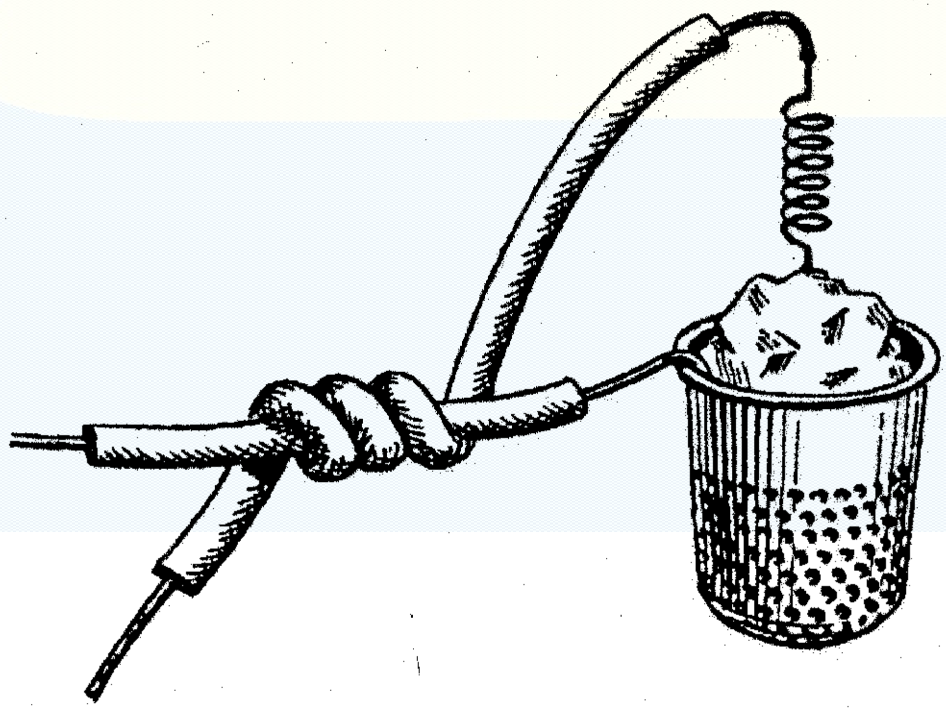
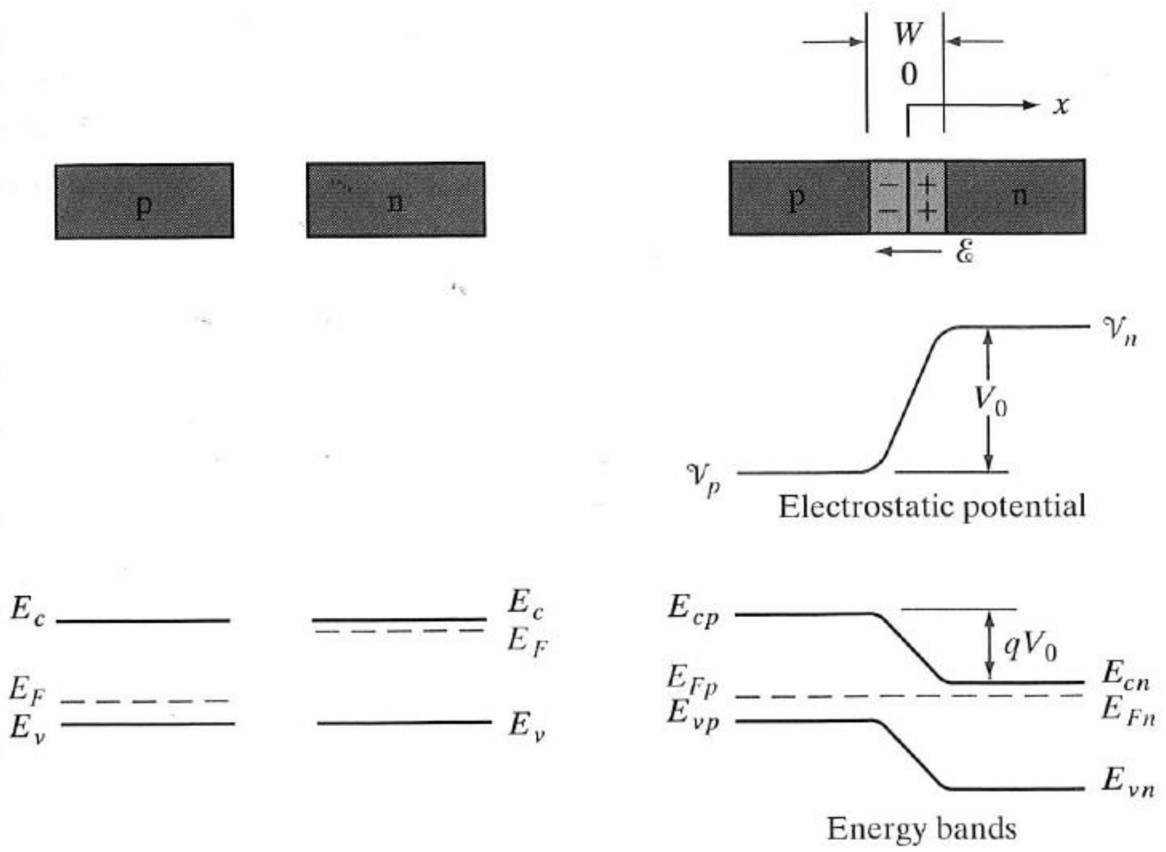
Semiconductor Devices
Lecture 5, pn-Junction Diode

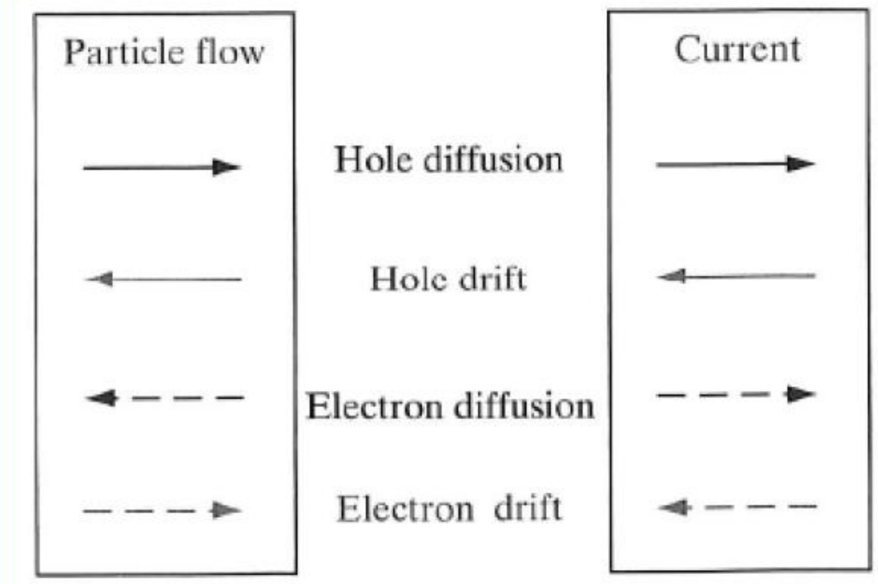


Content

– Contact potential
– Space charge region, Electric Field, depletion depth
– Current-Voltage characteristic
– Depletion layer capacitance
– Diffusion capacitance
– Transient Behavior
– Junction Breakdown

Contact potential, in Equilibrium and without applied voltage





$$J_p(\text{drift}) + J_p(\text{diff.}) = 0$$

$$J_n(\text{drift}) + J_n(\text{diff.}) = 0$$

Contact potential, in Equilibrium and without applied voltage

$$\boxed{J_p(x) = q\left[\mu_p p(x)\mathscr{E}(x) - D_p \frac{dp(x)}{dx}\right] = 0}$$

Current density is =0

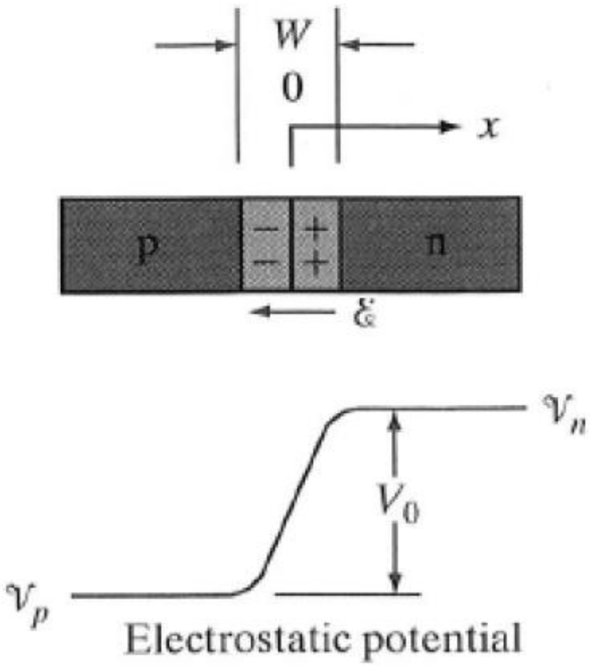
$$\boxed{\frac{\mu_p}{D_p}\mathscr{E}(x) = \frac{1}{p(x)}\frac{dp(x)}{dx}}$$

$$\xrightarrow[\boxed{\frac{D}{\mu} = \frac{kT}{q}}]{\boxed{\mathscr{E}(x) = -d\mathscr{V}(x)/dx,}}$$

$$\boxed{-\frac{q}{kT}\frac{d\mathscr{V}(x)}{dx} = \frac{1}{p(x)}\frac{dp(x)}{dx}}$$

Einstein-relation

Contact potential, in Equilibrium and without applied voltage



$$-\frac{q}{kT}\int_{\mathcal{V}_p}^{\mathcal{V}_n} d\mathcal{V} = \int_{p_p}^{p_n}\frac{1}{p}dp$$

$$-\frac{q}{kT}(\mathcal{V}_n - \mathcal{V}_p) = \ln p_n - \ln p_p = \ln\frac{p_n}{p_p}$$

$$V_0 = \frac{kT}{q}\ln\frac{p_p}{p_n}$$

Contact potential, in Equilibrium and without applied voltage

$$p_p = N_a$$

$$p_p n_p = n_i^2 = p_n n_n$$

$$\frac{p_p}{p_n} = \frac{n_n}{n_p} = e^{qV_0/kT}$$

$$V_0 = \frac{kT}{q} \ln \frac{N_a}{n_i^2/N_d} = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2}$$

$$p_n \cdot n_n = p_n \cdot N_d = n_i^2$$

Contact potential, in Equilibrium and without applied voltage

Problem

Calculate the built-in potential for a silicon $p-n$ junction with $N_A = 10^{18}\ \mathrm{cm}^{-3}$ and $N_D = 10^{15}\ \mathrm{cm}^{-3}$ at 300 K.

