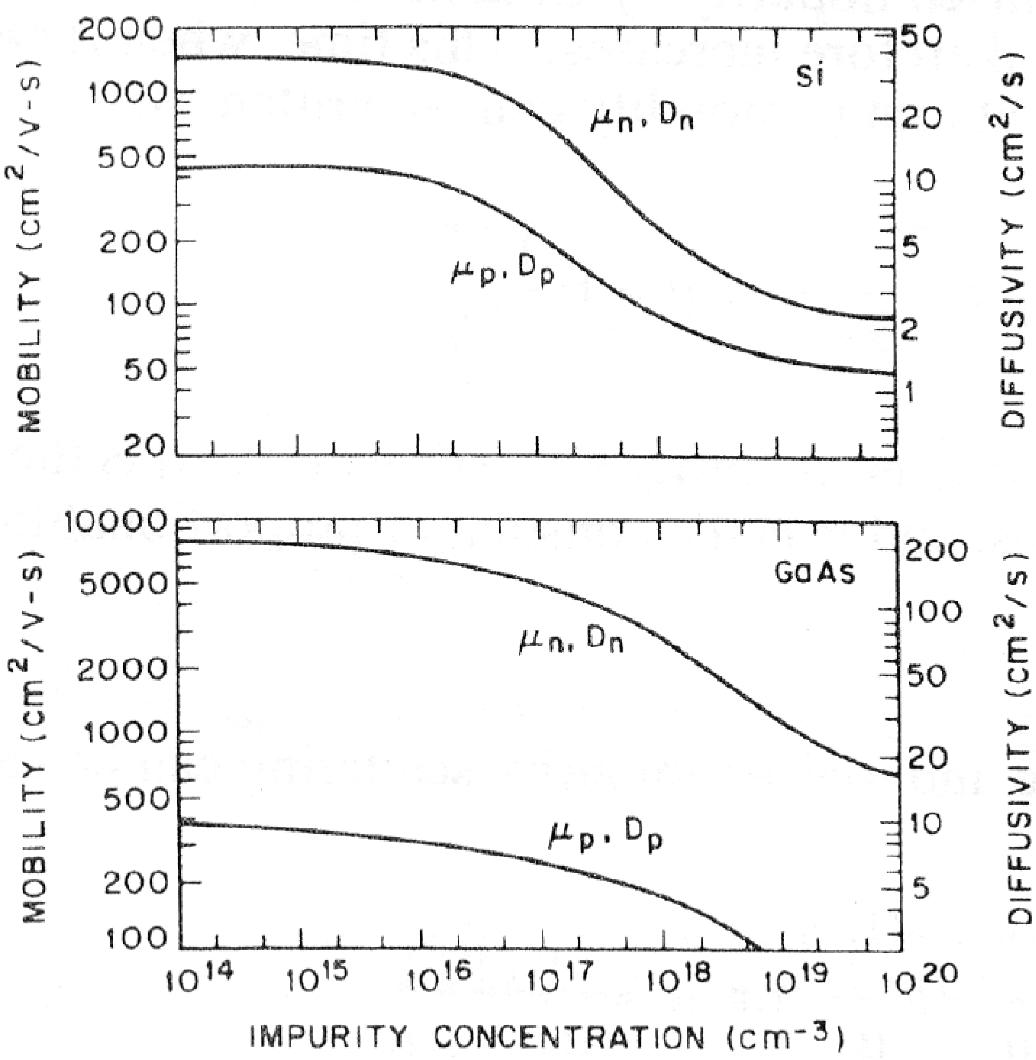
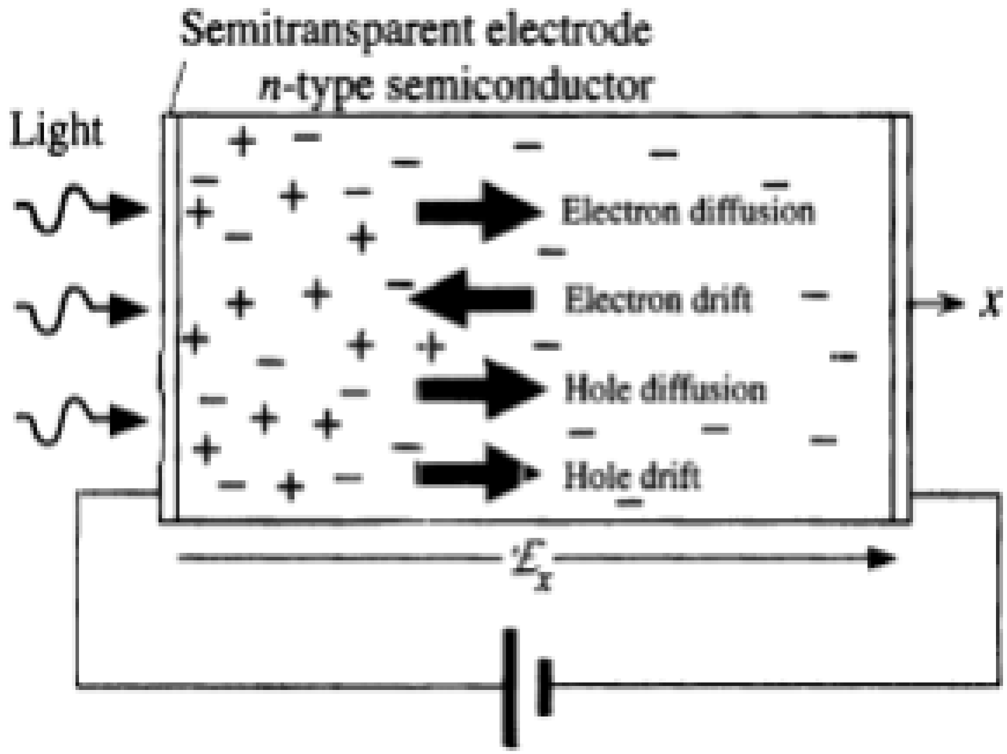
P-n junction: Recombination & Depletion Capacitance

