Carrier transport in semiconductor

1) **Drift current:-**

Drift velocity $v_d = \mu E$

$\mu \rightarrow$ mobility.

$E \rightarrow$ electric field.

For electron, drift current density =

$$J_{de} = n e v_{de} = n e \mu_e E$$

For hole, drift current density

$$J_{dh} = p e v_{dh} = p e \mu_h E$$

Total drift current density $J_d = J_{de} + J_{dh}$

$$= n e \mu_e E + p e \mu_h E$$

$$= (n e \mu_e + p e \mu_h) E$$

$\therefore$ Drift ~~current~~ electrical conductivity

$$\sigma = \frac{J_d}{E} = n e \mu_e + p e \mu_h$$

For intrinsic semiconductor

$$\sigma_i = n_i (\mu_e + \mu_h) e$$

P. ~ N

2) **Diffusion current:-** In a semiconductor, in addition to conduction current, transport of charge carriers also occurs by diffusion process.

Diffusion:- Process in ~~which~~ which the particles (e or h) move from a region of higher concentration to region of lower concentration.

Diffusion Current: current due to concentration gradient of the charge carriers.

No. of electrons crossing through unit area per unit time due to diffusion $n_d \propto -\frac{\delta n}{\delta x}$ [$\frac{\delta n}{\delta x} \rightarrow$ Concentration gradient]

$$\therefore \boxed{n_d = -D_e \frac{\delta n}{\delta x}}$$

[$D_e \rightarrow$ Diffusion constant for electron]

Diffusion current density for diffusion of electron

$$J_e(\text{diffusion}) = -e n_d = e D_e \frac{\delta n}{\delta x}$$

Diffusion current density for diffusion of hole

$$J_h(\text{diffusion}) = e p_d = e\left(-D_p \frac{\delta p}{\delta x}\right) = -e D_p \frac{\delta p}{\delta x}$$

$\therefore$ Total diffusion current density

$$J(\text{diffusion}) = J_e(\text{diffusion}) + J_h(\text{diffusion}) = e D_e \frac{\delta n}{\delta x} - e D_p \frac{\delta p}{\delta x}$$

Consider

Einstein Relation

P-N junction at equilibrium

Total current through the junction = sum of drift current + diffusion current.

In equilibrium condition,

total current through the junction = 0

$\Rightarrow J(\text{drift}) + J(\text{diffusion}) = 0$

$\Rightarrow \cancel{(ne\mu_e + pe\mu_h)}\,\mathcal{E}$

$\Rightarrow J_e(\text{drift}) + J_h(\text{drift}) + J_e(\text{diffusion}) + J_h(\text{diffusion}) = 0$

$\Rightarrow [J_e(\text{drift}) + J_e(\text{diffusion})] + [J_h(\text{drift}) + J_h(\text{diffusion})] = 0$

$\Rightarrow \left[ne\mu_n\mathcal{E} + eD_e\frac{\delta n}{\delta x}\right] + \left[pe\mu_h\mathcal{E} - eD_p\frac{\delta p}{\delta x}\right] = 0$

For electron :-

$n \rightarrow$ electron concentration

$$ne\mu_n\mathcal{E} + eD_e\frac{\delta n}{\delta x} = 0$$

$$\Rightarrow \frac{\delta n}{\delta x} = -\frac{n\mu_n\mathcal{E}}{D_e} \Rightarrow \boxed{\frac{1}{n}\frac{\delta n}{\delta x} = -\frac{\mu_n\mathcal{E}}{D_e}} \quad -(1)$$

$\Rightarrow$

Electron Concentration in a N-D semiconductor in terms of electrons in conduction band.

$$n = N_c\, e^{(E_F - E_c)/KT}$$

$$n = \text{Constant } e^{-E_c/KT} = \text{Constant } e^{-E/KT}$$

$$\Rightarrow \ln n = \text{Constant} - \frac{E}{KT} = \text{Const}^n + \frac{eV}{KT}$$

[As E_c varies at the junction
$E \to$ energy]
$= -eV \to$ -ve for electron
PCA^n

Diff^n both sides w.r.t. x

$$\boxed{\frac{1}{n}\frac{\delta n}{\delta x} = \frac{e}{KT}\frac{\delta V}{\delta x}} \quad -(2)$$

Comparing 1 & 2 $\Rightarrow$

$$-\frac{\mu_n \mathcal{E}}{D_e} = \frac{e}{KT}\frac{\delta V}{\delta x}$$

$$\Rightarrow -\frac{\mu_n}{D_e}\cdot\left(-\frac{\delta V}{\delta x}\right) = \frac{e}{KT}\frac{\delta V}{\delta x}$$

[As electric field $\mathcal{E} = -\frac{\delta V}{\delta x}$]

$$\Rightarrow \boxed{D_e = \frac{KT}{e}\mu_n}$$

This relation is known as Einstein relation for electron considering a p-n junction under equilibrium condition.