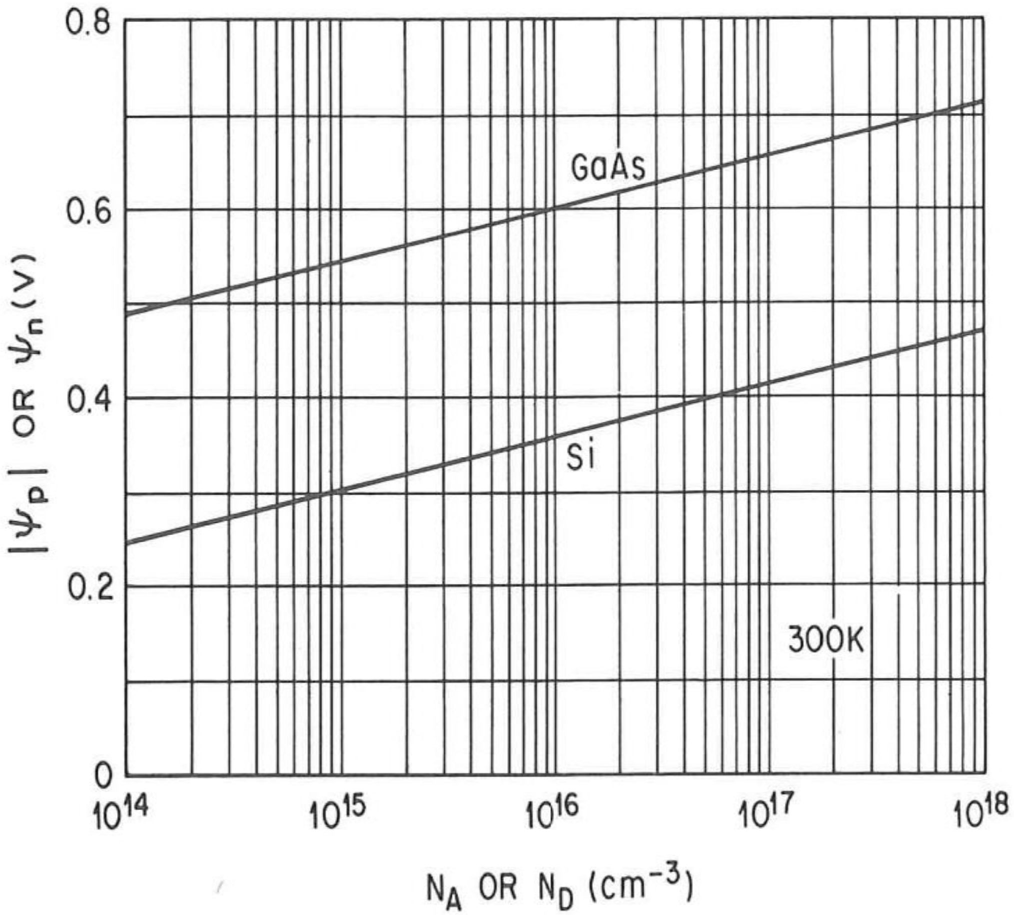
Solution

From Eq. 12 we obtain

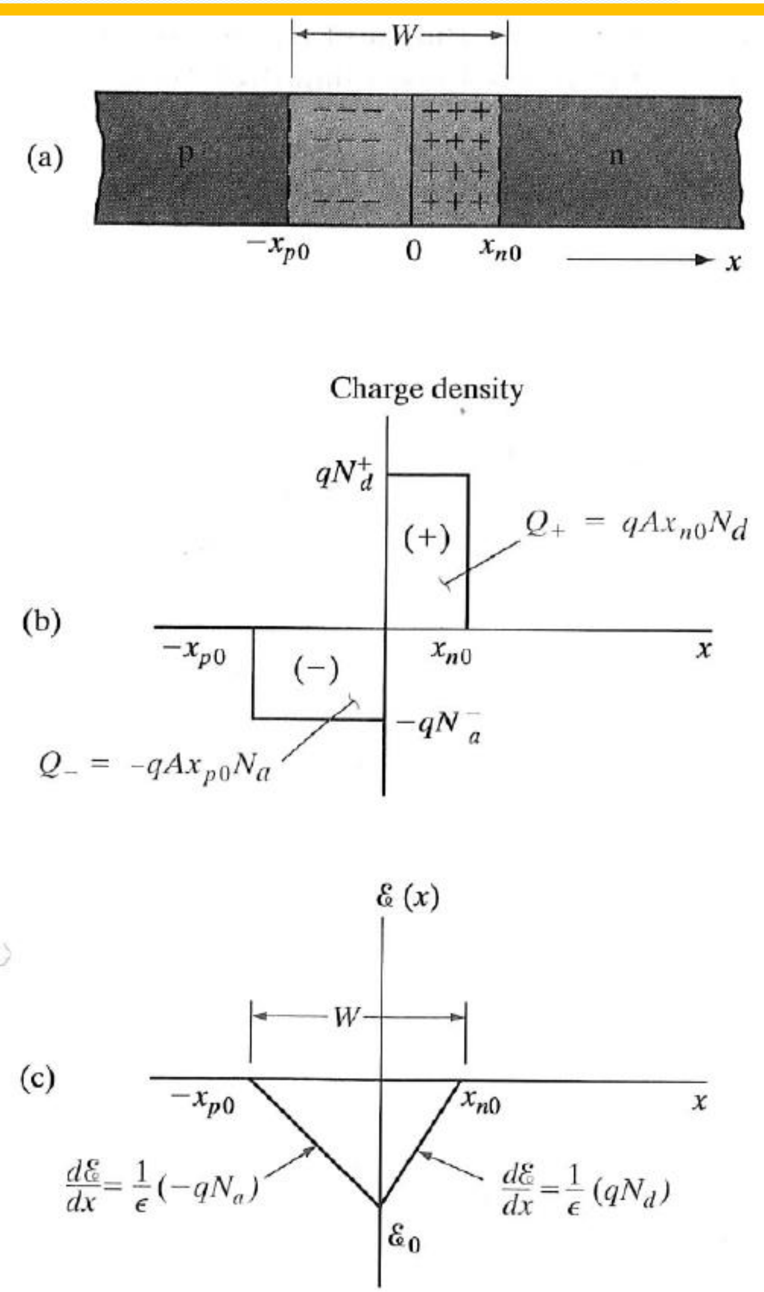
$$V_{bi} = (0.0259)\ \ln \frac{10^{18} \times 10^{15}}{(1.45 \times 10^{10})^2} = 0.755\ \mathrm{V}$$

Also from Fig. 4,

$$V_{bi} = \psi_n + |\psi_p| = 0.30\,\mathrm{V} + 0.46\,\mathrm{V} = 0.76\,\mathrm{V}.$$



Space charge region, Electric Field



$$qAx_{p0}N_a = qAx_{n0}N_d$$

Poisson's ekvation

$$\frac{d\mathscr{E}(x)}{dx} = \frac{q}{\epsilon}(p - n + N_d^+ - N_a^-)$$

Only fixed charge is used!

$$\frac{d\mathscr{E}}{dx} = \frac{q}{\epsilon}N_d, \qquad 0 < x < x_{n0}$$

$$\frac{d\mathscr{E}}{dx} = -\frac{q}{\epsilon}N_a, \qquad -x_{p0} < x < 0$$

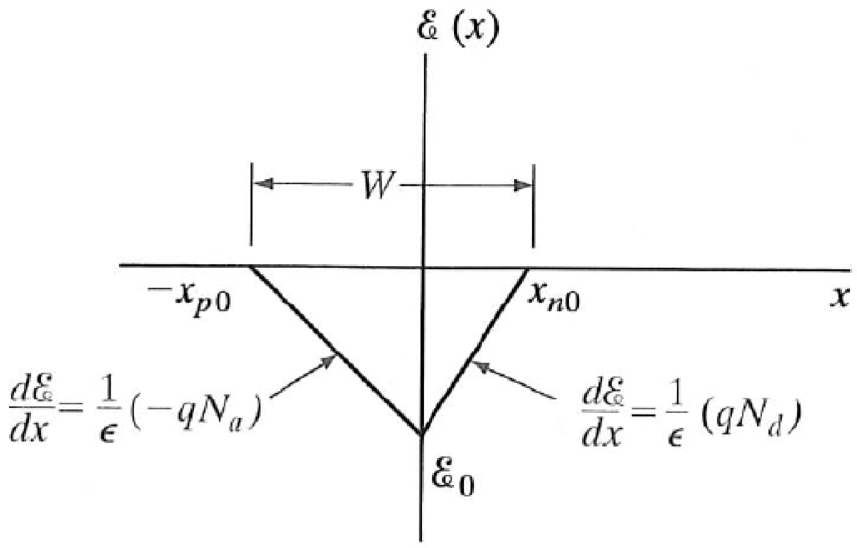
Space charge region, Electric Field

$$\int_{\mathcal{E}_0}^{0} d\mathcal{E} = \frac{q}{\epsilon} N_d \int_{0}^{x_{n0}} dx, \qquad 0 < x < x_{n0}$$

$$\int_{0}^{\mathcal{E}_0} d\mathcal{E} = -\frac{q}{\epsilon} N_a \int_{-x_{p0}}^{0} dx, \quad -x_{p0} < x < 0$$

$$\mathcal{E}_0 = -\frac{q}{\epsilon} N_d x_{n0} = -\frac{q}{\epsilon} N_a x_{p0}$$

(c)



Space charge region, Electric Field

$$\mathscr{E}(x) = -\frac{d\mathscr{V}(x)}{dx} \quad \text{or} \quad -V_0 = \int_{-x_{p0}}^{x_{n0}} \mathscr{E}(x)dx$$

$$V_0 = -\frac{1}{2}\mathscr{E}_0 W = \frac{1}{2}\frac{q}{\epsilon}N_d x_{n0} W$$

The area under E(x)

$x_{n0}N_d = x_{p0}N_a$,

$W = x_{n0} + x_{p0}$

$$V_0 = \frac{1}{2}\frac{q}{\epsilon}\frac{N_a N_d}{N_a + N_d}W^2$$

Contact potential expressed in doping level and depletion depth

Space charge region, depletion depth

$$W = \left[\frac{2\epsilon V_0}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2} = \left[\frac{2\epsilon V_0}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)\right]^{1/2}$$

$$W = \left[\frac{2\epsilon kT}{q^2}\left(\ln\frac{N_a N_d}{n_i^2}\right)\left(\frac{1}{N_a} + \frac{1}{N_d}\right)\right]^{1/2}$$

$$x_{p0} = \frac{W N_d}{N_a + N_d} = \frac{W}{1 + N_a/N_d} = \left\{\frac{2\epsilon V_0}{q}\left[\frac{N_d}{N_a(N_a + N_d)}\right]\right\}^{1/2}$$

$$x_{n0} = \frac{W N_a}{N_a + N_d} = \frac{W}{1 + N_d/N_a} = \left\{\frac{2\epsilon V_0}{q}\left[\frac{N_a}{N_d(N_a + N_d)}\right]\right\}^{1/2}$$

What happened with x_{p0} and x_{n0} if N_a or N_d is large?

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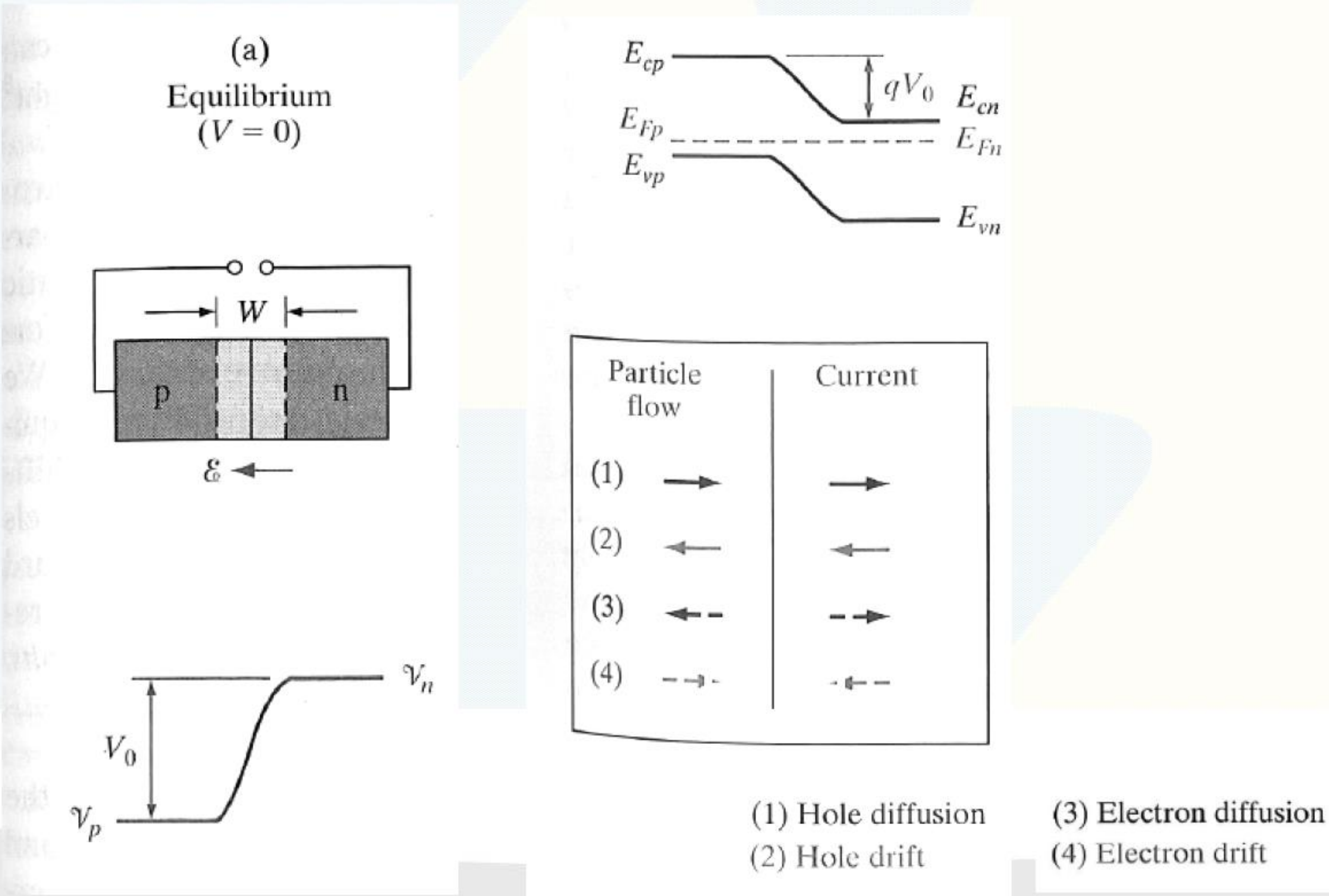
Current-Voltage characteristic



