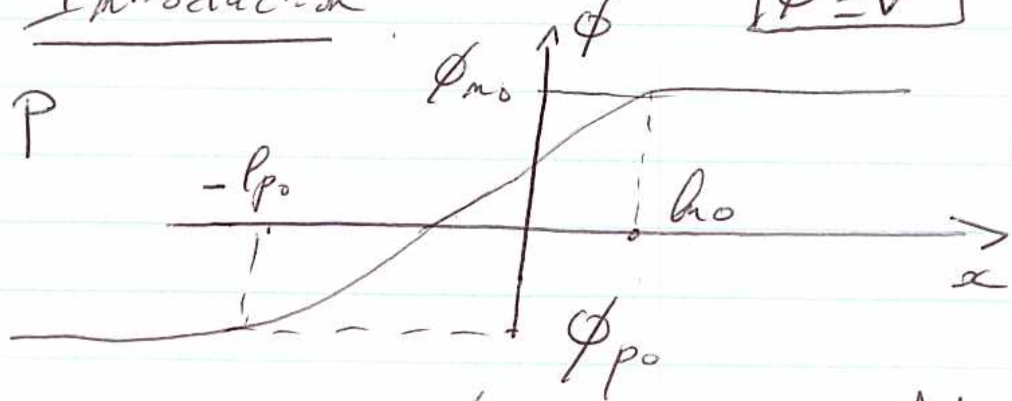
3 Biased Junction

an external bias, Va, is now applied to the junction we want to obtain the current-voltage characteristics.

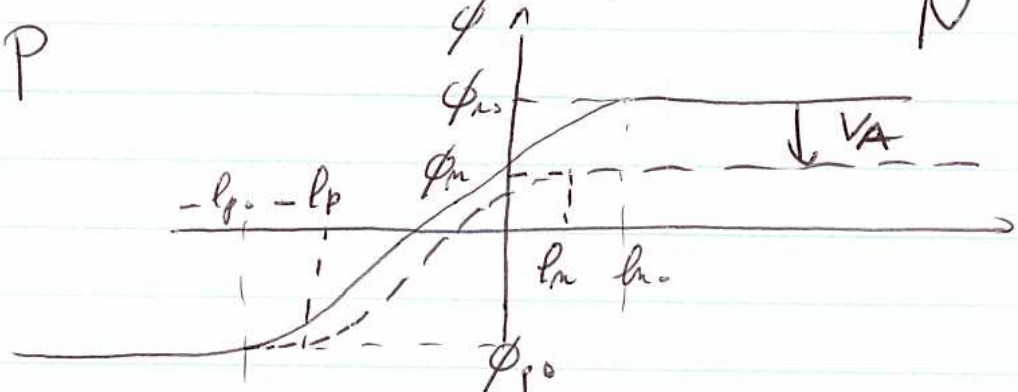
a Introduction

$\boxed{\phi \equiv V}$



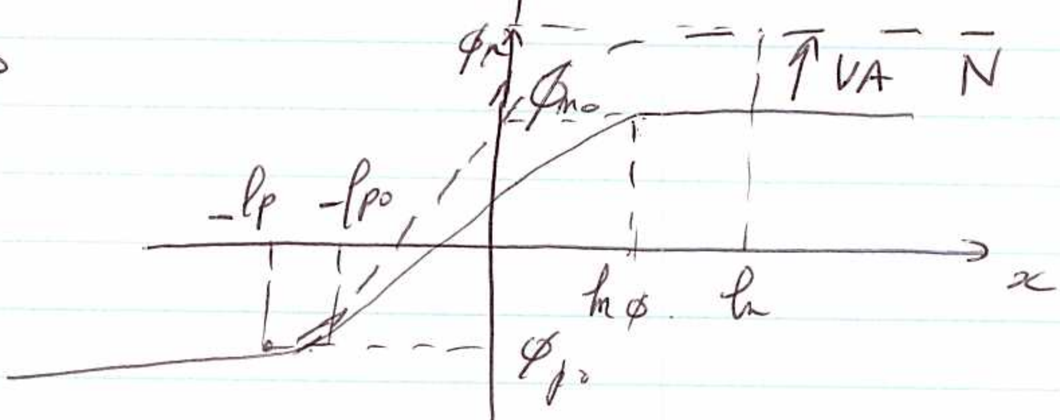
$\boxed{Va = 0}$

Forward bias



$\boxed{Va > 0}$

Reverse bias



$\boxed{Va < 0}$

Assumption Potential drops across the quasi-neutral region are negligible (small current) $\Rightarrow$ potential drops across the transition region.

