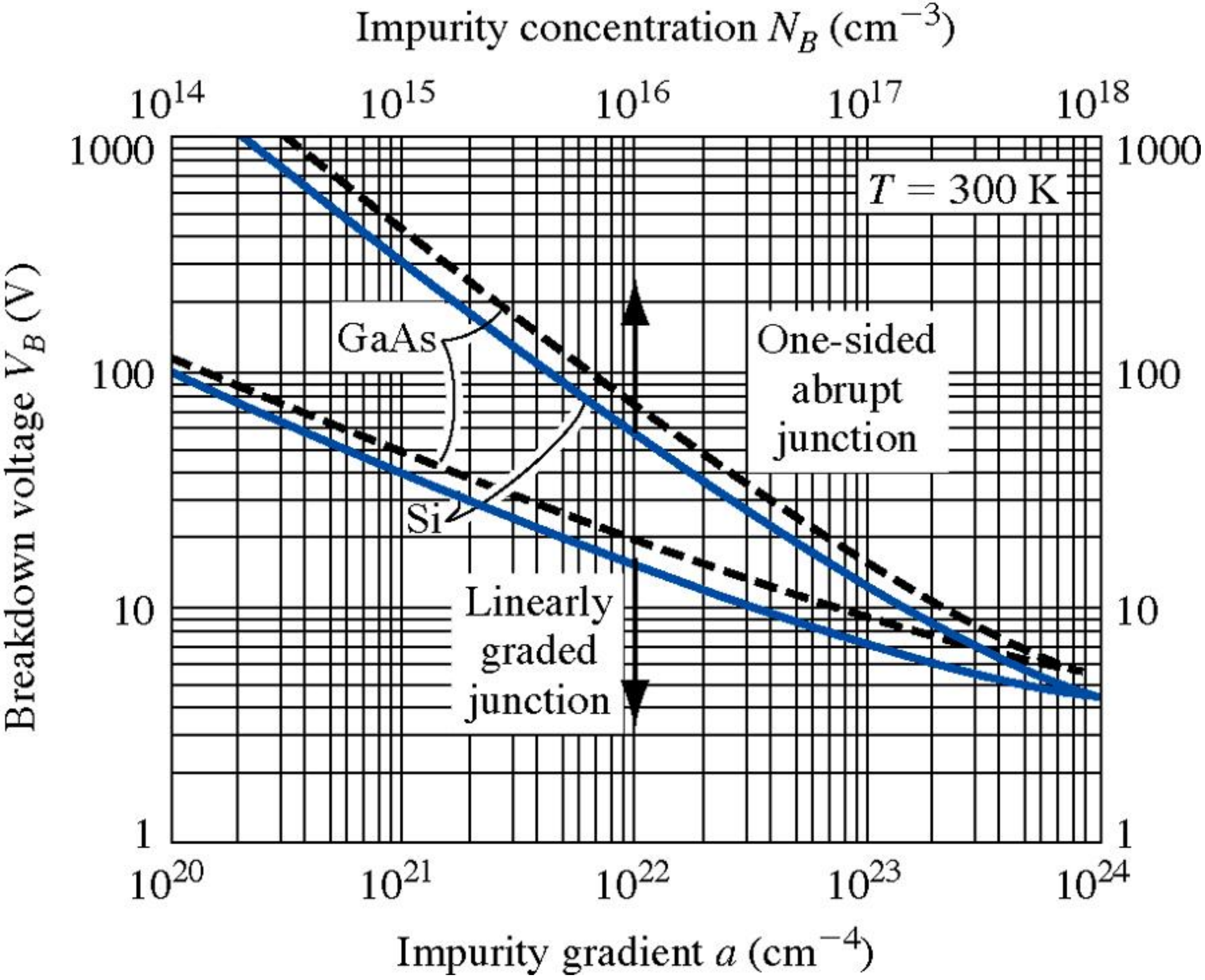
$$When\quad V_R = V_B\,(break\quad down\quad potential\quad),\quad then\quad E_{\mathbf{max}} = E_{critical}$$

$$Putting\quad these\quad values\quad ,$$

$$\left|V_B\right| \quad = \quad \frac{\varepsilon_s\ E_{critical}^2}{2qN_d}$$

If N_d ↑, $|V_b|$ ↓.

For higher breakdown voltage, silicon must be purer.


Impurity concentration N_B (cm^{-3})
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
1000
100
10
1
T = 300 K
GaAs
Si
One-sided abrupt junction
Linearly graded junction
Breakdown voltage V_B (V)
10^{20}
10^{21}
10^{22}
10^{23}
10^{24}
Impurity gradient a (cm^{-4})