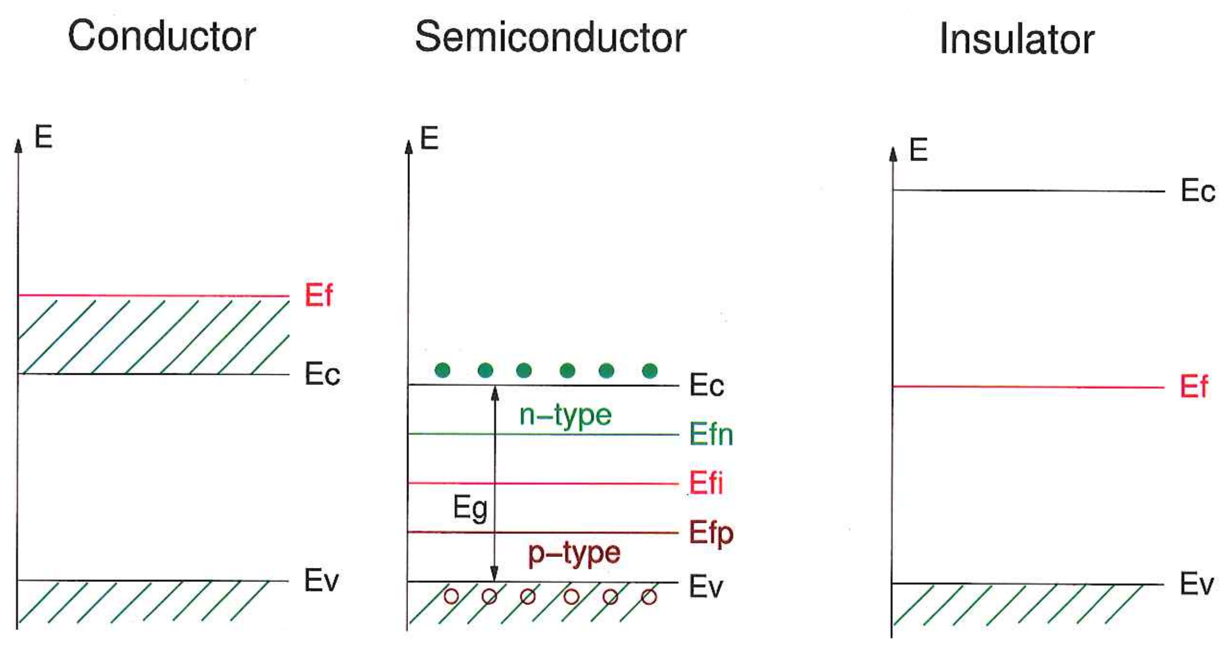
Energy Band Diagrams



Carrier Densities

Intrinsic:

$$n_{io}(T) = n_{io}(T_o)\left[\frac{T}{T_o}\right]^{3/2} e^{\frac{E_G}{2kT_o}\left(1-\frac{T_o}{T}\right)}$$

T: absolute Temp. [°K]

k: Boltzman's const. ($1.38\times10^{-23}\ \frac{J}{°K}$)

E_G: Band Gap of Semiconductor

Silicon @ $T = 300k$: $n_{io} = 1.5\times10^{16}\ m^{-3}$

Extrinsic:

$$n_o = N_c\, e^{-\frac{E_c - E_F}{kT}} \qquad N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$$

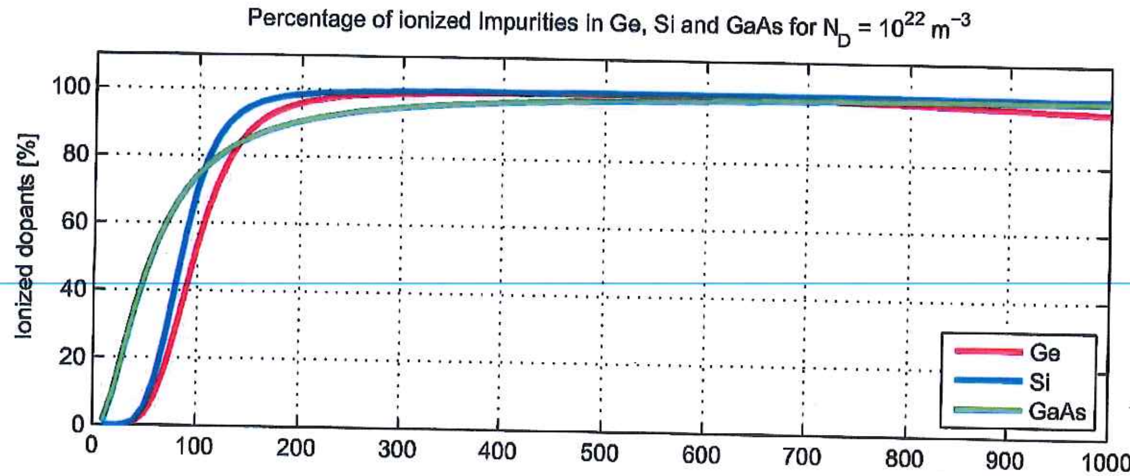
$$p_o = N_v\, e^{-\frac{E_F - E_v}{kT}} \qquad N_v = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2}$$