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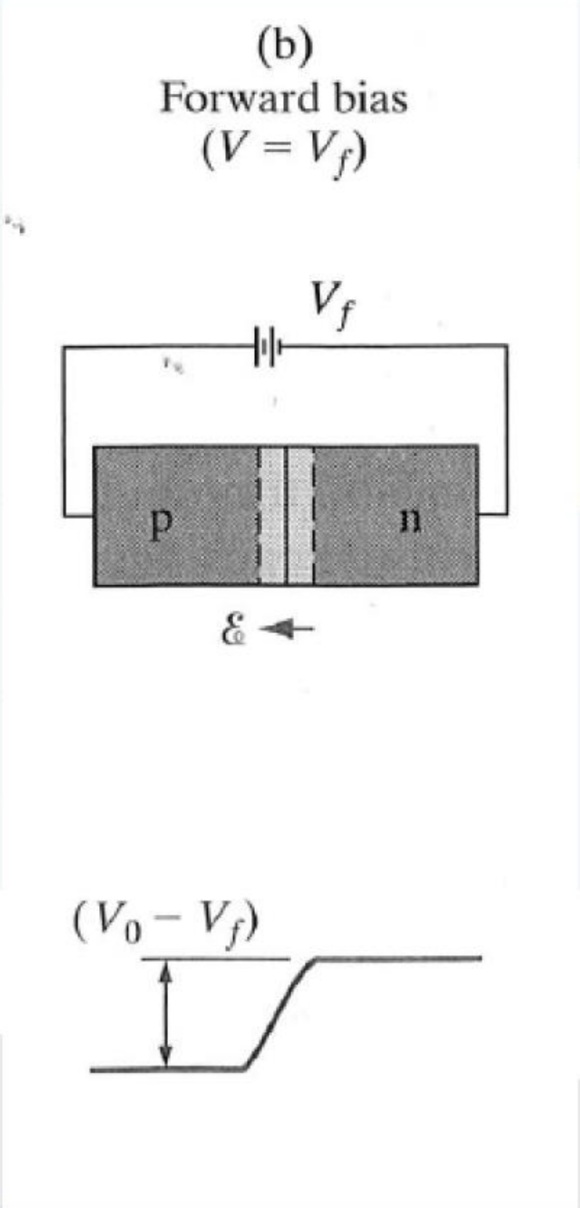
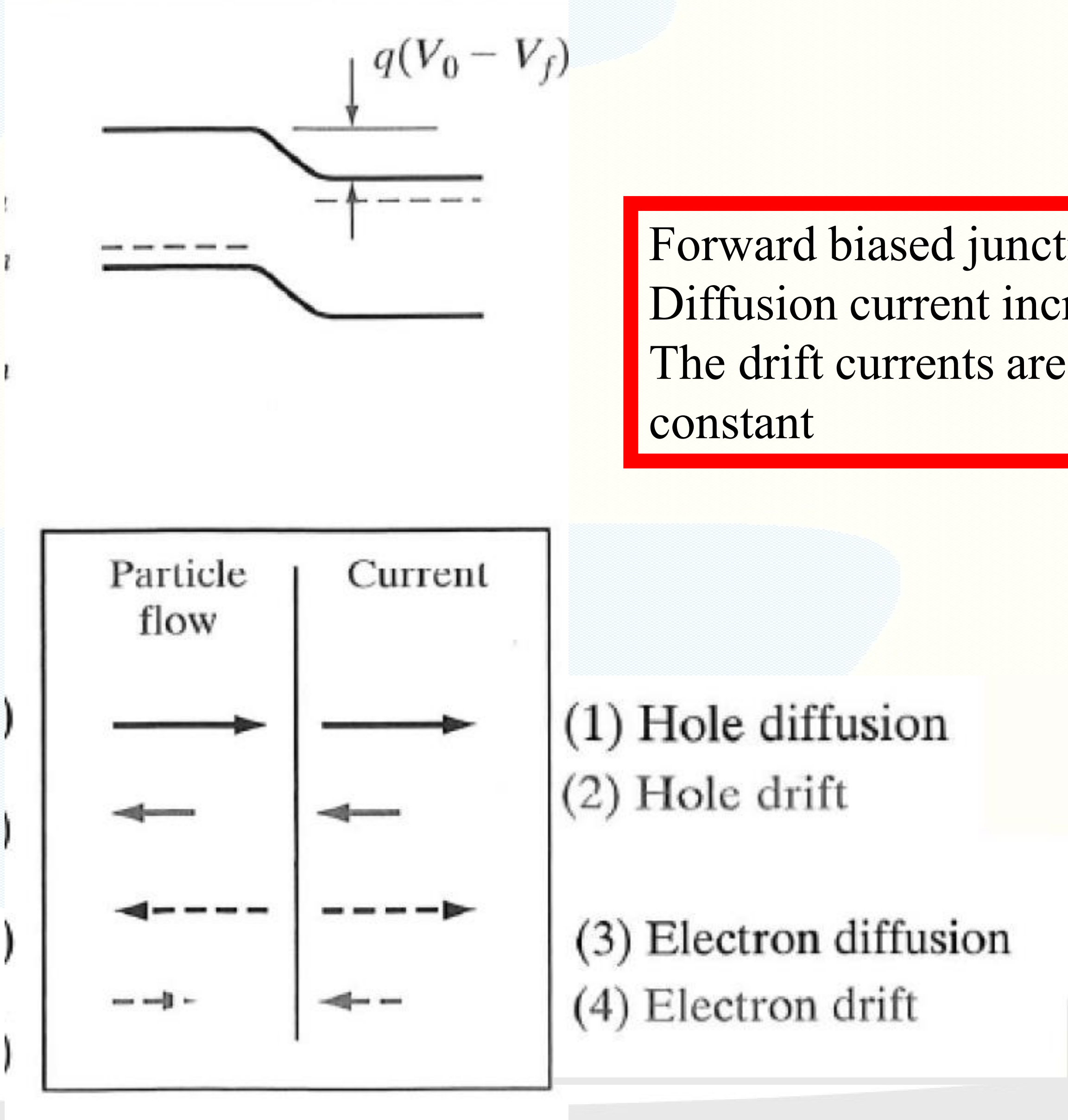
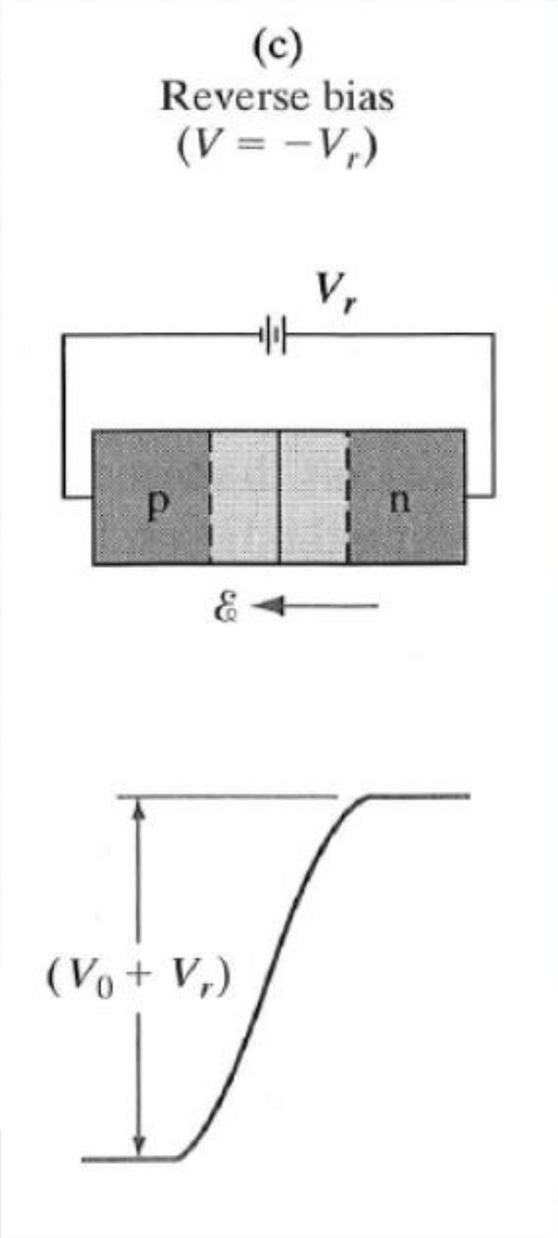
Current-Voltage Characteristic

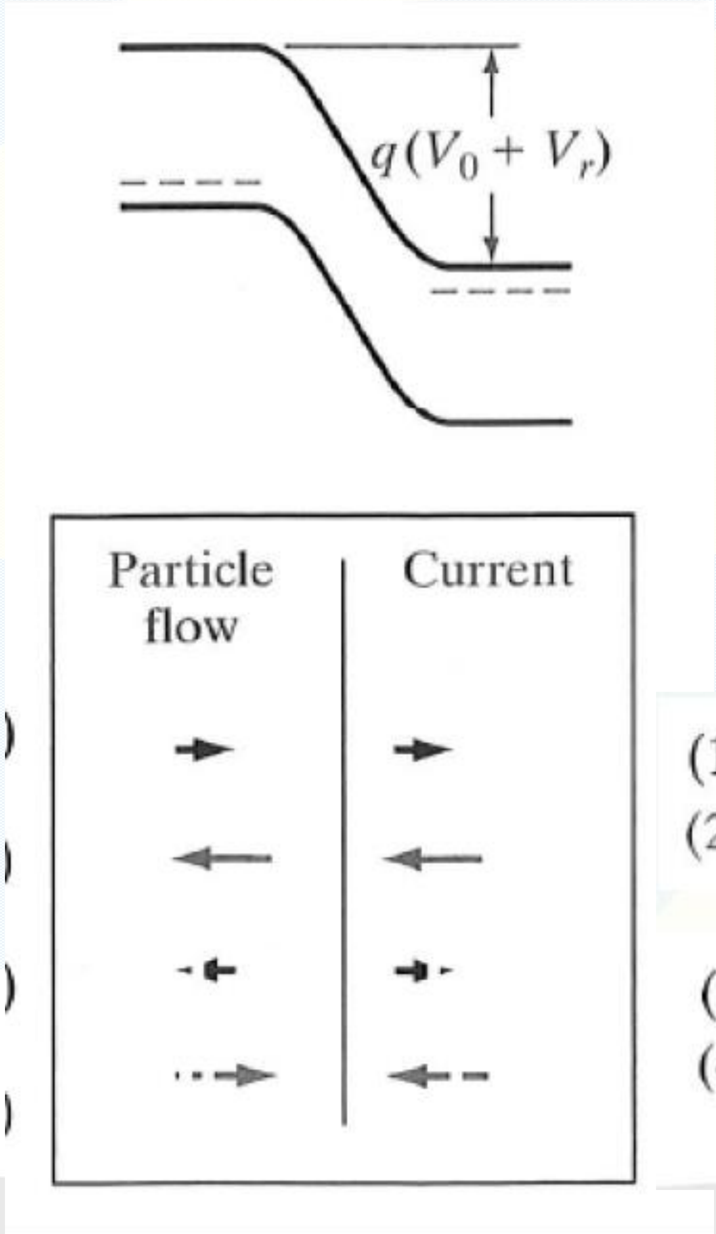




Forward biased junction: Diffusion current increase. The drift currents are almost constant

Current-Voltage Characteristic



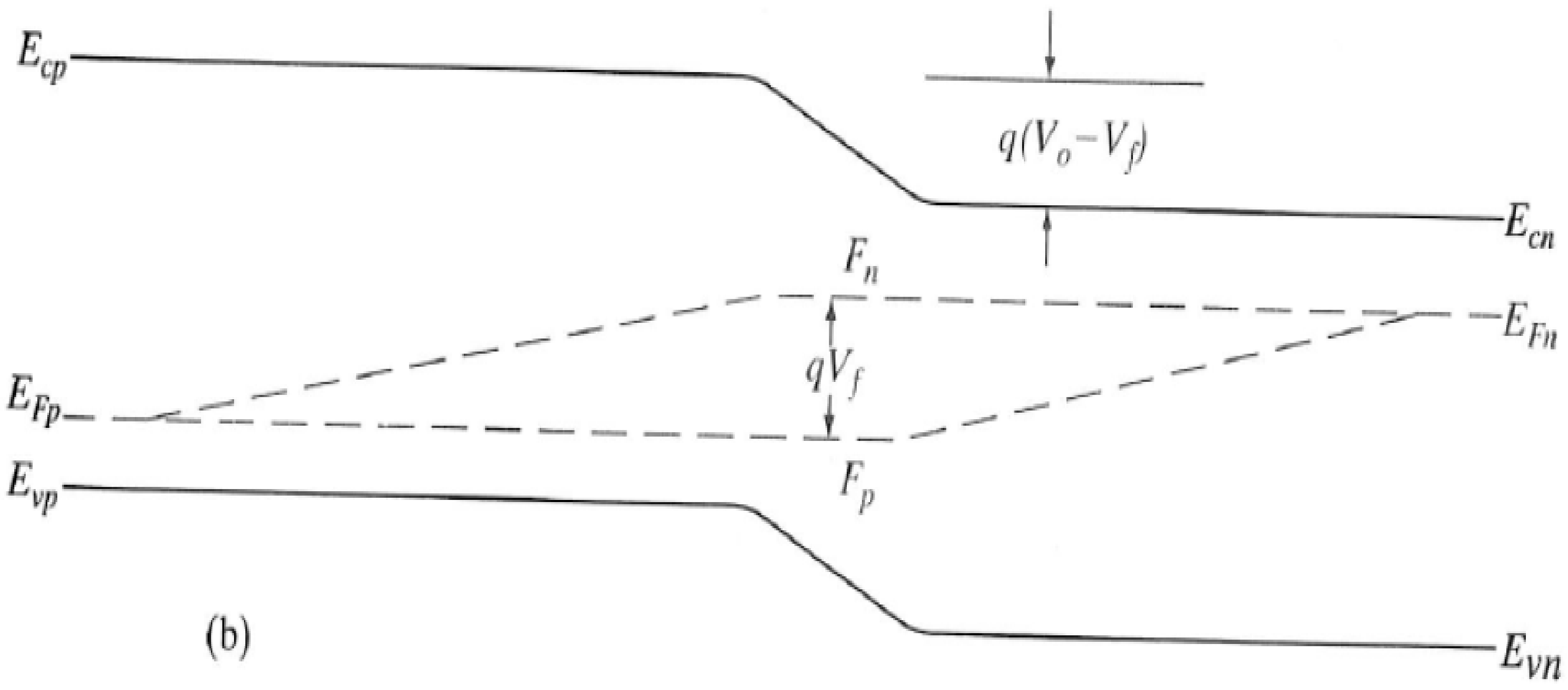


Reverse biased junction: Diffusion current decrease. The drift currents are almost constant