$$\boxed{\begin{aligned}\phi &= \phi_N - \phi_P \\ \phi &= \phi_0 - V_A\end{aligned}}$$

we get for l_n and l_p (using previous expressions where we replace $\phi_0 \to \phi_0 - V_A$).

$$\Rightarrow \quad l_p = \sqrt{\frac{2\epsilon}{q}\frac{(\phi_0 - V_A)N_d}{N_a(N_a+N_d)}} \qquad l_n = \sqrt{\frac{2\epsilon}{q}\frac{(\phi_0 - V_A)N_A}{N_d(N_d+N_A)}}.$$

$$W = l_n + l_p = \sqrt{\frac{2\epsilon}{q}\frac{(\phi_0 - V_A)(N_A+N_d)}{N_A N_d}}.$$

Note. $W \nearrow$ if $V_A < 0$
. $W \searrow$ if $V_A > 0$

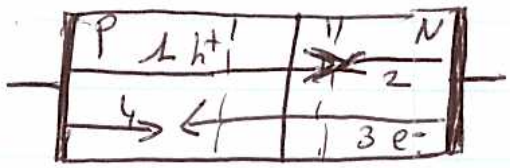
* Forward bias

Diffusion and electric field (drift) forces are no longer equal and of opposite sign.

$\Rightarrow$ Non-equilibrium situation where
Diffusion process > drift phenomena.

$\Rightarrow$ e^- can flow from $N \to P$
holes can flow from $P \to N$.

These carriers diffuse into N or P-type region with an average distance "diffusion length" before they start recombining with majority carriers.



1: hole injected from P → N. 2: $\bar{e}$ recombining.
3: $\bar{e}$ injected from N → P ; 4: hole recombining..

current 1 == current 2.
Current 3 == current 4

* <u>Reverse Bias</u>

the electric field in the depletion region ↗ and the associated drift current > diffusion current

the magnitude of the resulting net current is very small. (few $\bar{e}$ in the P region, few hole in the N region).

⇒ P-N junction behave like a diode rectifying current flow.

* the derivation of current-voltage characteristics will make use of currents 1 and 3 (minority carriers injection).

the total current is equal to the sum of these two currents.

b) Ideal diode

$\boxed{\text{No G/R in the depletion region}}$

Let us make the following simplifying assumptions:

→ ① Low_level injection: the concentration of free carriers injected in a quasi_neutral region is low compared to the charge of the majority carriers while solving the Poisson equation.

→ ② The Boltzmann relationships are valid in the quasi_neutral region as well as in the transition region.

→ ③ Current flow in the quasi_neutral region is due to a diffusion mechanism. (no electric field in these region).

→ ④ The quasi_neutral regions of the diode are infinitely long

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→ ① Low_level injection:

excess concentration of minority carriers are

$p'_n(x)$ in the N_type quasi_neutral region $p'_n(x) = p_n(x) - p_{no}$

$n'_p(x)$ in the P_type region $n'_p(x) = n_p(x) - n_{po}$

$$\boxed{\begin{array}{l} p'_n(x) \ll n_{no} \text{ (charge of majority carriers)}. \\ n'_p(x) \ll p_{po} \text{ (")} \end{array}}$$

Also ~~that~~ the concentration of the majority carriers is not modified by the injection of minority carriers.

$$\left[\begin{array}{l} n_n(x) = n_{n0} = N_d \text{ in the N-type quasi-neutral region.} \\ p_p(x) = p_{p0} = N_a \text{ in the P-type } '' \quad '' \quad '' . \end{array}\right.$$

→ (2) Boltzmann relationship

$$n(x) = n_i \exp\left[\beta\left(E_{FN} - E_{i0}\right)\right] \exp\left[q\beta V(x)\right]$$

- $n_n(x) = n_{n0} = N_d$ for $l_n \leq x \leq \infty$ and $\underline{V(x) = V_n}$.