E_c: Conduction Band Edge

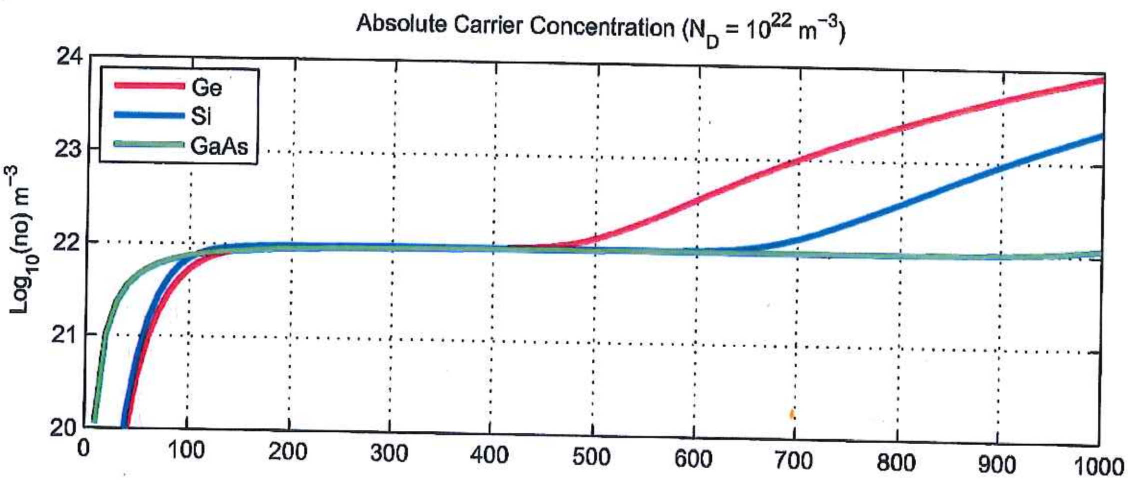
E_V: Valence Band Edge

E_F: Fermi Energy

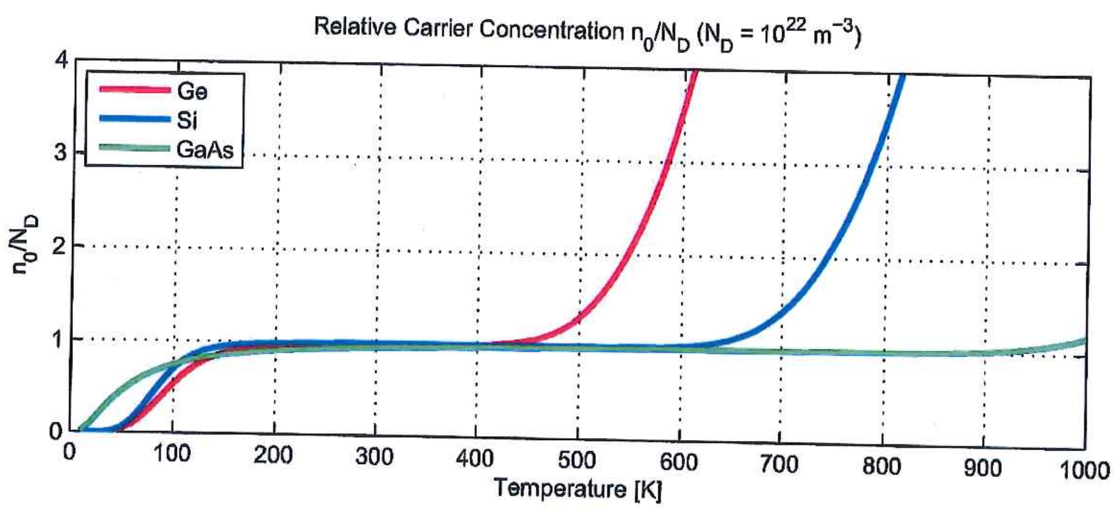
$$n_o \cdot p_o = n_{io}^2$$



Percentage of ionized Impurities in Ge, Si and GaAs for $N_D = 10^{22}\ m^{-3}$
Ionized dopants [%]
0
20
40
60
80
100
0
100
200
300
400
500
600
700
800
900
1000
Ge
Si
GaAs