Carrier Transport - Drift

The figures below show the variation of both electron and hole mobilities in two semiconductors, Si and GaAs, as a function of doping concentration. The small effective masses for GaAs result in higher values of μ_n and μ_p for all impurity concentrations compared with Si.



Diffusion & Conduction



In the general case the total current in a semiconductor is carried by electrons and holes and has drift and diffusion components

$$J = J_n + J_p = J_{n,drift} + J_{n,diff} + J_{p,drift} + J_{p,diff}$$

Recombination

- During the diffusion process, an electron will experience **recombination:**
  → They will not travel in space indefinitely but will be stopped when it recombines
  → Encounters with a **hole**.

- It is possible to express the effects of recombination using a characteristic time:
  → Called the electron recombination lifetime: τ_n

- We can then define a distance called **diffusion length** for electrons and holes given by:

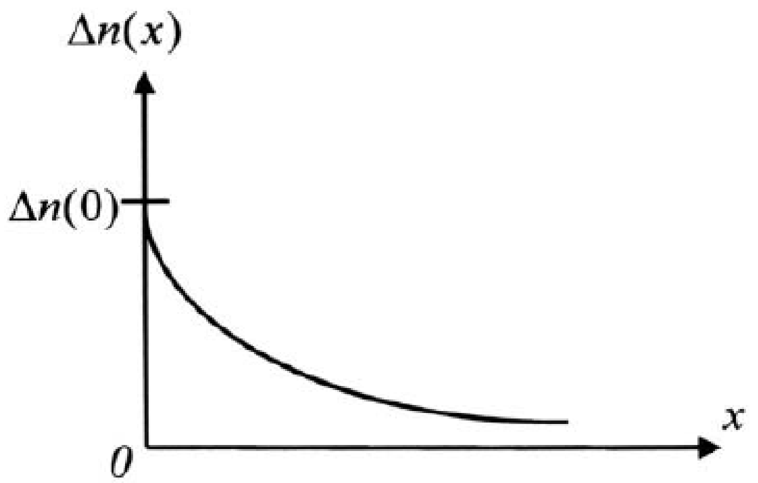


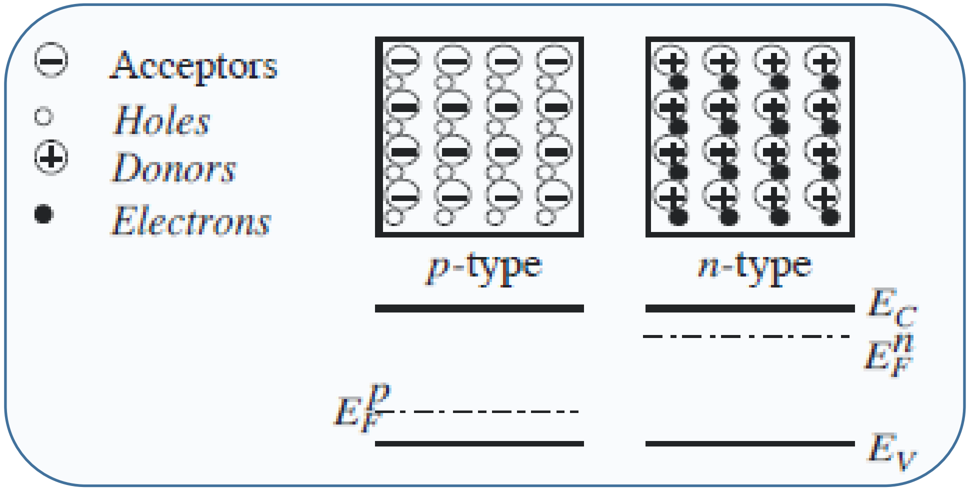
Fig. 9.7. Excess electron concentration in a one-dimensional model. The excess concentration decreases as it gets deeper into the material as a result of recombination. The decrease follows an exponential dependence.