- so $n_{n0} = \exp\left[\beta\left(E_{FN} - E_{i0}\right)\right] \exp\left[q\beta V_n\right]$

$$\Rightarrow \quad n(x) = n_{n0} \exp\left[\beta q \underline{\left(V(x) - V_n\right)}\right]$$

- if this equation valid also in the transition region. at $x = -l_p$ where $V(x) = -V_p$.

$$n_p(-l_p) = n_{n0} \exp\left[\beta q \left(V_p - V_n\right)\right]$$

and since $V_p - V_n = V_A - V_0$ it comes.

$$\boxed{n_p(-l_p) = n_{n0} \exp\left[-q V_0 \beta\right] \exp\left[q V_A \beta\right]}$$

we know that $V_0 = \frac{1}{q\beta} \ln\left(\frac{N_a N_d}{n_i^2}\right) = \frac{1}{q\beta} \ln\left(\frac{p_{p0}\, n_{n0}}{n_i^2}\right)$

we get ~~finally~~

$$n_p(-l_p) = \frac{n_i^2}{p_{p0}} \exp[\beta q V_A] \quad ,$$

Since

$$n_{p0}\, p_{p0} = n_i^2$$

$$\Rightarrow \quad \boxed{n_p(-l_p) = n_{p0} \exp[q\beta V_A]}$$

Similarly,

$$\boxed{p_n(l_n) = p_{n0} \exp(q\beta V_A)}$$

So excess of e^- at the P-side edge of the transition region

$$n'_p(-l_p) = n_{p0}\left[\exp(q V_A \beta) - 1\right]$$

and excess of holes

$$p'_n(l_n) = p_{n0}\left[\exp(q V_A \beta) - 1\right]$$

→ 3 $\vec{\mathcal{E}} = 0$ in the quasi neutral region.

$$\Rightarrow \quad J_p = -q D_p \frac{dp}{dx} \quad \text{N-type quasi-neutral region.}$$

$$J_n = q D_n \frac{dn}{dx} \quad \text{P-type quasi neutral region.}$$

[we need first to derive p and n]

Using the continuity equation (no external source)

$$\frac{\partial p_n}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} - \frac{p_n - p_{n0}}{\tau_p}$$

if we replace J_p, we get:

$$\frac{\partial p_n}{\partial t} = D_p \frac{\partial^2 p_n}{\partial x^2} - \frac{p_n - p_{n0}}{\tau_p} = 0$$

if steady state conditions

So $D_p \dfrac{\partial^2 p_n}{\partial x^2} = \dfrac{p_n - p_{n0}}{\tau_p}$

$$\Rightarrow \frac{\partial^2 p_n}{\partial x^2} - \frac{1}{D_p \tau_p}(p_n - p_{n0}) = 0$$

$$p_n(x) = p_{n0} + A\exp(-x/L_p) + B\exp(x/L_p) \qquad \underbrace{\boxed{L_p = \sqrt{D_p \tau_p}}}_{\text{diffusion length}}$$

Similarly

$$n_p(x) = n_{p0} + A\exp(-x/L_n) + B\exp(x/L_n) \qquad \boxed{L_n = \sqrt{D_n \tau_n}}$$

→ 4 quasi-neutral regions are infinitely long ⇒ "long-base diode"

$p_n(\infty) = p_{n0}$ (Boundary condition due to thermodynamic equilibrium far from the junction)

$\Rightarrow B = 0$

$$p_n(l_n) = p_{n0} \exp[qV_A\beta] = p_{n0} + A \exp\left(-\frac{l_n}{L_p}\right)$$

$$\Rightarrow \quad A = p_{n0}\left[\exp(qV_A\beta) - 1\right] \exp\left(\frac{l_n}{L_p}\right)$$

we get finally for the holes

$$\boxed{p_n(x) = p_{n0} + p_{n0}\left[\exp(qV_A\beta) - 1\right] \exp\left(\frac{-(x - l_n)}{L_p}\right)}$$