Absolute Carrier Concentration ($N_D = 10^{22}\ m^{-3}$)
$Log_{10}(no)\ m^{-3}$
20
21
22
23
24
0
100
200
300
400
500
600
700
800
900
1000
Ge
Si
GaAs



Relative Carrier Concentration n_0/N_D ($N_D = 10^{22}\ m^{-3}$)
n_0/N_D
0
1
2
3
4
0
100
200
300
400
500
600
700
800
900
1000
Temperature [K]
Ge
Si
GaAs

Carrier Transport

A) Drift (El. Field)

n-type

$$\| \bar{J}_n = q \cdot n \cdot \mu_n \cdot \bar{E} \|$$

n: free el. conc. $[m^{-3}]$

μ_n: el. mobility $[\frac{m^2}{Vs}]$

$\bar{E}$: El. field $[\frac{V}{m}]$

p-type

$$\| J_p = q p \mu_p \bar{E} \|$$

p: free hole conc.

μ_p: hole mobility

J: current dens.

B) Diffusion (Carr. Concentr. Gradient)

n-type

$$\| J_n = q D_n \frac{dn}{dx} \|$$

D_n: el. Diffusity $[\frac{m^2}{s}]$

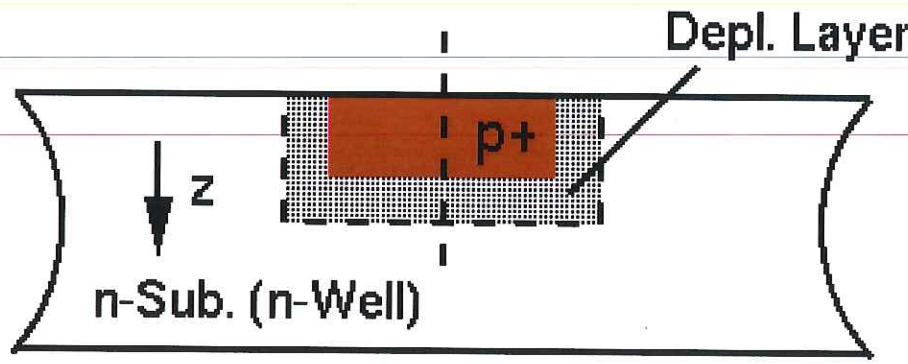
p-type