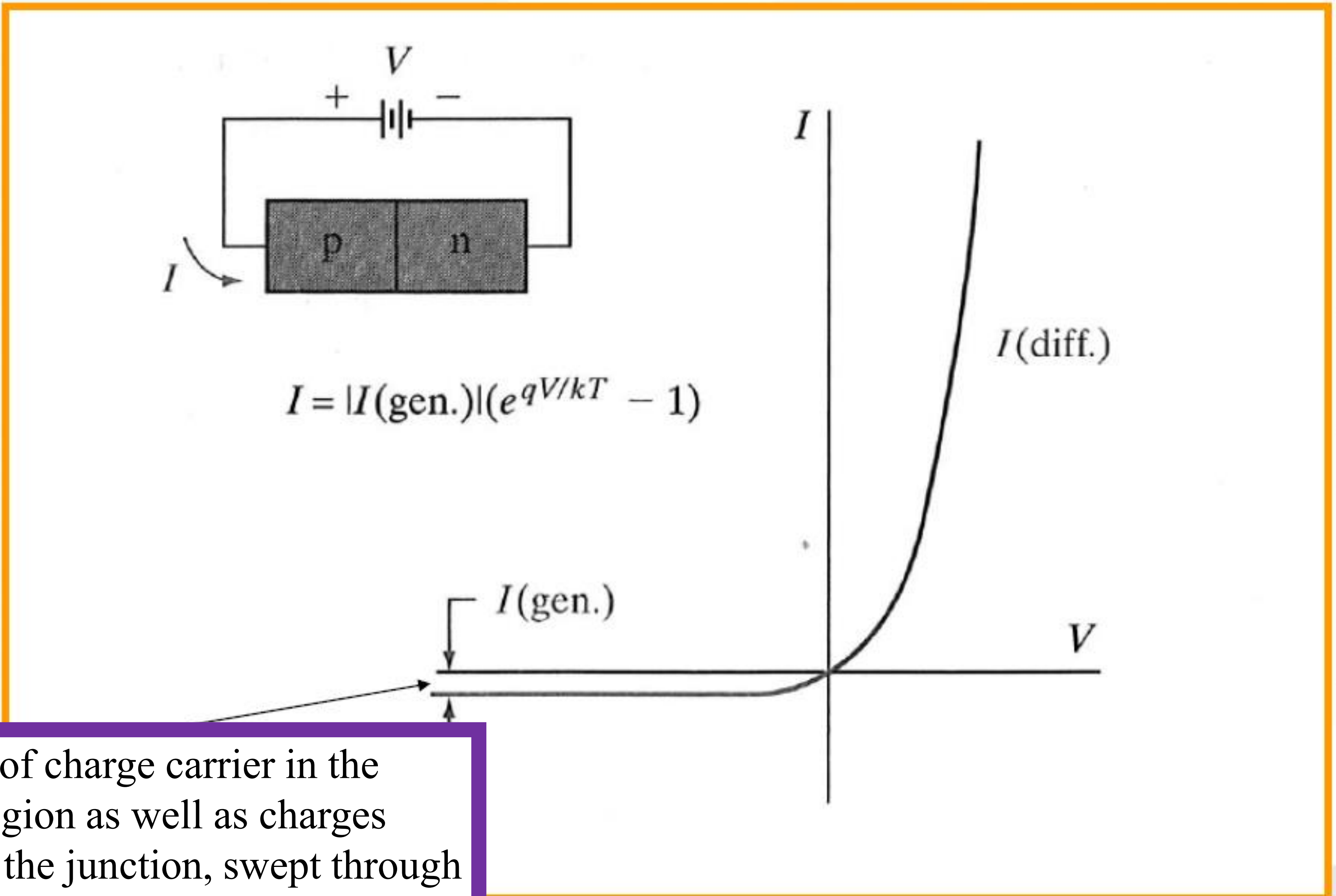
(1) Hole diffusion
(2) Hole drift

(3) Electron diffusion
(4) Electron drift

Current-Voltage Characteristic, forward bias junctions



Current-Voltage Characteristic



Generation of charge carrier in the depletion region as well as charges diffuse into the junction, swept through the depletion layer by the electric field, result into a leakage current of the device

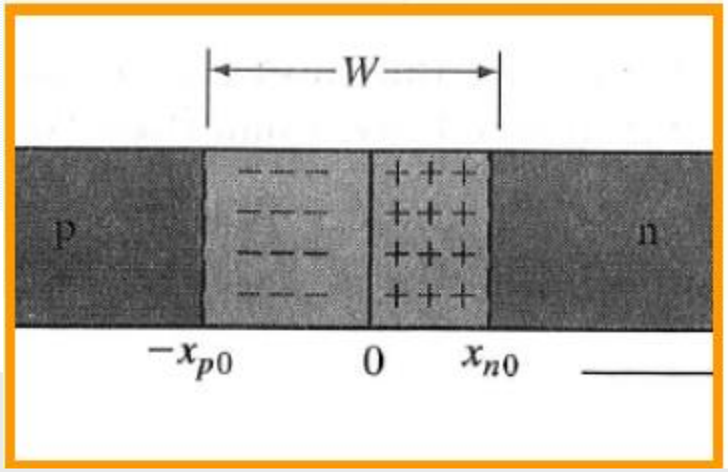
Current-Voltage Characteristic, injection of minority carrier (forward bias)

$$\frac{p_p}{p_n} = e^{qV_0/kT}$$

1) Contact potential caused by a different concentration across the junction

$$\frac{p(-x_{p0})}{p(x_{n0})} = e^{q(V_0-V)/kT}$$

2) With bias applied



1/2 gives

$$\frac{p(x_{n0})}{p_n} = e^{qV/kT}$$

Current-Voltage Characteristic, injection of minority carrier (forward bias)

$$p(xno) = pne^{qv/kT}$$
$$p(xno) - pn = pne^{qv/kT} - pn$$

Subtracting equilibrium hole and electron conc.

$$\Delta p_n = p(x_{n0}) - p_n = p_n(e^{qV/kT} - 1)$$

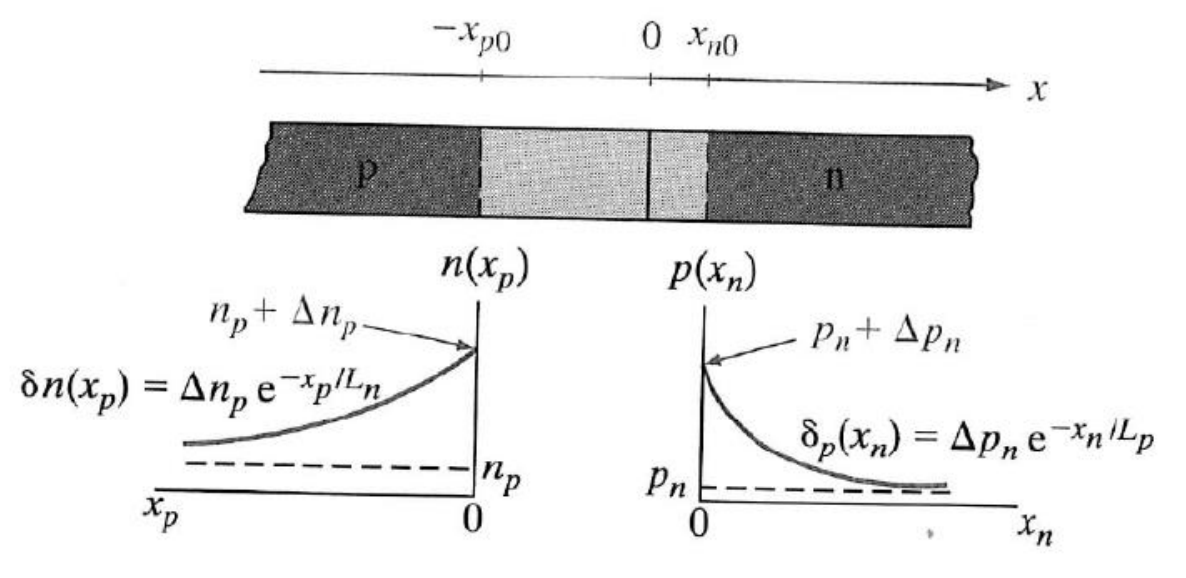
$$\Delta n_p = n(-x_{p0}) - n_p = n_p(e^{qV/kT} - 1)$$

$$\delta n(x_p) = \Delta n_p e^{-x_p/L_n} = n_p(e^{qV/kT} - 1)e^{-x_p/L_n}$$

$$\delta p(x_n) = \Delta p_n e^{-x_n/L_p} = p_n(e^{qV/kT} - 1)e^{-x_n/L_p}$$

Diffusion length

$$L_n \equiv \sqrt{D_n \tau_n}$$



Current-Voltage Characteristic, injection of minority carrier (forward bias)

Hole diffusion current at point x_n

$$I_p(x_n) = -qAD_p\frac{d\delta p(x_n)}{dx_n} = qA\frac{D_p}{L_p}\Delta p_n e^{-x_n/L_p} = qA\frac{D_p}{L_p}\delta p(x_n)$$

Hole current injected into the n-material

$$I_p(x_n = 0) = \frac{qAD_p}{L_p}\Delta p_n = \frac{qAD_p}{L_p}p_n(e^{qV/kT} - 1)$$

Electron current injected into the p-material

$$I_n(x_p = 0) = -\frac{qAD_n}{L_n}\Delta n_p = -\frac{qAD_n}{L_n}n_p(e^{qV/kT} - 1)$$

Current-Voltage Characteristic, the diode equation.

Total current at $x_n = x_p = 0$

$$I = I_p(x_n = 0) - I_n(x_p = 0) = \frac{qAD_p}{L_p}\Delta p_n + \frac{qAD_n}{L_n}\Delta n_p$$

Voltage depended minority injection included

$$I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)(e^{qV/kT} - 1) = I_0(e^{qV/kT} - 1)$$

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Current-Voltage Characteristic, the diode equation.

Reversed bias!

$$I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)\left(e^{-qV_r/kT} - 1\right)$$

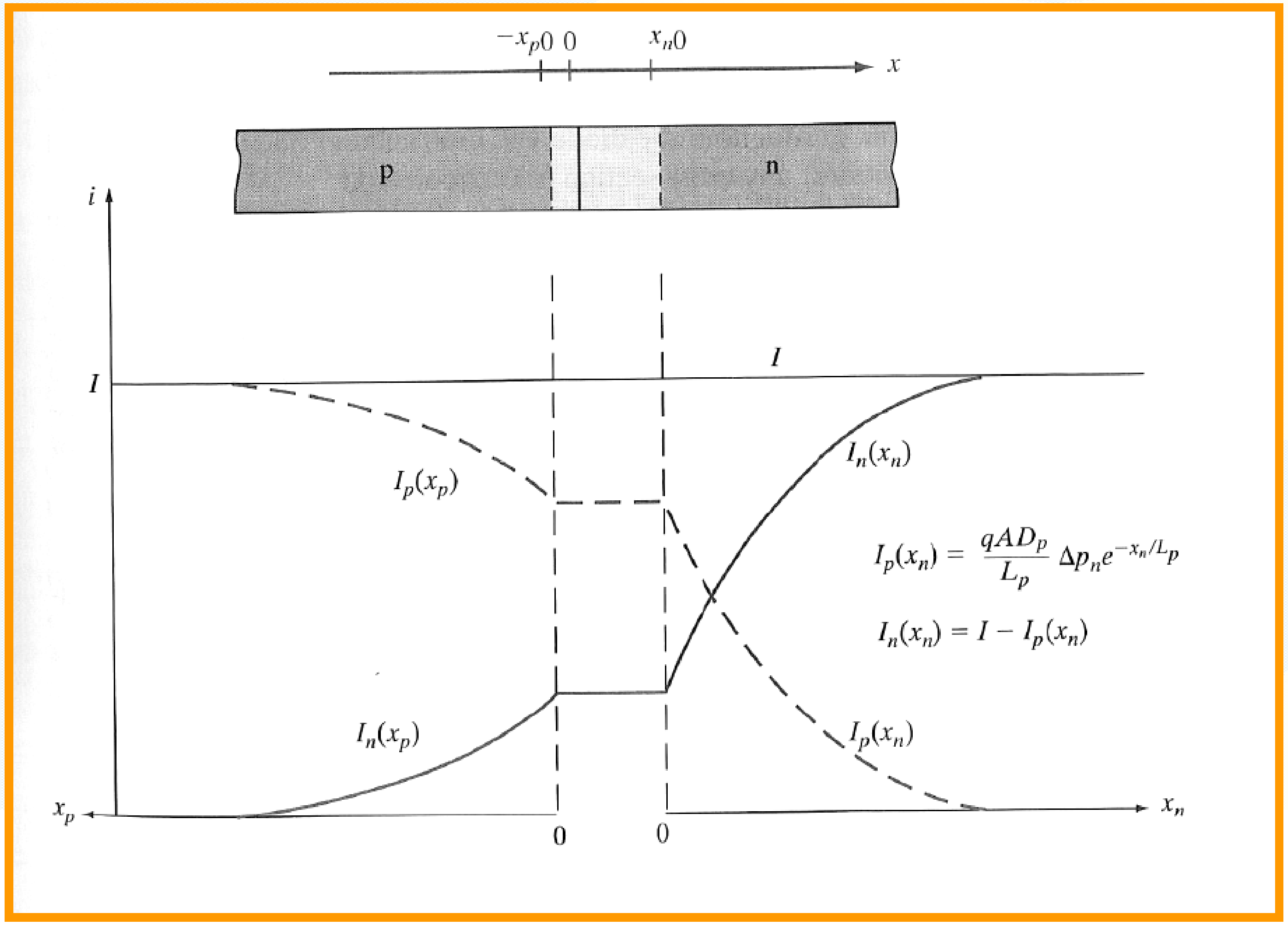
Increasing *Vr* gives:

$$I = -qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right) = -I_0$$

Shockley Equation

Good agreement for Ge. Bad for Si

Current-Voltage Characteristic, the diode equation.



