I] P_N junctions

1) Introduction

P_N junction is formed when a P-type and an N-type semiconductor are in contact.

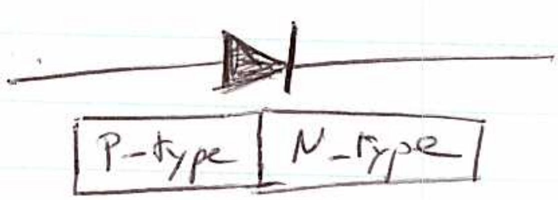
- if the N-type and P-type are made out of the same semic. material ⇒ homojunction
- if the semicond. are different ⇒ heterojunction (we will study this later)

Application of P_N junctions.

- diode = ~~pn~~ single P-N junction - (2 terminal device) present a highly non-linear current_voltage characteristics and it is often used as a rectifying element. Some diode can emit light
- BJT = two P_N junction - (3 terminal devices) capable of amplifying electrical signals

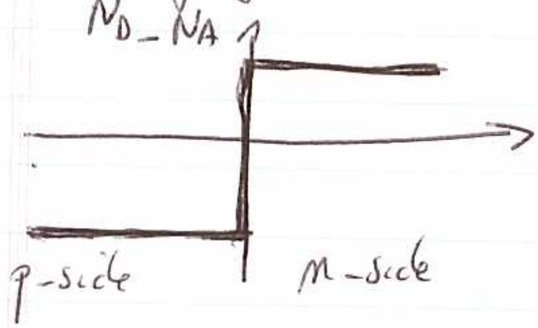
Properties :

P_N junction allows the current flow in one bias direction, but not in the other..

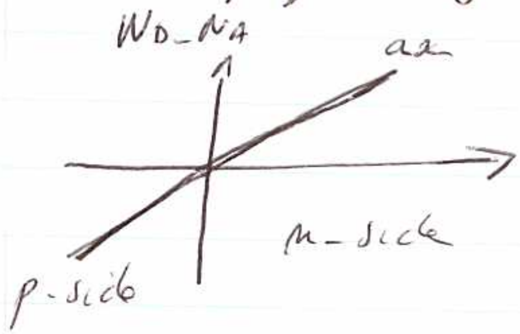


1. P-N junction can be separated into two major categories:

- step junction



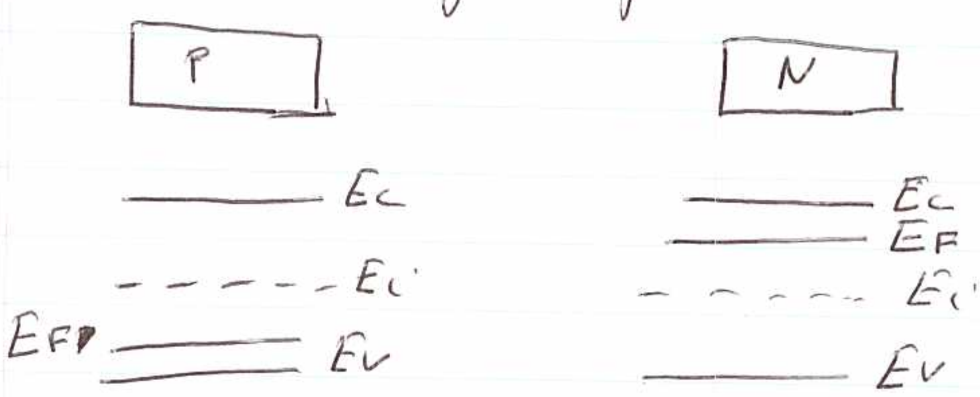
- Linearly-graded junction



2 unbiased junction

P-N junction is considered at equilibrium. (no applied bias)

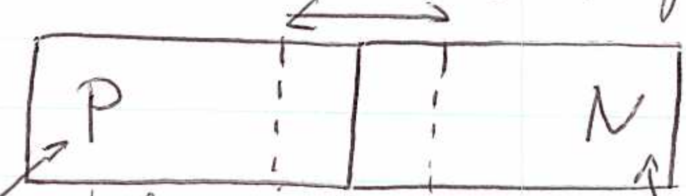
- If we consider 2 separate pieces:



$$E_i - E_F = \frac{1}{\beta} \ln\left(\frac{N_a}{n_i}\right) \qquad E_F - E_i = \frac{1}{\beta} \ln\left(\frac{N_d}{n_i}\right)$$