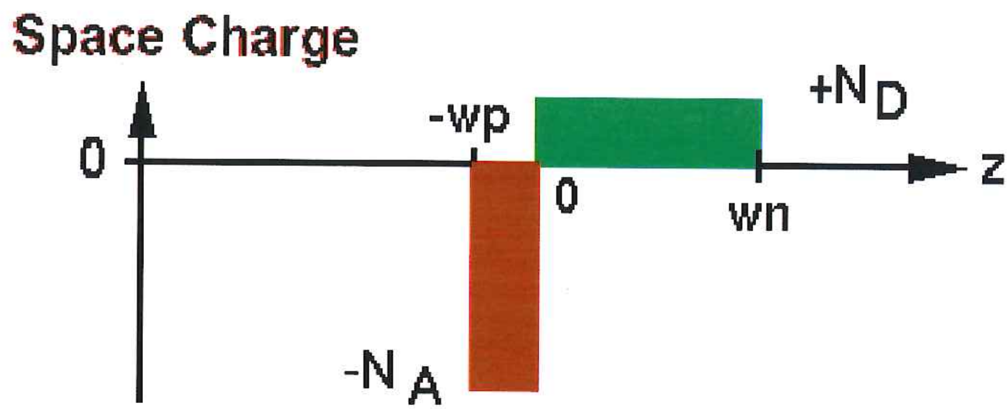
$$\| J_p = -q D_p \frac{dp}{dx} \|$$

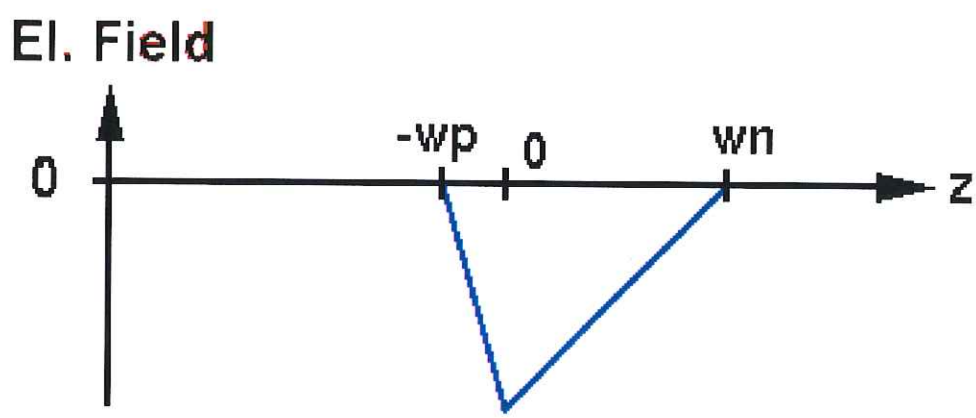
D_p: Hole Diffusity

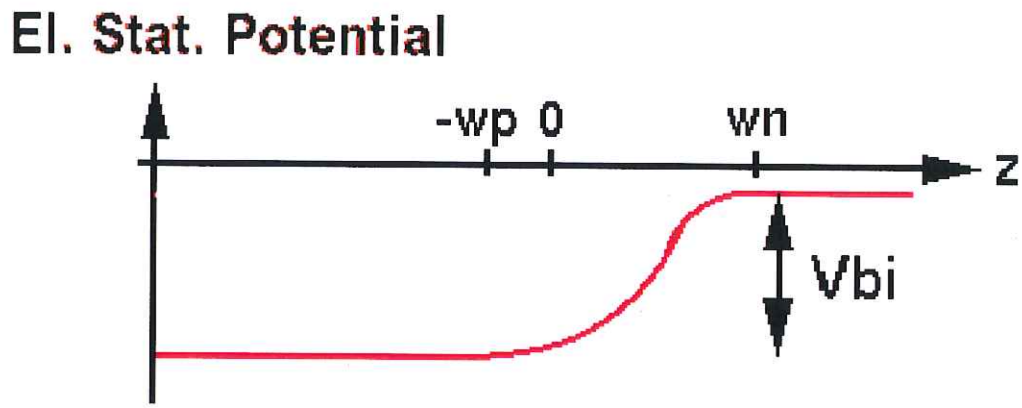
Einstein Relation

$$| D = \mu \frac{kT}{q} |$$


Depl. Layer
p+
z
n-Sub. (n-Well)


Space Charge
0
-wp
+N D
0
wn
z
-N A


El. Field
0
-wp
0
wn
z


El. Stat. Potential
-wp 0
wn
z
Vbi

The ideal p-n Junction (Thermal eq.)

Charge Density

$$\rho(x) = \begin{cases} -q N_A & -x_p \le x < 0 \\ q N_D & 0 < x \le x_n \\ 0 & \text{else} \end{cases}$$

charge Neutrality

$q N_A x_p = q N_D x_n$

Electric Field

$$E_{el}(x) = \frac{1}{\varepsilon}\int \rho(x)\,dx = \begin{cases} -\frac{q}{\varepsilon} N_A (x + x_p) & -x_p \le x < 0 \\ -\frac{q}{\varepsilon} N_D (x_n - x) & 0 < x \le x_n \\ 0 & \text{else} \end{cases}$$