$$L_p = \sqrt{D_p \tau_p}$$

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

Distance between Fermi Levels

Let us consider initially that the two parts of the *p-n* junction are separated.



Both parts are electro-neutral. Electrons compensate the ionised donors and holes compensate the ionised acceptors.

Taking into account that

$$\boxed{\begin{aligned} n \approx N_D &= n_i \exp\left(\left(E_F^n - E_i\right)/k_B T\right) \\ p \approx N_A &= n_i \exp\left(\left(E_i - E_F^p\right)/k_B T\right) \end{aligned}}$$

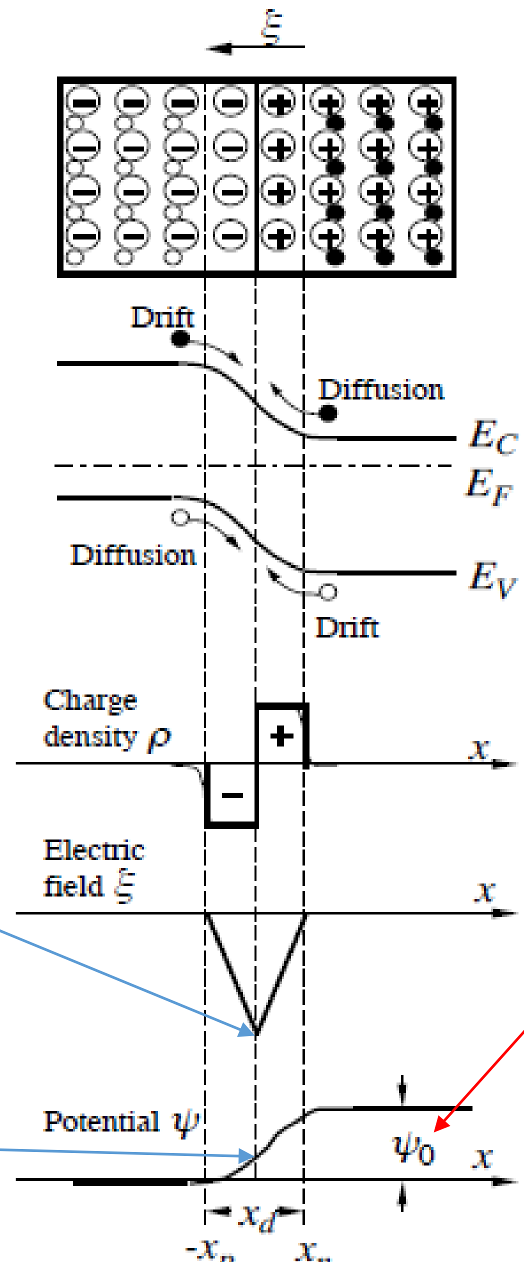
We can calculate the distance between the Fermi levels on the both sides

$$\begin{aligned} E_F^n - E_F^p &= \left(E_F^n - E_i\right) + \left(E_i - E_F^p\right) \\ &= k_B T \ln\left(N_D / n_i\right) + k_B T \ln\left(N_A / n_i\right) \\ &= k_B T \ln\left(\frac{N_D N_A}{n_i^2}\right) \end{aligned}$$

Depletion Region

The height of the potential barrier that supports the junction field is called the **contact potential**

At equilibrium, both drift and diffusion currents are equal and cancel each other.