Let us connect the 2 pieces end for a PN step junction.

transition region (depletion region).
(or Space charge region)



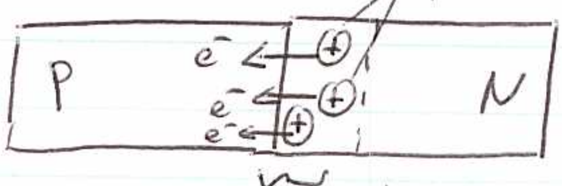
quasi-neutral P region

(metallurgical junction)

quasi-neutral N-region.

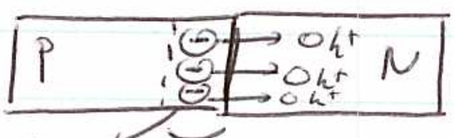
• e^- diffusion

positive ions (cannot move)



region depleted of e^- (positively charged).

• hole diffusion

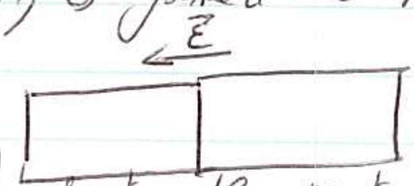


negative ions (cannot move)

region depleted of holes (negatively charged).

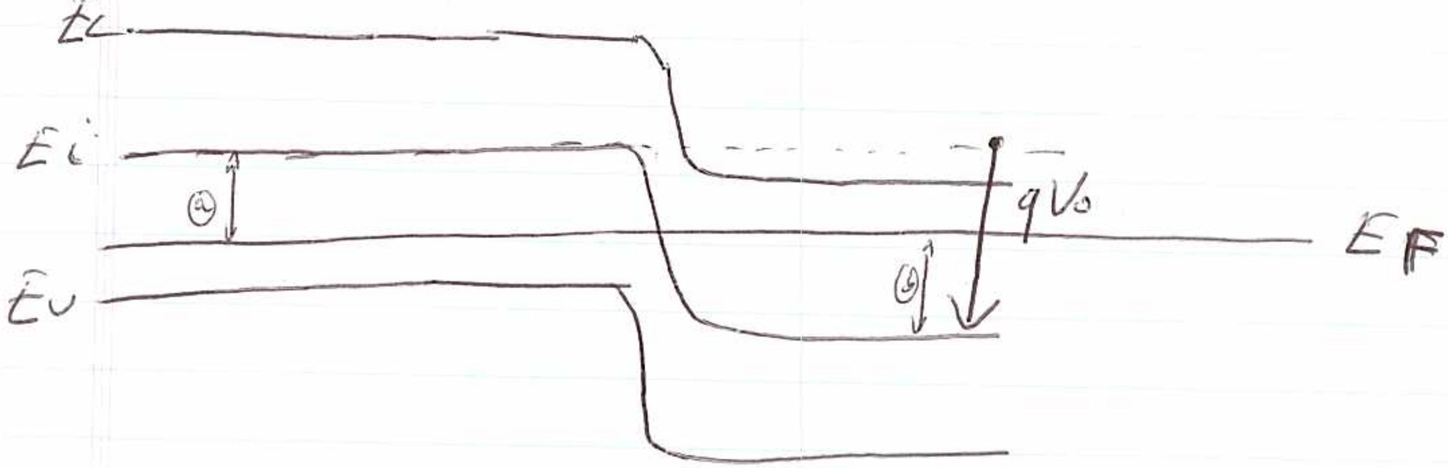
• Built-in potential

as a result to the diffusion processes, a built-in potential, V_0, is formed at the junction.



$\vec{E}$ pulls the e^- back to the n-type region.

$\vec{E}$ // holes back to the p-type region.



$$qV_0 = \overbrace{(E_i - E_F)_p}^{(a)} + \overbrace{(E_F - E_i)_n}^{(b)}$$

$$= \frac{1}{\beta} \ln\left(\frac{N_a N_d}{n_i^2}\right) \Rightarrow \boxed{V_0 = \frac{k_B T}{q} \ln\left(\frac{N_a N_d}{n_i^2}\right)}$$

- What are the potential variation and electric field in the depletion region?