So

in the N-region $x > l_n$

$$\boxed{J_p = -qD_p \frac{dp_n}{dx} = q\frac{D_p\, p_{n0}}{L_p} \exp\left(\frac{-(x - l_n)}{L_p}\right)\left[\exp(qV_A\beta) - 1\right]}$$

Similarly in the P-region $x < -l_p$

$$\boxed{J_n = qD_n \frac{dn_p}{dx} = q\frac{D_n\, n_{p0}}{L_n} \exp\left(\frac{x + l_p}{L_n}\right)\left[\exp(qV_A\beta) - 1\right]}$$

Remarks:

These currents depend on x, for example $J_p(x) \searrow$ if $x \nearrow$. This is due because of the recombination process. Here the hole current is transformed into an e^- current (via recombination). So, the total current is independent of x.

the cte potential can be obtained using our assumption that there is no G/R in the depletion region.
we can evaluate these current at a position in which they have not yet started to decay: at $x = l_n, -l_p$

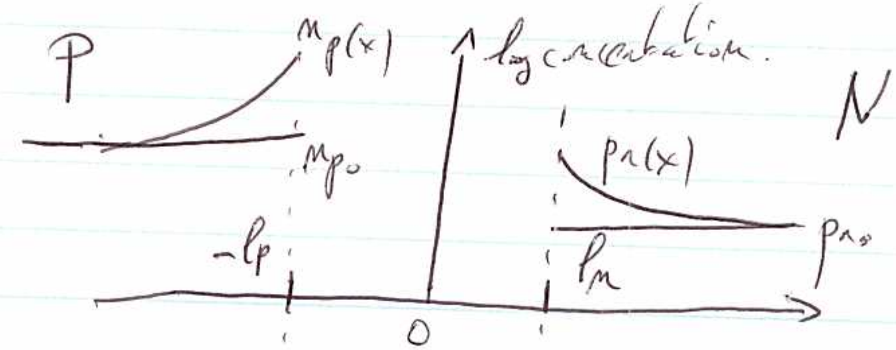
⇒ the total current is then given by:

$$J_{total} = J_p(l_n) + J_n(-l_p) = \left[q\frac{D_n}{L_n} n_{p0} + q\frac{D_p}{L_p} p_{n0} \right] \exp\left[(q\beta V_A) - 1\right]$$

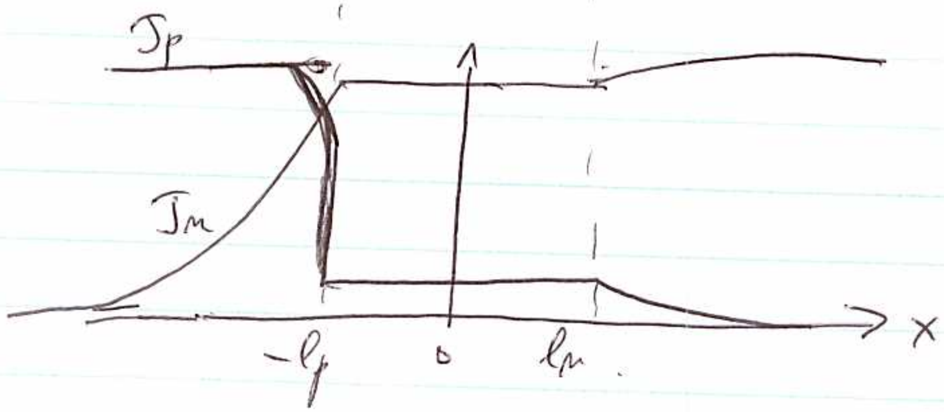
$$\boxed{J_{total} = J_S \left(\exp[q\beta V_A] - 1 \right)}$$ ⇒ Shockley's equation

⇒ with J_S the 'saturation current density'

density carrier concentration



Current



Remark if $V_A < 0$, the total current is I_S independent of V_A, and the electric field in the structure.