Similarly considering the drift and diffusion of hole,

$$pe\mu_h \mathcal{E} - eD_p\frac{\delta p}{\delta x} = 0$$

$$\Rightarrow \frac{\delta p}{\delta x} = \frac{p\mu_h \mathcal{E}}{D_p} \Rightarrow \boxed{\frac{1}{p}\frac{\delta p}{\delta x} = \frac{\mu_h \mathcal{E}}{D_p}} \quad -(3)$$

hole concentration in a N-D semiconductor

$$p = N_v e^{(E_v - E_F)/KT} = \text{Const}^n e^{E_v/KT} = \text{Const}^n e^{E/KT}$$

[$\because E_F$ is fixed, E_v Varies at the junction]

$$\ln p = \text{Const}^n + \frac{E}{KT} = \text{Const}^n + \frac{eV}{KT}$$

[Electric field $\mathcal{E} = \frac{eV}{\cancel{e}}$ for hole]

Diff. w.r.t. x

$$\boxed{\frac{1}{p}\frac{\delta p}{\delta x} = \frac{e}{KT}\frac{\delta V}{\delta x}} \quad \text{--- (4)}$$

$$\mathcal{E} = \frac{\delta V}{\delta x}$$

Comparing (3) + (4) $\Rightarrow$

$$\frac{\mu_h \mathcal{E}}{D_p} = \frac{e}{KT}\frac{\delta V}{\delta x}$$

$$\Rightarrow \frac{\mu_h}{D_p}\frac{\delta V}{\delta x} = \frac{e}{KT}\frac{\delta V}{\delta x}$$

$$\Rightarrow \boxed{D_p = \frac{KT}{e}\mu_h}$$

This is the Einstein Relation for hole considering a p-n junction under equilibrium condition.

In general $\boxed{D = \frac{KT}{e}\mu}$

$$\boxed{\frac{D_e}{D_p} = \frac{\mu_e}{\mu_h}}$$

$D \rightarrow$ Diffusion constant

$\mu \rightarrow$ mobility.

(7)

Potential barrier across p-n-junction [at equilibrium condition] or potential barrier

At equilibrium : ~~Drift current = Diffisun current~~
Total current through junction = 0

for motion of electron:

$$n e \mu_n \mathcal{E} + e D_n \frac{\delta n}{\delta x} = 0$$

$$\Rightarrow n \mu_n \mathcal{E} = -D_n \frac{\delta n}{\delta x} = -\frac{KT}{e}\mu_n \frac{\delta n}{\delta x}$$

$$\Rightarrow \mathcal{E} = -\frac{KT}{e\, n}\frac{\delta n}{\delta x}$$

$$\Rightarrow -\frac{\delta v}{\delta x} = -\frac{KT}{e\, n}\frac{\delta n}{\delta x}$$

$$\Rightarrow \int_{v_p}^{v_n} \delta v = \frac{KT}{e}\int_{n_p}^{n_n} \frac{\delta n}{n}$$

$$\Rightarrow (v_n - v_p) = \frac{KT}{e}\ln\left(\frac{n_n}{n_p}\right)$$

$$\Rightarrow \boxed{\Delta\phi = \frac{KT}{e}\ln\left(\frac{n_n}{n_p}\right)}$$

$$\hookrightarrow \frac{n_n}{n_p} = e^{\left(\frac{e\Delta\phi}{KT}\right)}$$

Again from law of mass action

$$n_p P_p = n_n P_n = n_i^2$$

Assuming full ionization of donar & acceptors

$$n_n \simeq N_d$$

$$P_p \simeq N_a$$

$n \rightarrow$ electron concentration

$\mu_n \rightarrow$ mobility of e

$D_n \rightarrow$ Diffusion coefficient for e.