$$E(0) = \frac{-eN_d x_n}{\epsilon} = \frac{-eN_a x_p}{\epsilon}$$

$$V(0) = \frac{eN_a . x_p^2}{2\epsilon}$$

$$qV_{bi} = E_{Fn} - E_{Fp}$$

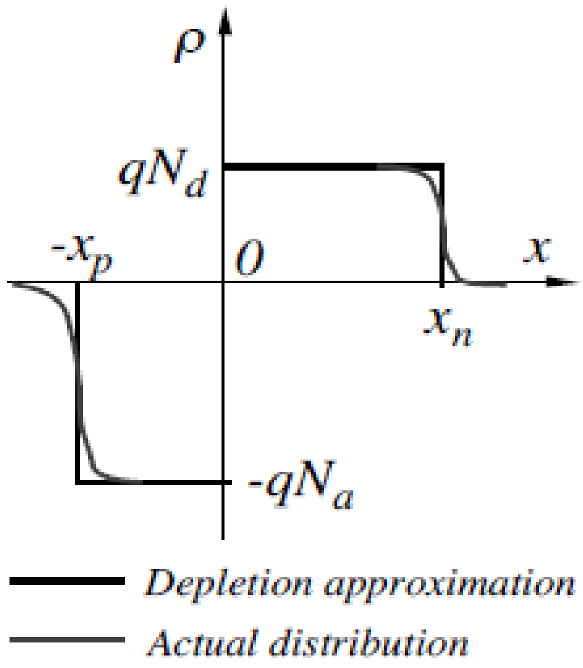
$$E_{Fp} = E_{Fi} - k_B T \ln\left(\frac{N_A}{n_i}\right)$$

$$E_{Fn} = E_{Fi} + k_B T \ln\left(\frac{N_D}{n_i}\right)$$

ψ_0

$$V_{bi} = \frac{k_B T}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

Depletion Region



The zone void of mobile charges is called depletion region. In depletion approximation the boundaries of the depletion region are abrupt and the charge density is equal to the charge density of the ionised acceptors or donors.

In order to obtain x_p and x_n and the depletion layer width $w = x_p + x_n$ the Poisson's equation must be solved. The solution gives

$$x_n = \left(\frac{2\varepsilon_0 \varepsilon_S (\psi_0 + V) N_A}{q N_D (N_A + N_D)} \right)^{1/2} , \quad x_p = \left(\frac{2\varepsilon_0 \varepsilon_S (\psi_0 + V) N_D}{q N_A (N_D + N_A)} \right)^{1/2}$$

$$w = x_p + x_n = \left(\frac{2\varepsilon_0 \varepsilon_S (\psi_0 + V)(N_D + N_A)}{q N_A N_D} \right)^{1/2}$$

Depletion Capacitance

The small signal capacitance of the space charge layer is given by $C \equiv \frac{dQ}{dV_R}$ where Q is the unipolar charge in the depletion region

$$Q = qAN_D x_n = qAN_A x_p = A\left(\frac{2q\varepsilon_0\varepsilon_S(\psi_0 + V_R)N_A N_D}{(N_A + N_D)}\right)^{1/2}$$