The current is constant through the component

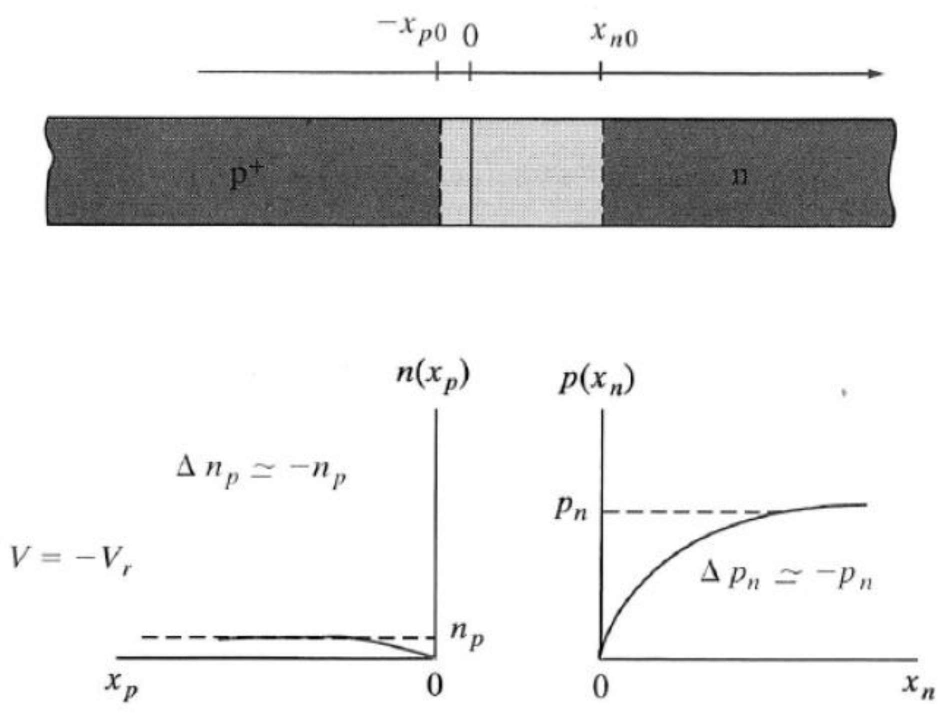
The doping affect the injection

The p-doping is higher than the n-doping which gives a bigger hole injection

Current-Voltage Characteristic, reverse biased junction

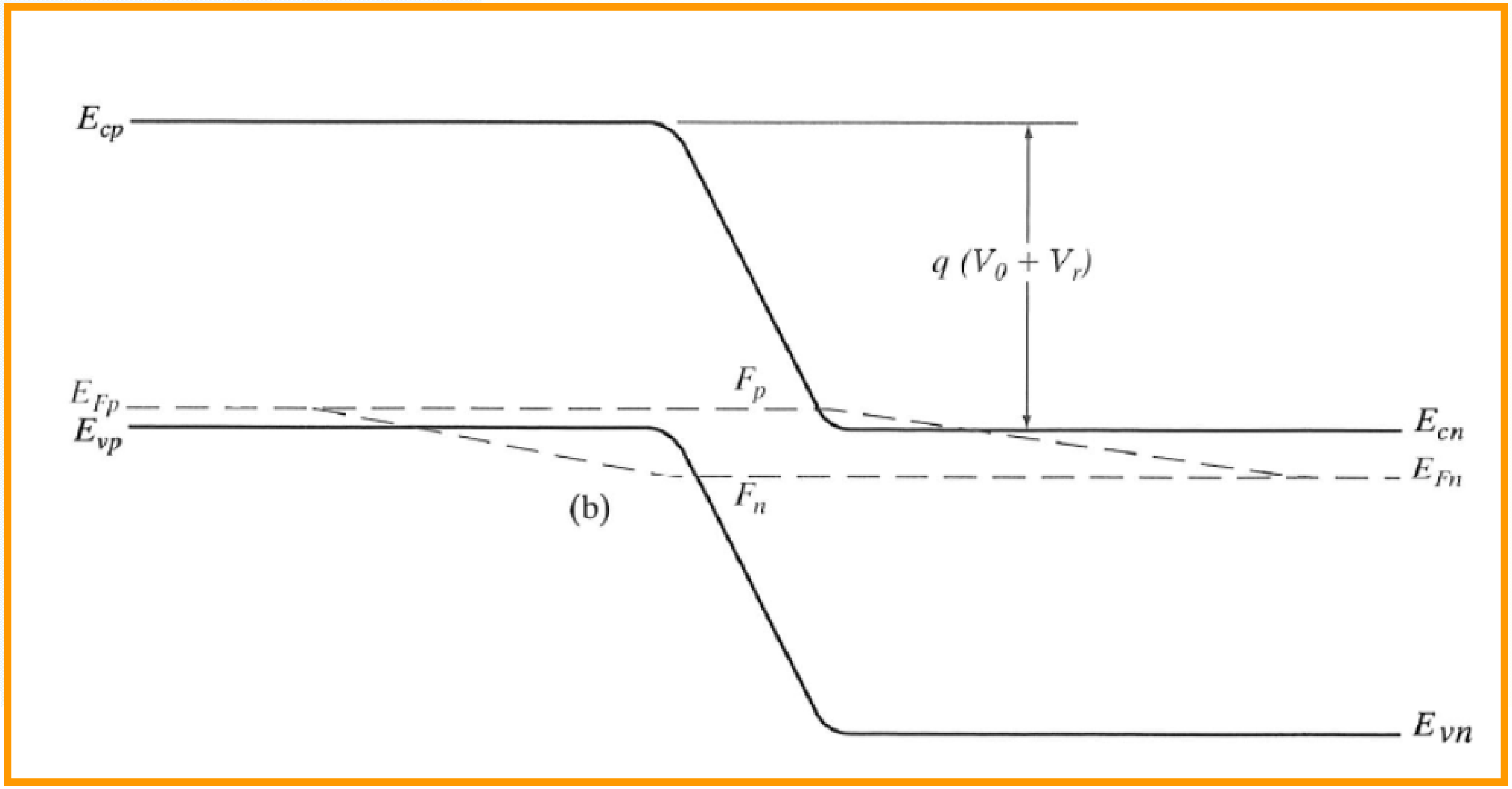
$$\Delta p_n = p_n(e^{q(-V_r)/kT} - 1) \simeq -p_n \quad \text{for } V_r \gg kT/q$$

$$\boxed{\Delta p_n = p(x_{n0}) - p_n = p_n(e^{qV/kT} - 1)}$$



(a)

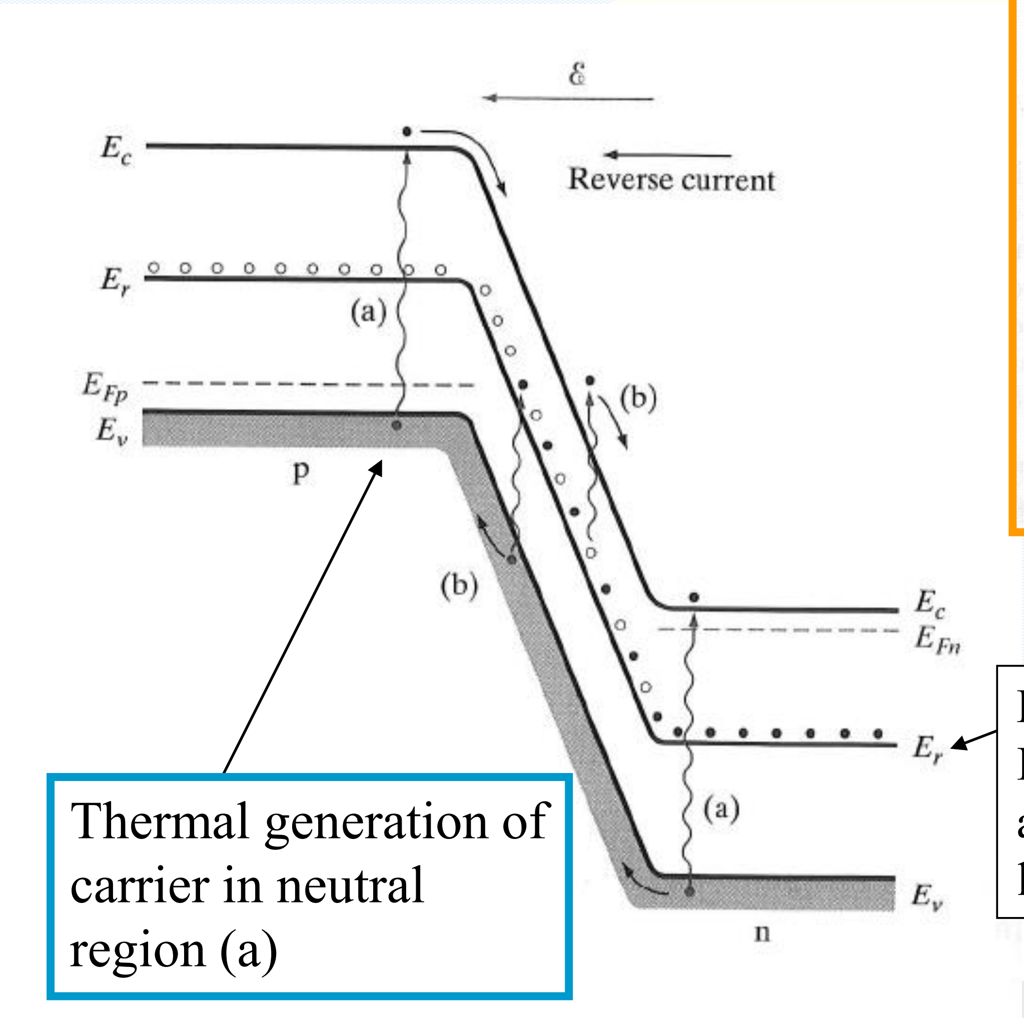
Current-Voltage Characteristic, reverse biased junction



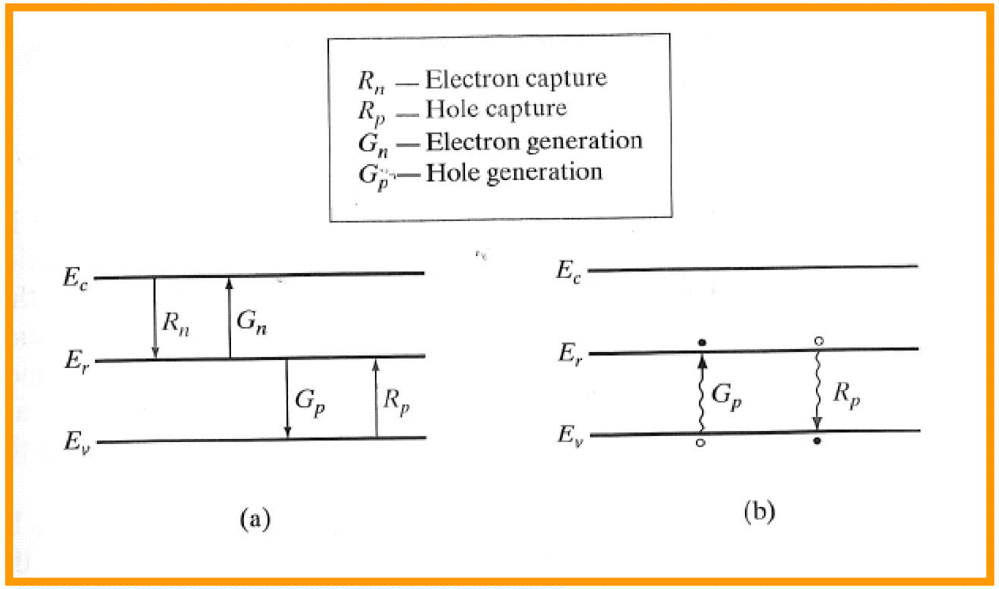
Current-Voltage Characteristic, 2 order effect

1. Generation and recombination in the depletion volume
2. Ohmic losses

Current-Voltage Characteristic, 2 order effect



Thermal generation of carrier in neutral region (a)



Recombination center in the bandgap. In reverse bias mode the center act as a generations center, which affect the leakage current. (b)

Current-Voltage Characteristic, 2 order effect

The diode equation is modified to take care of the effect of recombination. An ideality factor n with a value from 1 to 2, is therefore introduced. 1 is pure diffusion and 2 is pure recombination. A real diode is somewhere in-between.

$$\boxed{I = I_0'(e^{qV/\mathbf{n}kT} - 1)}$$

I_0' is modified to better explain the current when recombination/generation center affect the leakage current.

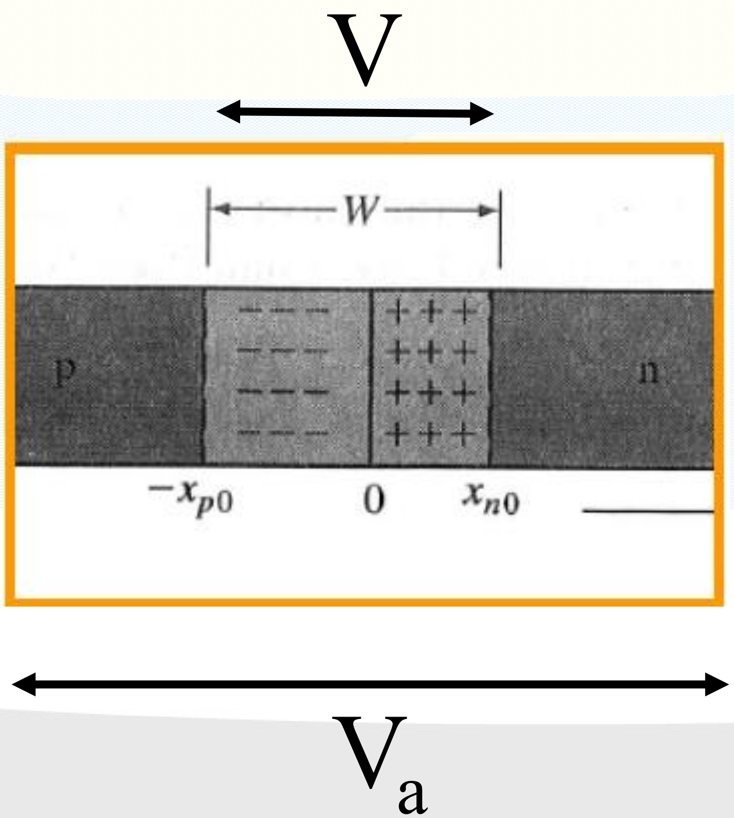
$$I_0' = A\left[q\sqrt{\frac{D_p}{\tau_p}}\cdot\frac{n_i^2}{N_D} + \frac{qn_iW}{\tau_g}\right]$$

Minority carrier lifetime in neutral n-doped region (p^+n-diode)

Generation life-time in depletion region

Ohmic losses

$$V = V_a - I[R_p(I) + R_n(I)]$$



Depletion layer capacitance

$$C = \left|\frac{dQ}{dV}\right|$$

Def. of Capacitance

$$W = \left[\frac{2\epsilon V_0}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2} \quad (equilibrium)$$

0 V bias

$$W = \left[\frac{2\epsilon (V_0 - V)}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2} \quad (with\ bias)$$

Depletion layer capacitance

$$|Q| = qAx_{n0}N_d = qAx_{p0}N_a$$

Equal amount of charge on each side, opposite charge

$$x_{n0} = \frac{N_a}{N_a + N_d}W, \quad x_{p0} = \frac{N_d}{N_a + N_d}W$$

Propagation of depletion region caused by the doping

$$|Q| = qA\frac{N_dN_a}{N_d + N_a}W = A\left[2q\epsilon(V_0 - V)\frac{N_dN_a}{N_d + N_a}\right]^{1/2}$$