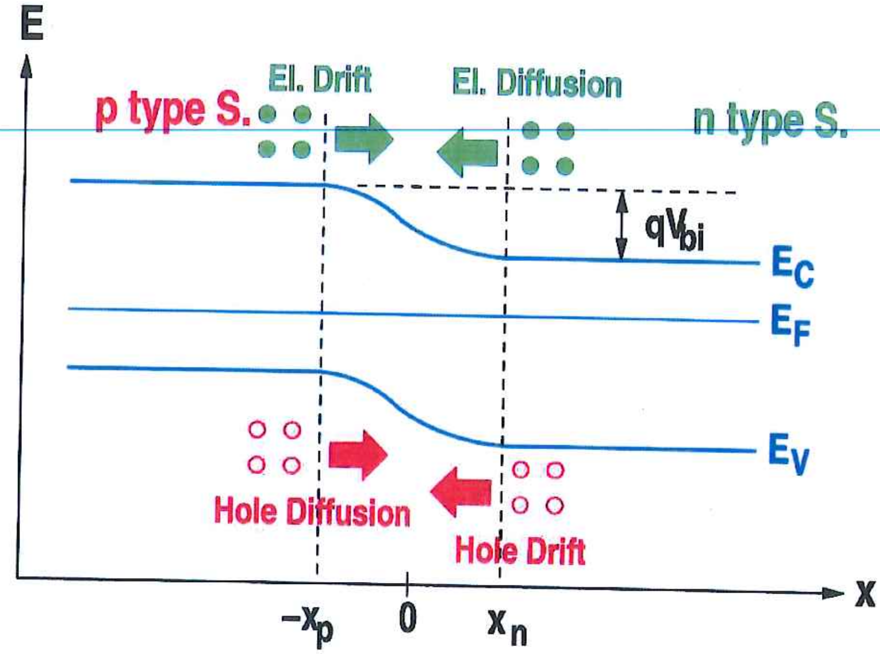
El. stat. Potential

$$\psi(x) = -\int E_{el}(x)\,dx = \begin{cases} 0 & x < -x_p \\ \frac{q}{2\varepsilon} N_A (x_p^2 + 2x x_p + x^2) & -x_p \le x < 0 \\ \frac{q}{2\varepsilon} N_D \left(\frac{N_D}{N_A} x_n^2 + 2x x_n - x^2\right) & 0 < x \le x_n \\ \frac{q}{2\varepsilon} N_D x_n^2 \left(1 + \frac{N_D}{N_A}\right) & x > x_n \end{cases}$$

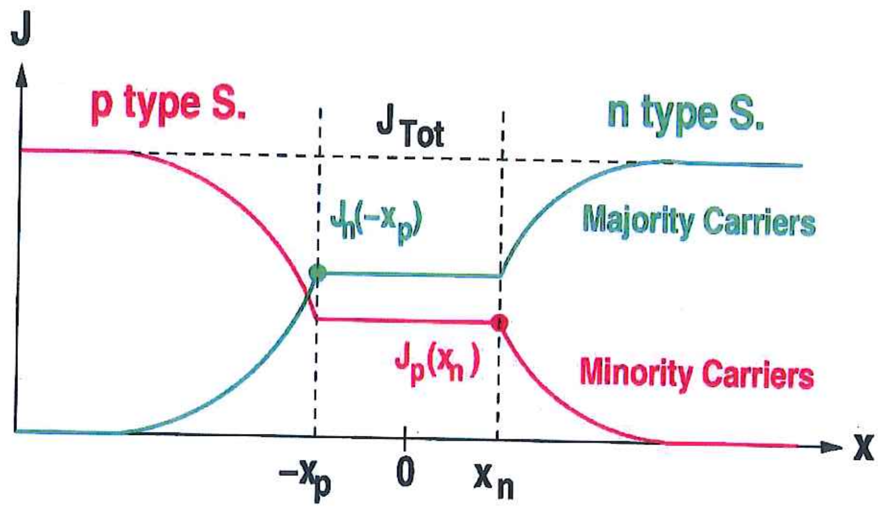
Energy

$$E(x) = -q\,\psi(x)$$

PN Junction in Thermal Equilibrium



Current Densities under forward Bias



PN Junction I/V Characteristic

$$I_d = I_S\left[e^{\frac{V_d}{V_T}} - 1\right]$$

$V_T = \frac{kT}{q}$ Thermal voltage

I_S : Reverse sat. voltage

$$I_S \cong A \cdot q \cdot n_{io}^2\left[\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D}\right]$$

N_A : Acceptor Conc. (p-side)

N_D : Donor Conc. (n-side)