Therefore

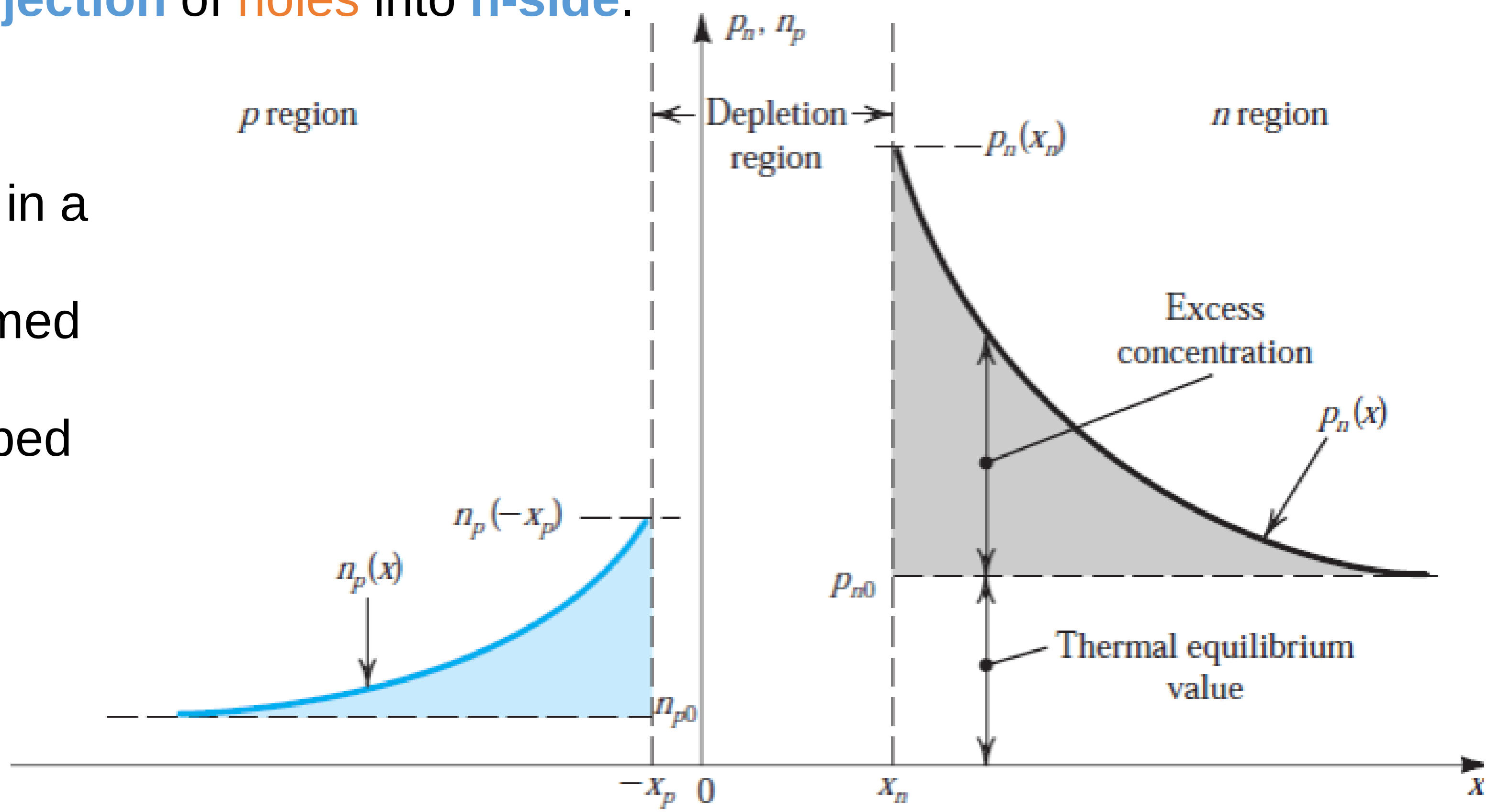
$$C = A\left(\frac{q\varepsilon_0\varepsilon_S N_D N_A}{2(N_A + N_D)(\psi_0 + V_R)}\right)^{1/2}$$

I-V Characteristics

Under **equilibrium** - **drift and diffusion** components of the electron current are equal but opposite in direction. Net electron current is zero. Same is true for net hole current.

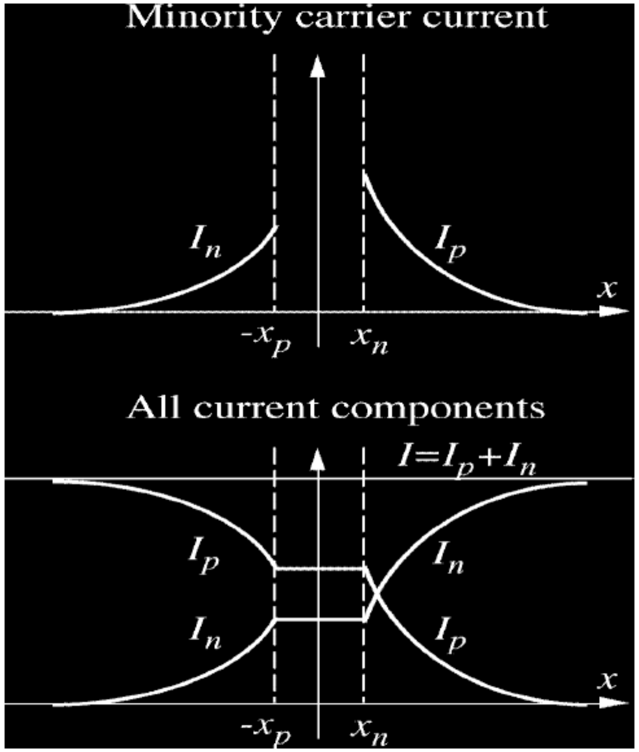
Under forward bias, depletion region is reduced, E-field in depletion region is reduced and drift current is reduced. However, there is an **injection** of electrons into **p-side** and **injection** of holes into **n-side**.