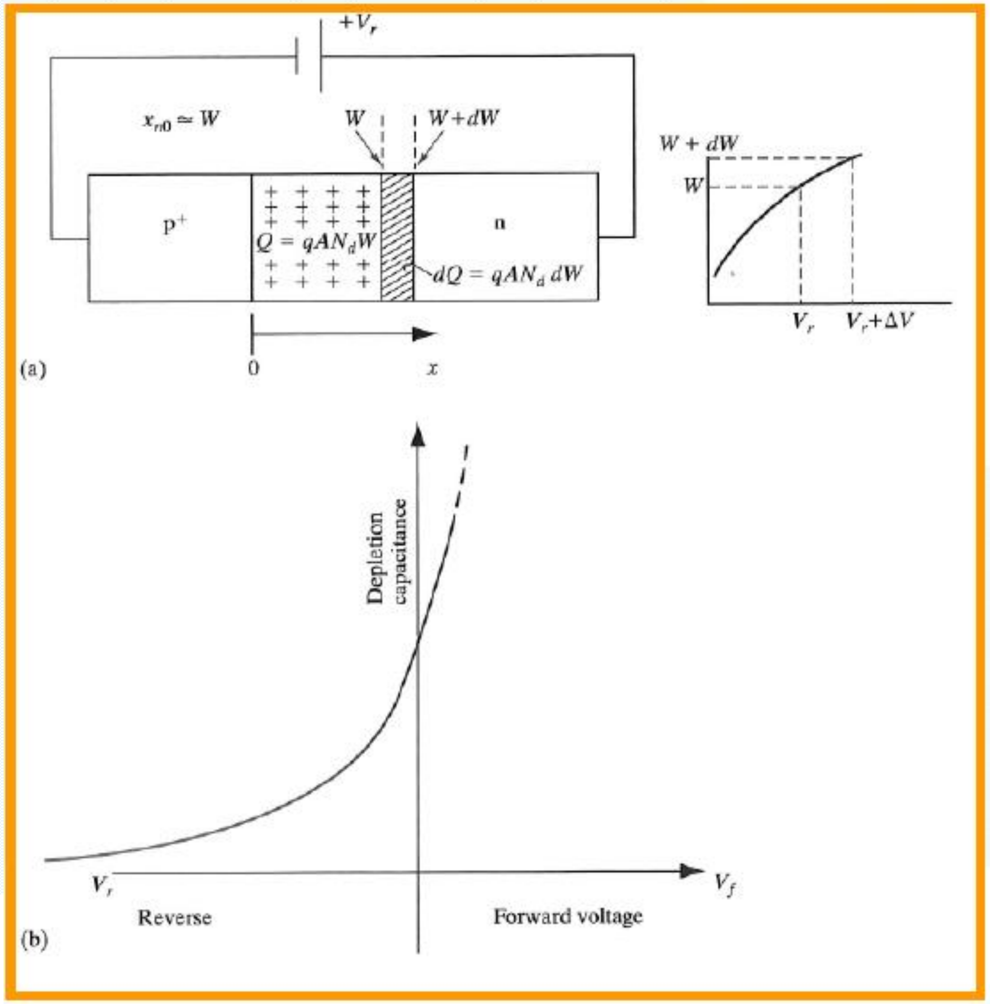
$$C_j = \left|\frac{dQ}{d(V_0 - V)}\right| = \frac{A}{2}\left[\frac{2q\epsilon}{(V_0 - V)}\frac{N_dN_a}{N_d + N_a}\right]^{1/2}$$

Differentiation gives the junction capacitance. The capacitance is voltage dependent and decrease with increased reverse bias

$$C_j = \epsilon A\left[\frac{q}{2\epsilon(V_0 - V)}\frac{N_dN_a}{N_d + N_a}\right]^{1/2} = \frac{\epsilon A}{W}$$

Can be written as a simple plate capacitor

Depletion layer capacitance



$$C_j = \left|\frac{dQ}{d(V_0 - V)}\right| = \frac{A}{2}\left[\frac{2q\epsilon}{(V_0 - V)}\,\frac{N_dN_a}{N_d + N_a}\right]^{1/2}$$

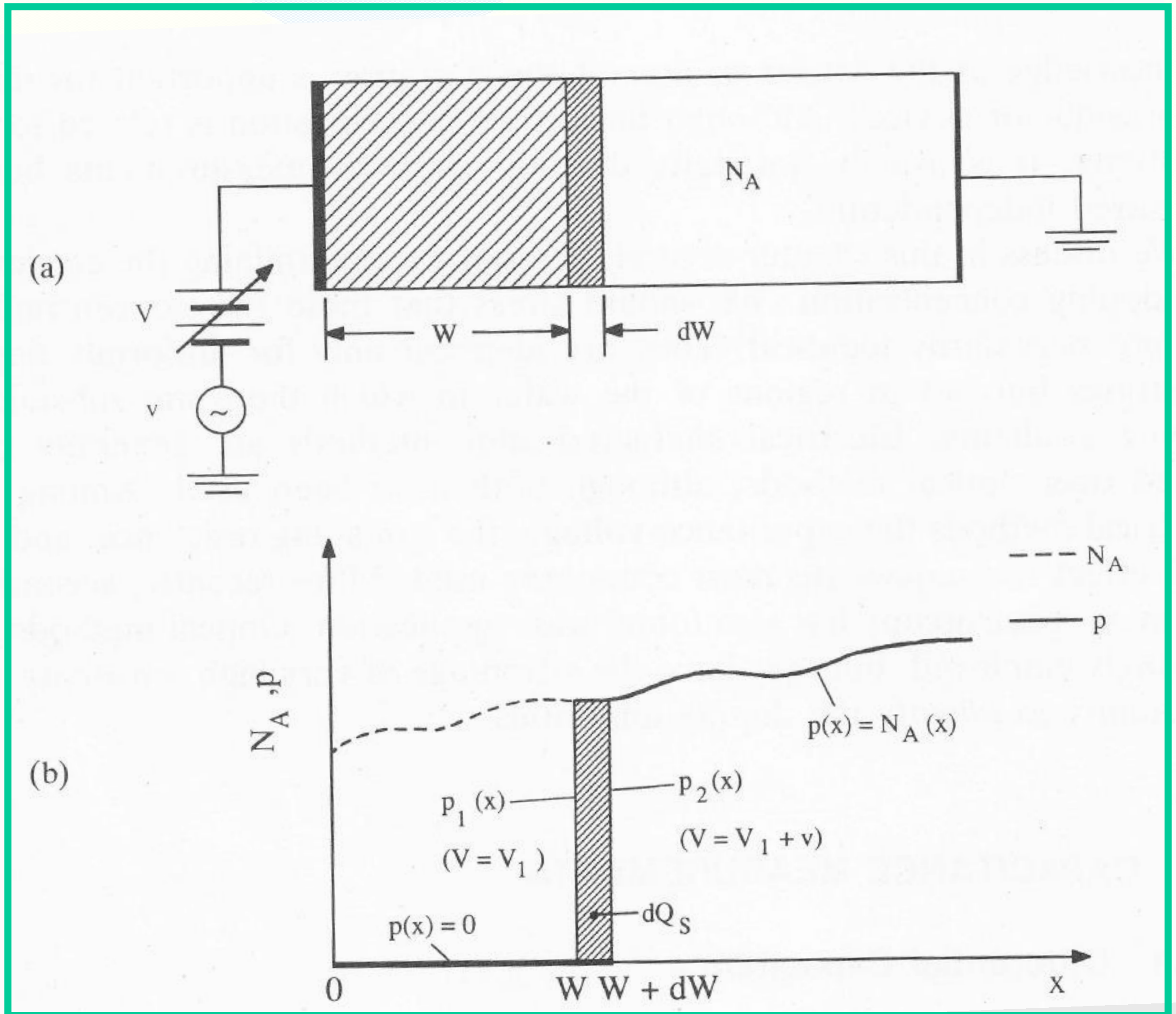
p^+n-diod

$$N_a >> N_d$$

$$C_j = \frac{A}{2}\left[\frac{2q\epsilon}{V_0 - V}N_d\right]^{1/2} \quad \text{for } p^+\text{-}n$$

Depletion layer capacitance

$$C = -\frac{dQ_s}{dV}$$



Depletion layer capacitance

$$N_A(W) = -\frac{C^3}{qK_s\varepsilon_0 A^2(dC/dV)}$$

$$N_A(W) = \frac{2}{qK_s\varepsilon_0 A^2[d(1/C^2)/dV]}$$

$$W = \frac{K_s\varepsilon_0 A}{C}$$

Si: $K_s = 12$

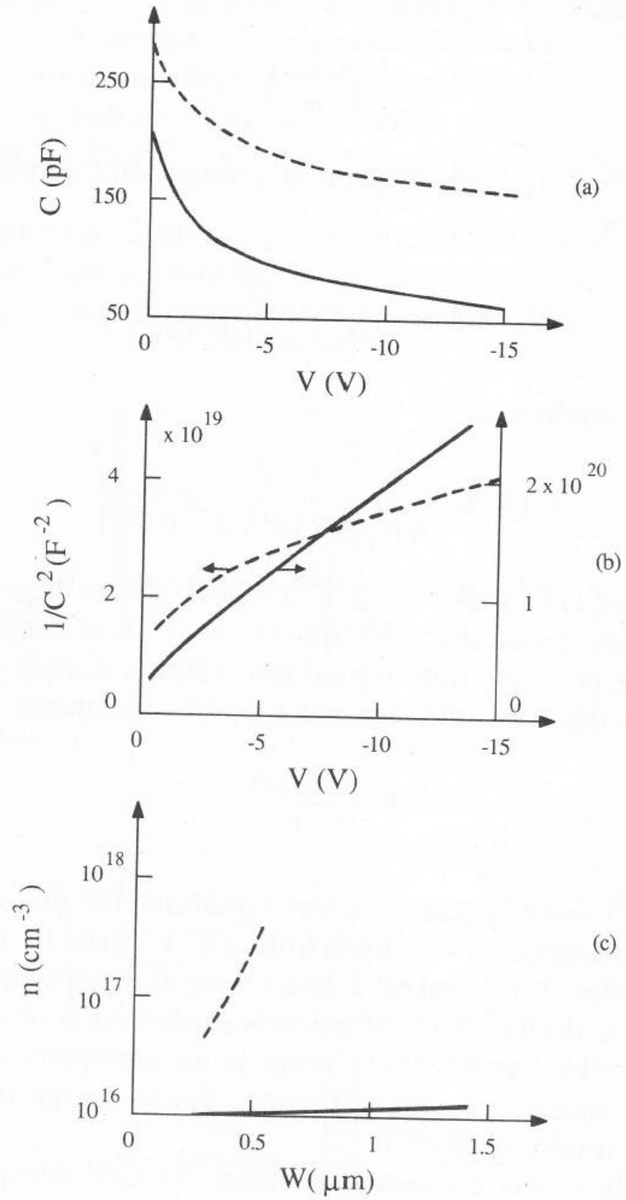
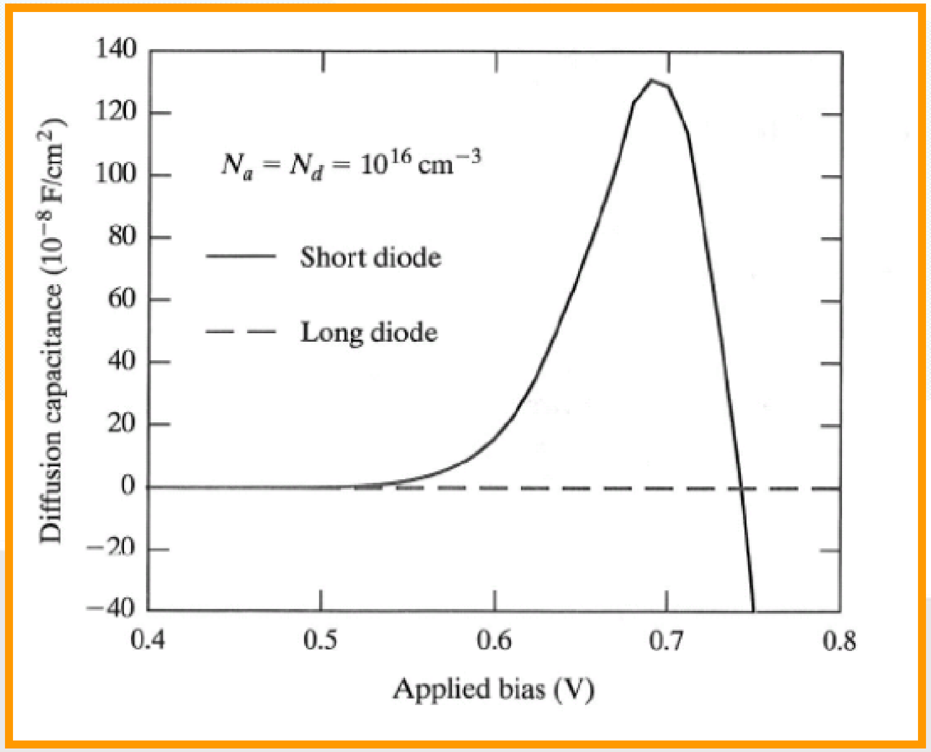


Fig. 2.2 (a) Capacitance-voltage curves for two Si p^+n diodes, (b) $1/C^2$ versus V curves, (c) n versus W profiles. $A = 7.9 \times 10^{-3}$ cm^2, $T = 300$ K.