L_n : el. Diff. Length

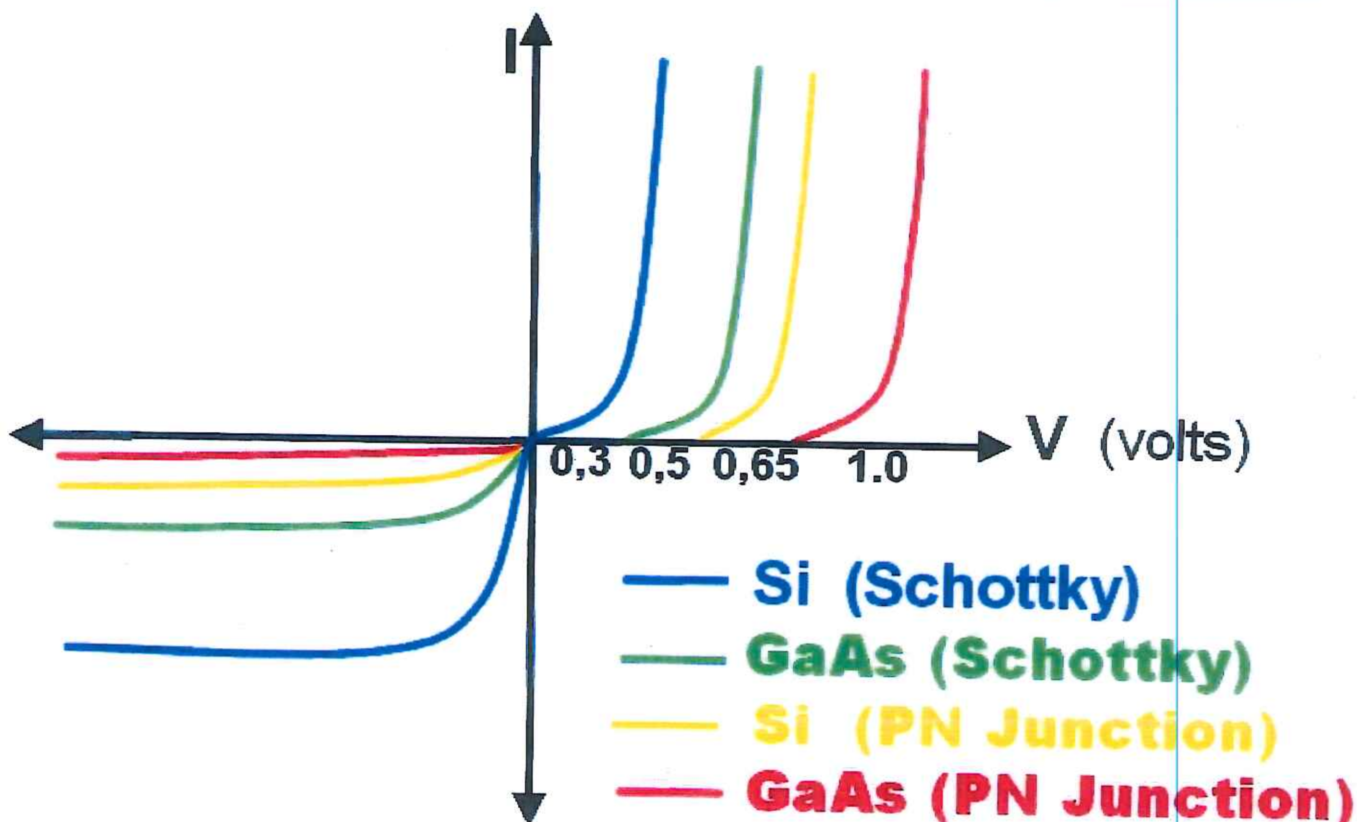
L_p : Hole Diff Length

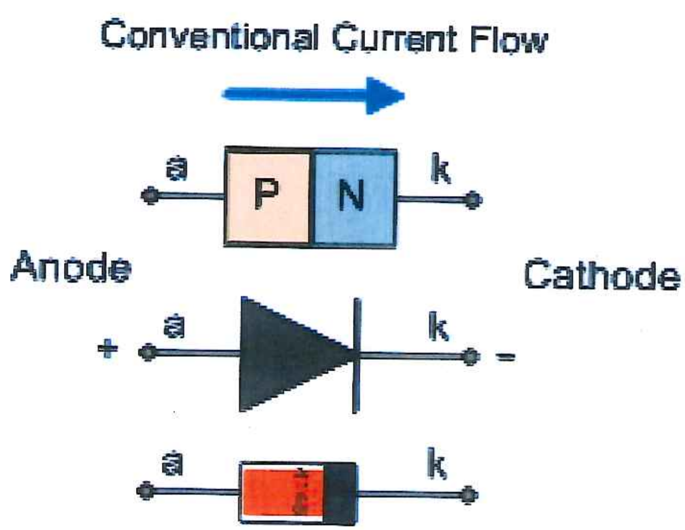
Temperature Dependance (Id const.)

$$\frac{dV_d}{dT} \cong -\frac{1}{T}\left[\frac{E_G}{q} + 3V_T - V_d\right]$$

Silicon: $\frac{dV_d}{dT} \cong -1.7 \frac{mV}{°K}$

Comparison of I-V Characteristics





Silicon Diode and its
V-I Characteristics