Carrier distribution in a forward biased ***pn*** junction. It is assumed that the ***p* region** is more heavily doped than the *n* region: NA >>ND.



I-V Characteristics

Shockley Relationship



The current continuity requires the total current to be constant at each point along the device.

$$\boxed{I(x) = I_n(x) + I_p(x) = \mathrm{C}}$$

This means that away from the depletion layer edges the minority diffusion current is gradually transferred in majority drift current and this happened via recombination.

I-V Characteristics

Hole diffusion into n-region:

$$p_n(x) = p_{n0} + p_{n0}(e^{V/V_T} - 1)e^{-(x-x_n)/L_p}$$

Injected minority carriers diffuse away from the depletion region edges and recombine with majority carriers. Thus, their concentration decays exponentially.

$$J_p(x) = -qD_p \frac{dp_n(x)}{dx}$$

$$J_p(x) = q\left(\frac{D_p}{L_p}\right)p_{n0}(e^{V/V_T} - 1)e^{-(x-x_n)/L_p}$$

$$J_p(x_n) = q\left(\frac{D_p}{L_p}\right)p_{n0}(e^{V/V_T} - 1)$$

NB for electron diffusion into p-region

$$J_n(-x_p) = q\left(\frac{D_n}{L_n}\right)n_{p0}(e^{V/V_T} - 1)$$

$$I = A(J_p + J_n)$$

$$I = Aq\left(\frac{D_p}{L_p}\,p_{n0} + \frac{D_n}{L_n}\,n_{P0}\right)(e^{V/V_T} - 1)$$

Substituting for $p_{n0} = n_i^2/N_D$ and for $n_{p0} = n_i^2/N_A$ gives

$$I = Aqn_i^2\left(\frac{D_p}{L_pN_D} + \frac{D_n}{L_nN_A}\right)(e^{V/V_T} - 1)$$

$$I_S = Aqn_i^2\left(\frac{D_p}{L_pN_D} + \frac{D_n}{L_nN_A}\right)$$

$$\boxed{I = I_S(e^{V/V_T} - 1)}$$

Famous **SHOCKLEY** equation

Where I_S is also know as the "**Reverse Bias Saturation**" Current

I-V Characteristics

$$p_n(x) = \left(p_n(x_n) - p_{n0}\right)\exp\left(-\frac{(x - x_n)}{L_p}\right) + p_{n0}$$

$$n_p(x) = \left(n_p(-x_p) - n_{p0}\right)\exp\left(\frac{(x + x_p)}{L_n}\right) + n_{p0}$$

where L_p, L_n are the minority carriers diffusion lengths. The minority carrier diffusion currents are given by

$$I_p(x) = -qAD_p\frac{dp_n(x)}{dx} = qA\frac{D_p}{L_p}\left(p_n(x_n) - p_{n0}\right)\exp\left(-\frac{(x - x_n)}{L_p}\right)$$

$$I_n(x) = qA\frac{D_n}{L_n}\left(n_p(-x_p) - n_{p0}\right)\exp\left(\frac{(x + x_p)}{L_n}\right)$$

At *low level of injection* at the depletion layer edges, it can be shown that

$$n_p(-x_p) = n_{p0}\exp\left(\frac{V_F}{V_T}\right) \quad , \quad p_n(x_n) = p_{n0}\exp\left(\frac{V_F}{V_T}\right) \longrightarrow V_T = \frac{K_B T}{q}$$

Therefore the minority carrier currents at the depletion layer edges are given by

$$I_p(x_n) = qA\frac{D_p}{L_p}p_{n0}\left(\exp\left(\frac{V_F}{V_T}\right) - 1\right) \quad , \quad I_n(-x_p) = qA\frac{D_n}{L_n}n_{p0}\left(\exp\left(\frac{V_F}{V_T}\right) - 1\right)$$

I-V Characteristics

$$I = I_S\left(\exp\left(\frac{V_F}{V_T}\right) - 1\right)$$

Normally $exp(V_F/V_T) >> 1$ and therefore

$$I = I_S\ \exp\left(\frac{V_F}{V_T}\right)$$

In reverse bias conditions

$$I = I_S\left(\exp\left(-\frac{V_R}{V_T}\right) - 1\right) \approx -\ I_S$$