Diffusion capacitance

Long diodes, The diode is longer than the diffusion length for the minority carrier, no contribution to the capacitance

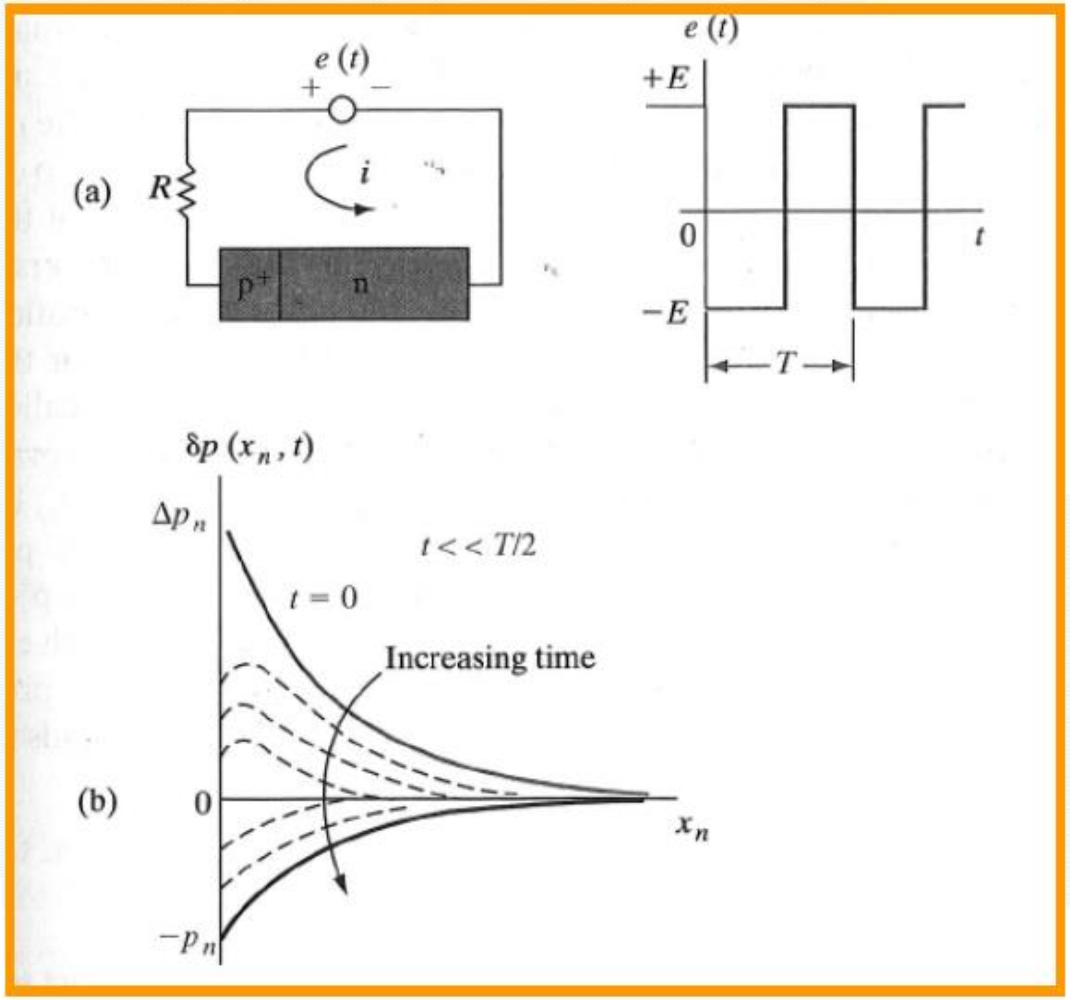
Short diodes, the most silicon diodes behave as short diodes



$$C_s = \frac{dQ_p}{dV} = \frac{1}{3}\frac{q^2}{kT} A c p_n e^{qV/kT}$$

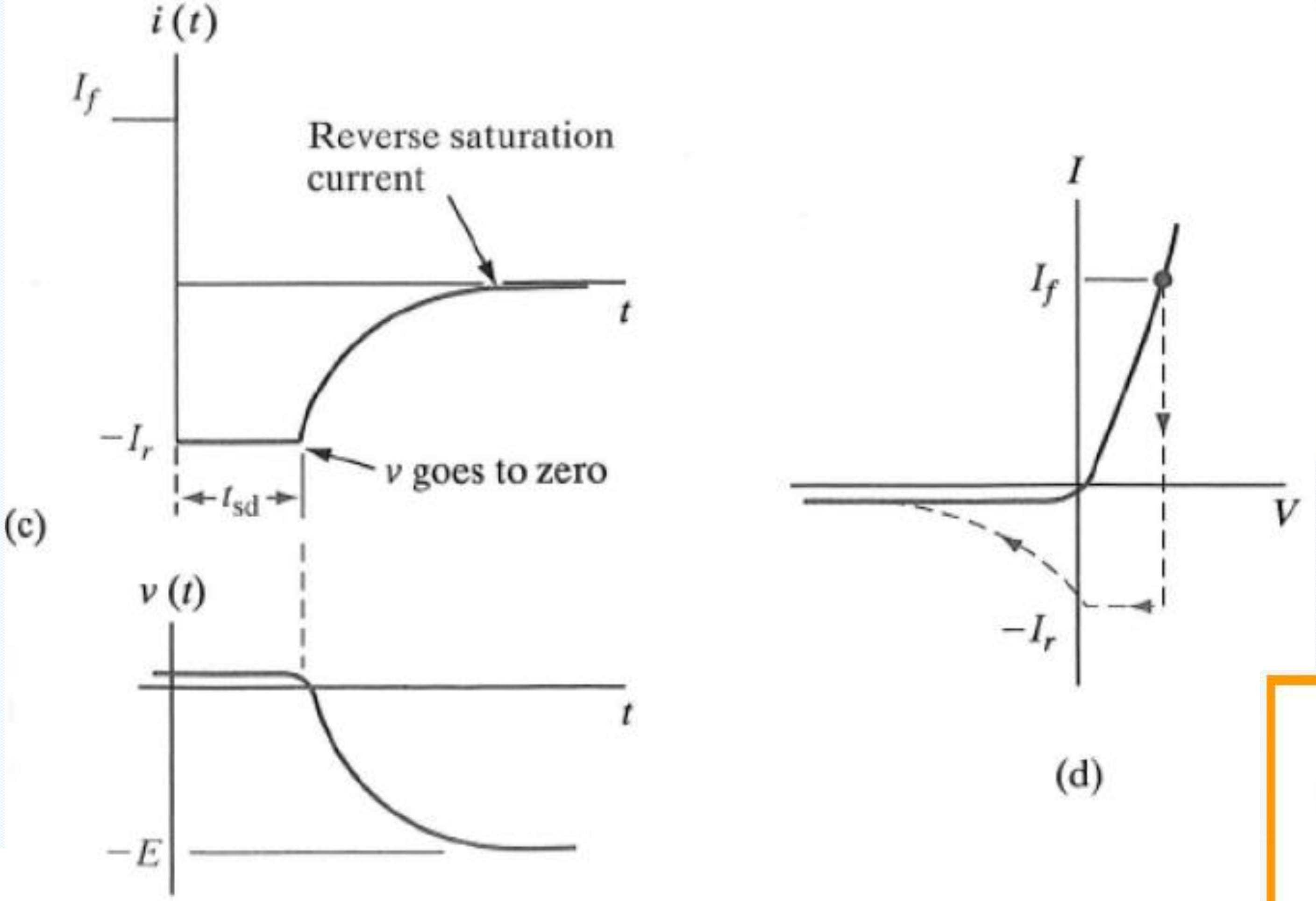
Storage length

Transient Behavior



Injection of minority carrier, when the diode is forward biased. p^+n-diode

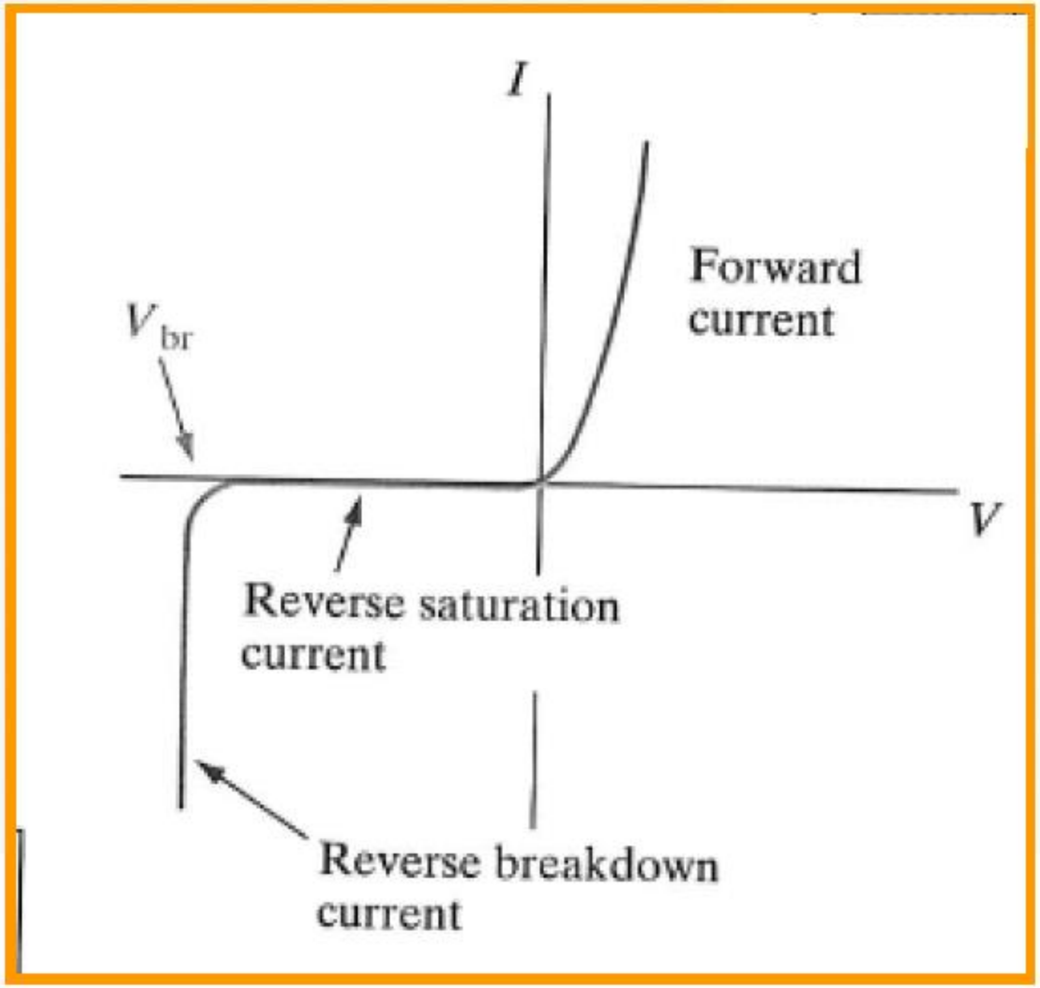
Transient Behavior



After injection of carrier, the diode is reversed biased. The diode conduct until all injected carrier have recombined.

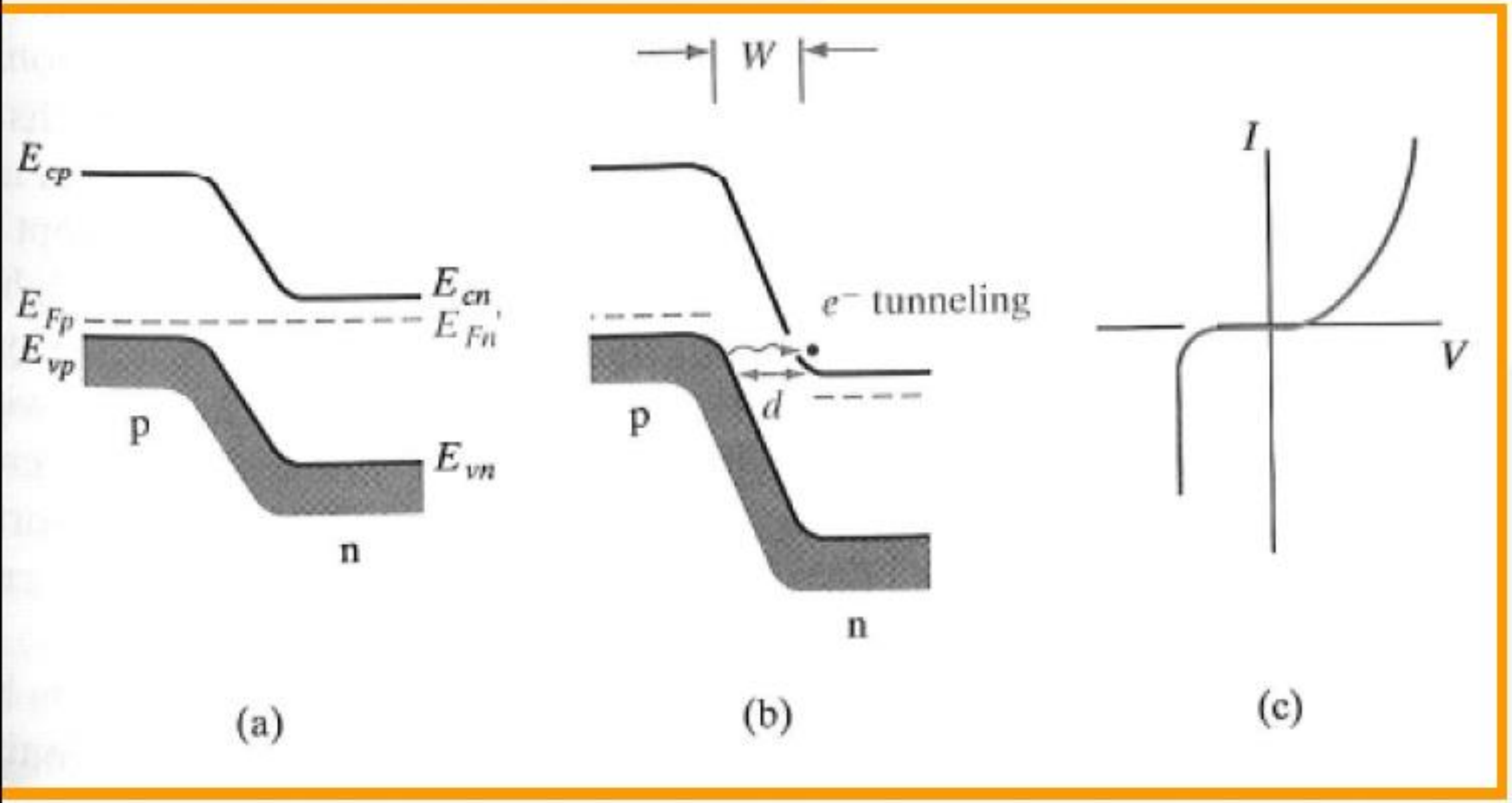
$$t_{sd} = \tau_p \left[\mathrm{erf}^{-1}\left(\frac{I_f}{I_f + I_r} \right) \right]^2$$