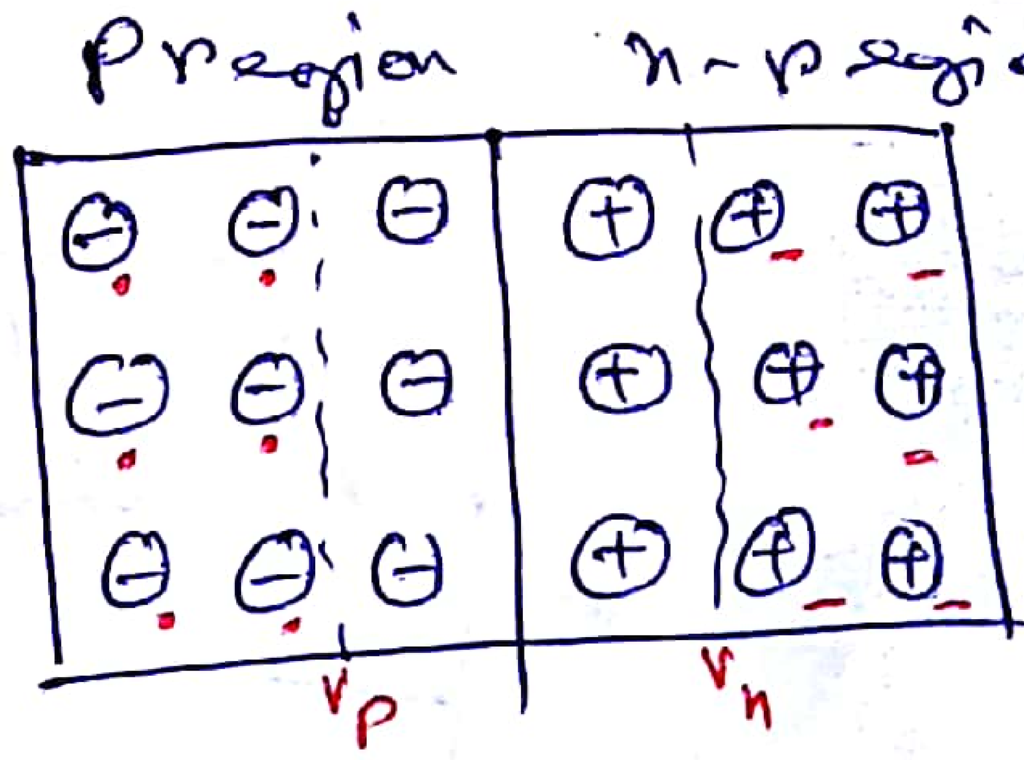
from Einstein's eqn.

$$D = \frac{KT}{e}\mu$$

$$\mathcal{E} = -\frac{\delta v}{\delta x}$$

$n_p \rightarrow$ no. of electron in P-region

$n_n \rightarrow$ " " " in n-region.



$P_p \rightarrow$ no. of holes in P-region

$P_n \rightarrow$ " " " in n-region

$n_i \rightarrow$ intrinsic concentration

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$$\Delta\phi = \frac{KT}{e}\ln\left[\frac{N_D}{\left(\frac{n_i^2}{P_p}\right)}\right] = \frac{KT}{e}\ln\left\{\frac{N_D P_p}{n_i^2}\right\}$$

$$= \frac{KT}{e}\ln\left(\frac{N_D N_a}{n_i^2}\right)$$

$$\boxed{\Delta\phi = \frac{KT}{e}\ln\left(\frac{N_D N_a}{n_i^2}\right)}$$ → Expression for barrier PDⁿ. which depends on donor & acceptor concentration.

* If we consider the hole current, we will get same expression ie $\Delta\phi = \frac{KT}{e}\ln\left(\frac{N_D N_a}{n_i^2}\right)$

$\Delta\phi$ →

Assu...

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Life time & diffusion length

Under thermal equilibrium → electron & hole concentration are steady.
(Actually → the equilibrium is dynamic)

at any instant → Rate of e-hole pair generation
= Rate of recombination,

Carrier → do not exist indefinite period of time.
But recombine to form neutral particle.

Excess carrier density decrease → exponentially with time.

carrier density at t $\propto e^{-t/\tau}$ → τ → life time of the carrier.

defn: τ is that time after which carrier density falls to $\frac{1}{e}$ of its initial value.

Diffusion length :- Average distance (L) that a carrier diffuses before recombination,

Injected excess carrier concentration $\delta P(x) = \Delta P_0 e^{-x/L_p}$ $\left(\text{or } n = n_0 e^{-x/L} \right)$

L_p → the distance at which the excess hole distribution is reduces to $\frac{1}{e}$ of its value at the Ref Point of injection.

for hole → $L_p = \sqrt{D_p \tau_p}$

D_p → diffusion constant for hole.

$L_n = \sqrt{D_n \tau_n}$