© Deviation from ideality

G/R in the depletion region; these processes are proportional to $np - n_i^2$.

if the external bias is applied, excess carriers are injected ($V_A > 0$) into or extracted ($V_A < 0$) from the transition region.

so $pn \neq n_i^2$

We consider two quasi Fermi-level, E_{Fn} for e^- and E_{Fp} for holes.

According to class notes p62.

we get

$$\boxed{pn = n_i^2 \exp\left[\frac{E_{FN} - E_{FP}}{k_B T}\right] = n_i^2 \exp\left[\frac{qV_A}{k_B T}\right]}$$

since $E_{FN} - E_{FP} = qV_A$

we know that the SRH G/R rate is

$$U = \frac{pn - n_i^2}{\tau_0 \left(p + n + 2n_i \cosh\left[\frac{E_t - E_i}{k_B T}\right]\right)}$$

* we assume that only only traps at energy $E_T = E_i$ contribute effectively to the G/R processes.

$\Rightarrow$ it comes (using the two last equations)

$$\boxed{U \simeq \frac{n_i^2\left[\exp(q\beta V_A) - 1\right]}{\tau_0(p + n + 2n_i)}}$$

using the continuity equation in steady state

$$\boxed{\frac{dJ_n}{dx} = -\frac{dJ_p}{dx} = q\,U(x)}$$

so far we have calculated $J_n(-l_p)$ that we ~~supposed~~ assumed equal to $J_n(l_n)$ since no G/R.

we want know to evaluate the influence of G/R:

$$\int_{-l_p}^{l_n} \frac{dJ_n}{dx}\,dx = \int_{-l_p}^{l_n} q\,U(x)\,dx$$

$$\Rightarrow \boxed{J_n(l_n) = J_n(-l_p) + q\int_{-l_p}^{l_n} U(x)\,dx}$$

the net current is then

$$\boxed{J = J_p(l_n) + J_n(l_n) = J_p(l_n) + J_n(-l_p) + J_{GR}}$$

$$= J_s\left[\exp(q\beta V_A) - 1\right] + J_{GR}$$

we want to evaluate J_{GR} (correction to the Schockley term) using a simple approximation.

$J_{G/R}$ will be dominated at a position where $p+n$ is a minimum, Also pn is constant:

we get $d(p+n)=0 \Rightarrow dp=-dn$.

and $pn = c^{te} \Rightarrow d(pn)=0 \quad ndp+pdn=0$

it comes $p=n$

so $\boxed{n=p=n_i \exp\left(\frac{qV_A\beta}{2}\right)}$

$$\Rightarrow U = \frac{n_i\left[\exp\left(\frac{qV_A\beta}{2}\right)-1\right]}{2\tau_0} = U_{max}$$

assuming that G/R take this value U_{max} over the entire transition region [not correct - we overestimate the effects here!]

$$\Rightarrow J_{GR} \simeq q\,U_{max}\,(l_n+l_p) \qquad \boxed{W = l_n+l_p}$$

$$J_{tot} \simeq J_s\left[\exp\left(qV_A\beta\right)-1\right] + q\frac{W n_i}{2\tau_0}\left[\exp\left(\frac{qV_A\beta}{2}\right)-1\right]$$

if $V_A > 0$ but small, the $J_{R/G}$ is the larger than the diffusion current.
if $V_A < 0$ $J_{R/G}$ adds to the reverse current.

if $V_A > 0$

Small bias

the I-V follows $\exp\left(q\frac{V_A}{2}\beta\right)$ laws $\Rightarrow$ characteristics of a recombination dominated current

high bias

I-V follows $\exp(qV_A\beta)$ $\Rightarrow$ diffusion current takes over and completely overshadows the recombination current

if $V_A < 0$

$$pn = n_i^2 \exp\left(\frac{qV_A}{k_BT}\right) < n_i^2$$

so generation current can be observed in the reverse bias.

I-V characteristics

(d) Junction Breakdown

if $V_A < 0$ strongly reversed biased, $\vec{E}$ near the metallurgical junction can reach high value. Carriers accelerated in that field can accumulate enough kinetic energy that they can, through a collision process, generate e^--hole pairs through impact ionization