→ Poisson equation

$$-\frac{d^2 V(x)}{dx^2} = \frac{-q}{\varepsilon_s}\left(n + N_a^- - p - N_d^+\right)$$

~~that~~ it is non-linear since

$$\left[\begin{array}{l} n(x) = n_{n0}\, e^{qV(x)\beta} \\ p(x) = p_{p0}\, e^{-qV(x)\beta} \end{array}\right\}$$

Boltzmann relationship.
with n_{n0}, p_{p0}, are the e^- (hole) densities in the quasi-neutral region N (and P)

we cannot solve the Poisson equation analytically, so we use here approximations.

'depletion approximation' $\Rightarrow$ $\vec{E}$ vanishes outside the depletion region (neutrality) and we ignore the charge due to free carriers in the depletion region. $\boxed{-l_p \leq x \leq l_n}$

so $N_D^+ \gg n$ for $0 \leq x \leq l_n$.
$N_A^- \gg p$ for $-l_p \leq x < 0$

$$
\begin{cases}
-\dfrac{d^2\psi(x)}{dx^2} = +\dfrac{q N_D}{\epsilon_s} & \text{for } 0 \leq x \leq l_n. \\[2ex]
-\dfrac{d^2\psi(x)}{dx^2} = -q\dfrac{N_A}{\epsilon_s} & \text{for } -l_p \leq x \leq 0
\end{cases}
$$

with B. condition $\left.\dfrac{dV}{dx}\right|_{-l_p} = \left.\dfrac{dV}{dx}\right|_{l_n} = 0$

By definition $\begin{cases} \psi(-l_p) = \psi_{p0} \\ \psi(l_n) = \psi_{n0} \end{cases}$

$$
\Rightarrow \boxed{\psi(x) = \begin{cases} -\dfrac{q N_D}{2\epsilon_s}(x - l_n)^2 + V_{n0} & (0 \leq x \leq l_n) \\[2ex] \dfrac{q N_A}{2\epsilon_s}(x + l_p)^2 + V_{p0} & (-l_p \leq x \leq 0) \end{cases}}
$$

it comes for the electric field $\mathcal{E} = -\frac{dV}{dx}$.

$$\Rightarrow \quad \mathcal{E}(x) = \begin{cases} \frac{q N_D}{\epsilon_s}(x - l_n) & (0 \le x \le l_n) \\ -\frac{q N_A}{\epsilon_s}(x + l_p) & (-l_p \le x \le 0) \end{cases}$$

- continuity of $\mathcal{E}(x)$ at $x = 0$ $\Rightarrow$ $\boxed{N_D l_n = N_A l_p}$ (*)

  charge neutrality equation

- Continuity of the potential at $x = 0$

$$\Rightarrow \quad 0 = V_{p0} - V_{n0} + \frac{q N_A}{2\epsilon_s} l_p^2 + q \frac{N_D}{2\epsilon_s} l_n^2$$

with (*)

$$\Rightarrow \quad 0 = V_{p0} - V_{n0} + q \frac{N_A N_D^2 l_n^2}{2\epsilon_s N_A^2} + q \frac{N_D}{2\epsilon_s} l_n^2$$

we know that

$$V_0 = V_{n0} - V_{p0} = q \frac{N_A N_D^2 l_n^2}{2\epsilon_s N_A^2} + q \frac{N_D}{2\epsilon_s} l_n^2 \left(= \frac{k_B T}{q} \log \frac{N_a N_d}{n_i^2} \right.$$

$$\Rightarrow \quad \boxed{\begin{aligned} l_n &= \sqrt{\frac{2\epsilon_s}{q} \frac{V_0 N_a}{N_d (N_a + N_d)}} \\ l_p &= \sqrt{\frac{2\epsilon_s}{q} \frac{V_0 N_d}{N_a (N_a + N_d)}} \end{aligned}}$$

width of the depletion region

$$\boxed{W = l_n + l_p = \sqrt{\frac{2\epsilon_s}{q}\frac{(N_a+N_d)}{N_a N_d}V_0}}$$

* Maximum electric field at $x=0$

$$\Rightarrow \boxed{\mathcal{E}_{max} = -q\frac{N_A}{\epsilon_s}l_p = -\frac{qN_D}{\epsilon_s}l_n}$$

Summary