Junction Breakdown



- Zener breakdown
- Avalanche breakdown

Junction Breakdown, zener



n and p are doped high, which result in tunneling through the potential barrier

Negative temp. coeff

Vb ↘ T ↗

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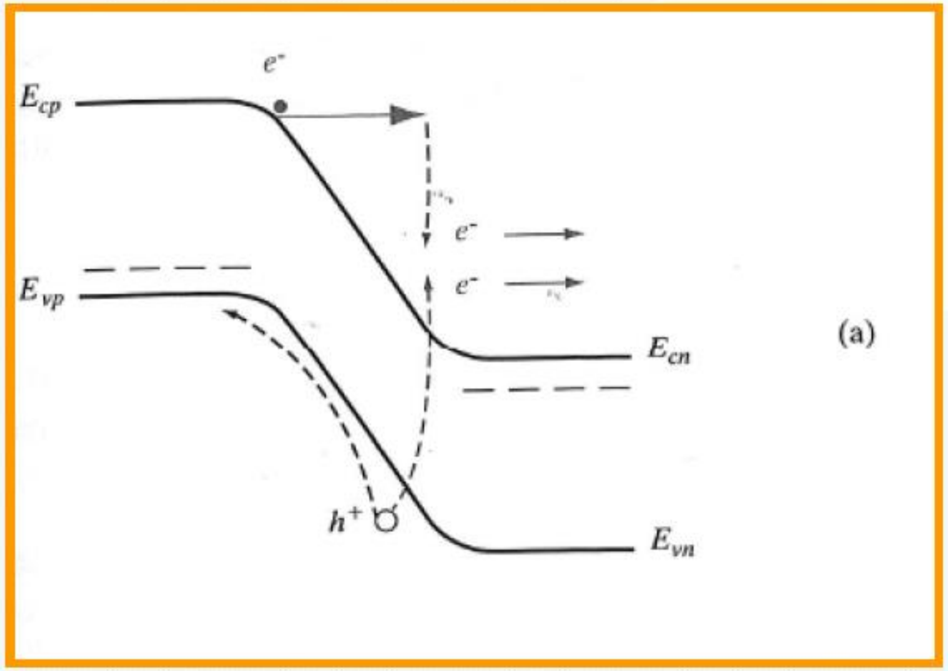
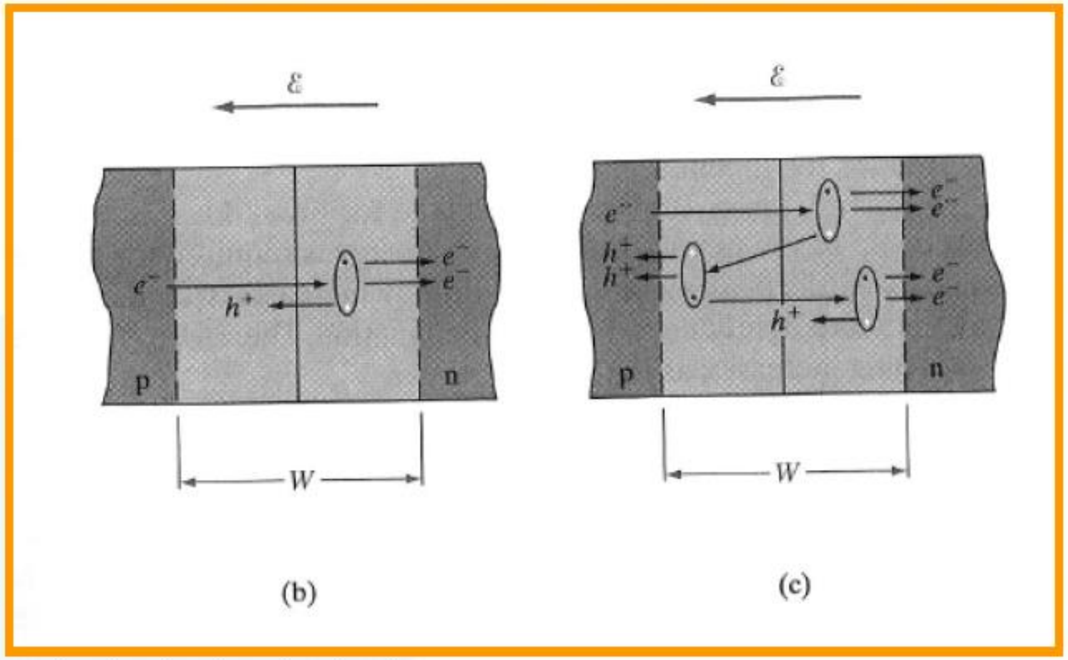
Junction Breakdown, Avalanche





An electron is accelerated in a high electric Field , which gives impact ionization. Positive temp coeff.

Junction Breakdown, PIN-diode

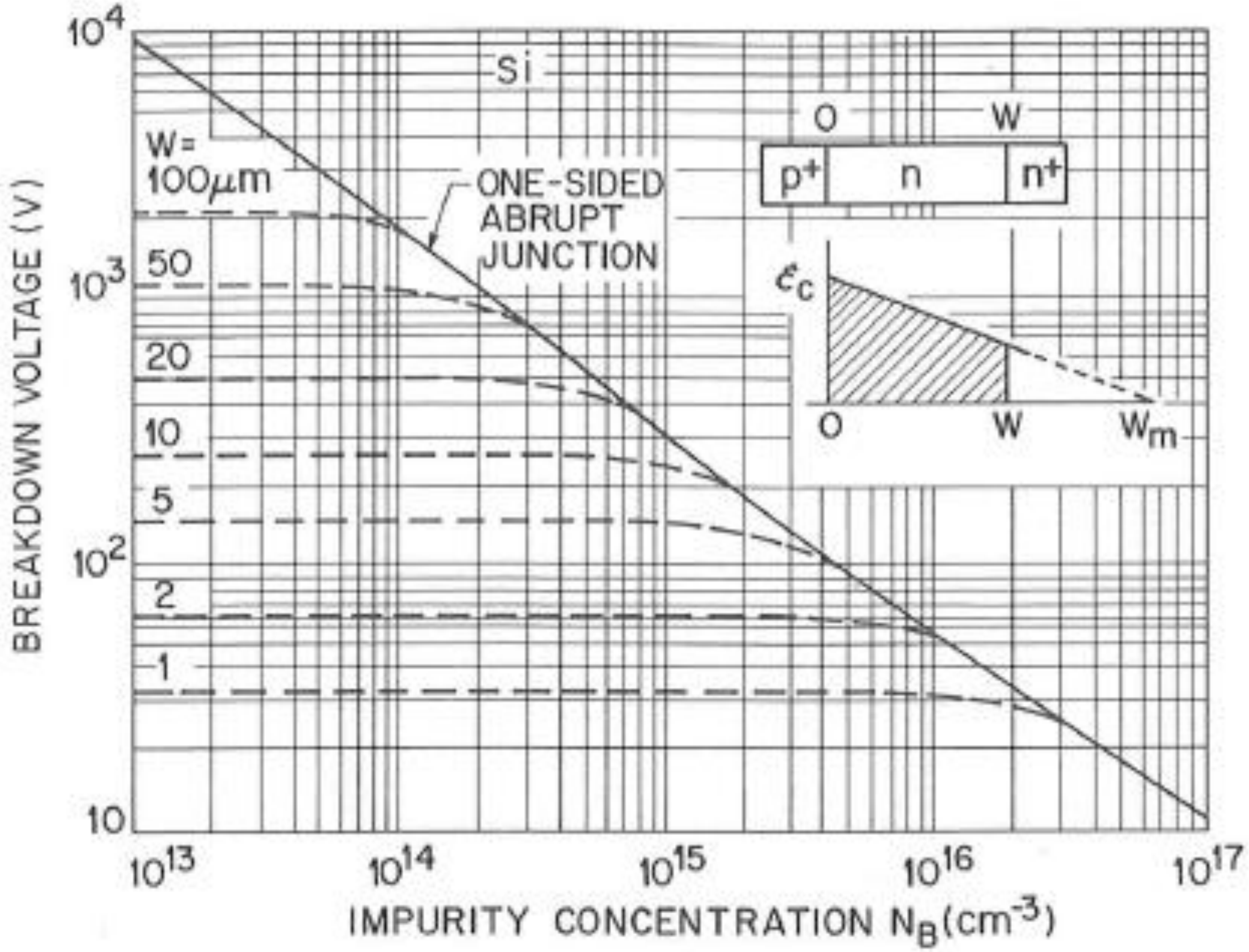


Fig. 27 Breakdown voltage for p^+–π–n^+ and p^+–ν–n^+ junctions. W is the thickness of the lightly doped p-type (π) or the lightly doped n-type (ν) region.

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Junction Breakdown, avalanche in surface

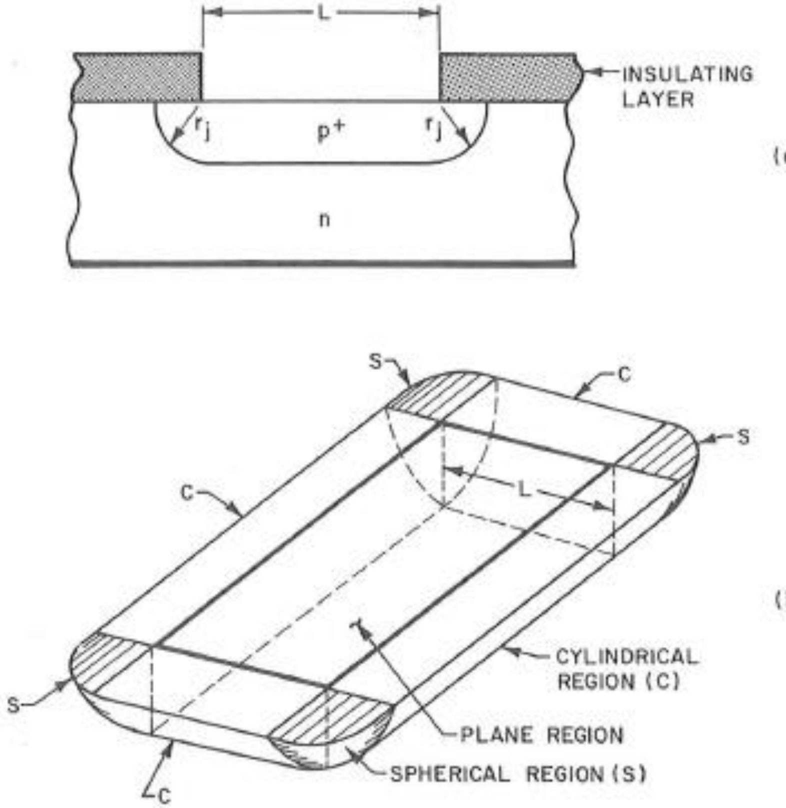
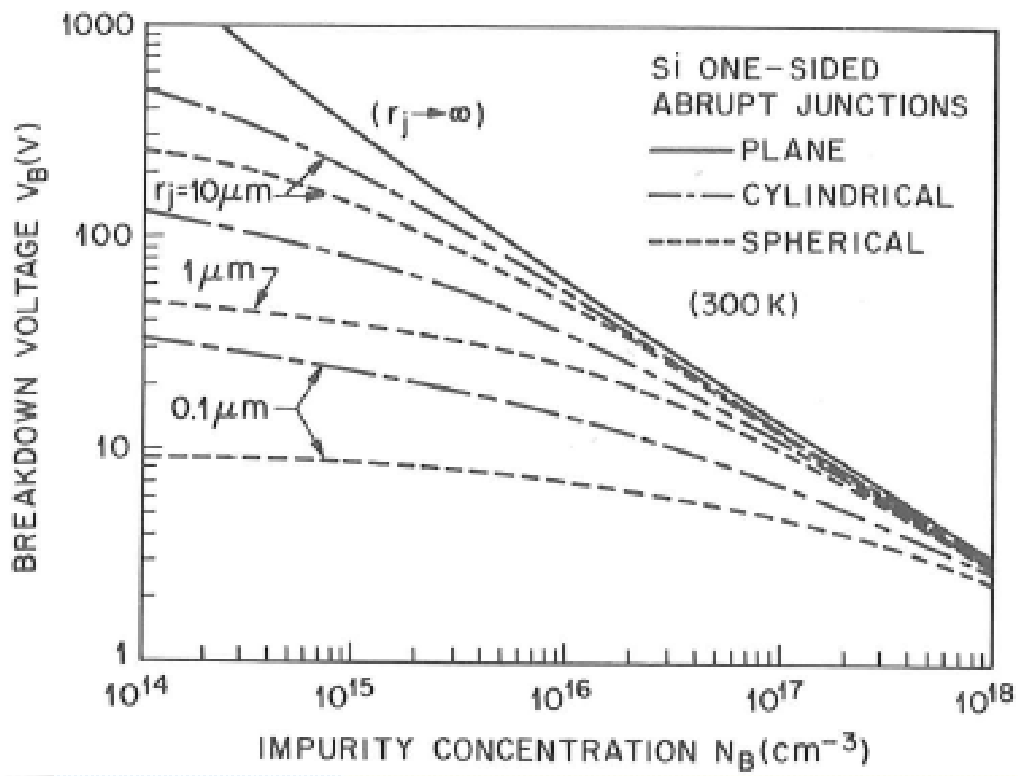


Fig. 28 (*a*) Planar diffusion process that forms junction curvature near the edge of the diffusion mask, where r_j is the radius of curvature. (*b*) Formation of cylindrical and spherical regions by diffusion through a rectangular mask.



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