Sumedh

Topics

1. Transition
2. Absorption
3. Recombination
4. Einstein eq
5. Emmision
6. DOS
7. FGR
8. Drude
9. PV (Solar)

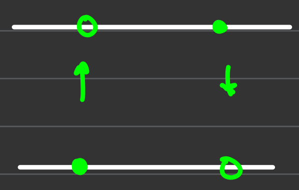
Transition

Optical transition in bulk semi-con

e^-s transite from one energy lvl to another

i) Band to band Transition (Inter band)

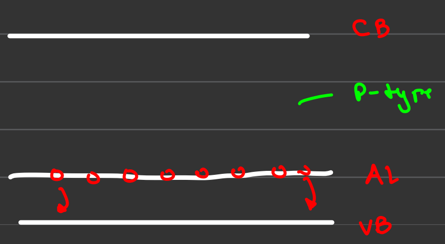
- The absorbed photon results in the transition of e^- from Valence band to Cond^n band
- e-h pair generation → then recomb

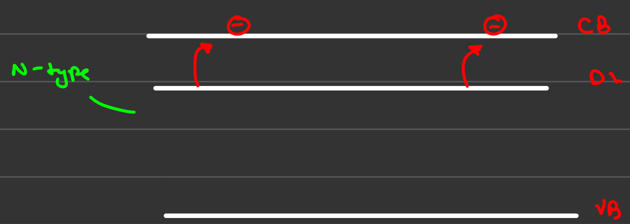


- emission of photon
- eg GaAs

ii) Impurity lvl to band transit^n

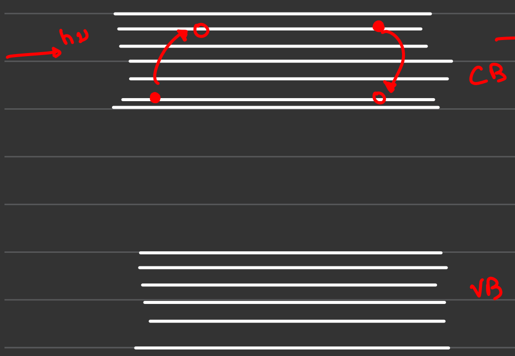
- Only in doped semi con
- e^- transits to either donar / acceptor lvl acc. to semicon
- For p-type, e^- transits frm V-band to acceptor lvl creating hole in VB and ionise acceptor lvl
- eg He with Ge dope





iii) Free - carrier transition (intra)

- If an e^- is in a lower lvl CB, by absorbing photons it moves to higher energy lvl in CB
- Due to thermalisation, it relaxes down to bottom of CB relasing $h\nu$



• Optical Absorption

Absorption is the process in which photons are absorbed by the semiconductor causing transition of e^- from VB to CB.
Condition: photon energy must be equal or greater than the bandgap.
$h\nu \geq E_g$. $\lambda = hc/E_g$.
Generation leads to inc. in conductivity due to inc. in mobile charge carriers. Used to detect light.
conductivity $\propto$ photon flux.

eq :- No of atoms excited per unit V per unit T

$$N_{ab} = Q B_{12} N_1$$

probab

no of atoms in ground state

• Obtical Recombination

- e^- trans to CB, e-h pair generated and trans of e from CB to VB is recomb

i) Radiative Recomb

e^- is released from $E \geq E_g$ it recombs and releases photons

ii) Non- Radiative

if $E < E_g$, releases phonons

The xcs carriers generated at non - eq^br^ cond^n^ :-

Generation Rate = Recomb Rate

This process is diff for direct & Indirect B-G semicon

For both Rad & Non Rad, the total lifetime is :-

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}} \quad ; \quad R = \frac{\Delta n}{\tau}$$

τ = lifetime of e-h pairs

$$R = R_r + R_{nr}$$

$$\eta_r = \frac{1}{1 + [\tau_r / \tau_{nr}]} \quad - \text{[efficiency]}$$

- η_r should be higher for high rad recombination (ex : LED)
- τ should be as high as possible to get max. η_r

  lifetime

- Emission

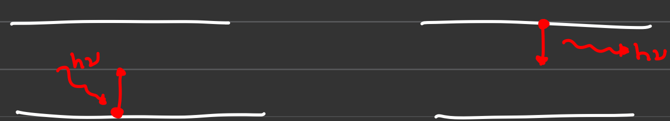
- e^- excites with $h\nu \geq E_2 - E_1$ shld de excite with $h\nu = E_2 - E_1$ is emission

i) Spontaneous emission

- No external factor involved
- A particle after spending its lifetime in excited state comes to ground state releasing energy

eq :- $N_{sp} = A_{21} N_2$ — no. of atoms in excited state

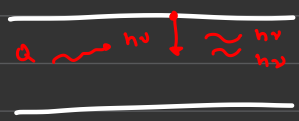
Probab



ii) Stimulated Emission

- Requires Factor
- A particle in excited state is stimulated to decay before its lifetime by external factor

eq:- $N_{st} = B_{21} N_2 Q$ — energy density
└ probab



- Einstein Equation

$$N_{ab} = N_{sp} + N_{st}$$

$$N_1 B_{12} Q = N_2 A_{21} + N_2 B_{21} Q$$

$$Q = \frac{A_{21}}{\left(\frac{N_1}{N_2}\right) B_{12} - B_{21}}$$

Acc. to Max-boltz

$$\frac{N_i}{N_0} = \exp\left[\frac{-E_i}{kT}\right]$$

$$\frac{N_1}{N_2} = \exp\left[E_2 - E_1\right]/kT$$

$$\frac{N_1}{N_2} = \exp h\nu/kT$$

$$\therefore Q = \frac{A_{21}}{\left(e^{h\nu/kT}\right) B_{12} - B_{21}}$$

$$= \frac{A_{21}}{B_{12}\left(e^{h\nu/kT}\right) - B_{21}}$$

$\because B_{12} = B_{21}$

$$Q = \frac{A_{21}}{B_{21}\left(e^{h\nu/kT}-1\right)}$$

Acc. to planck blackbody radiation

Compare

$$Q = \frac{8\pi hc}{\lambda^5} \cdot \frac{1}{\left(e^{h\nu/kT}-1\right)}$$

$$\frac{A_{21}}{B_{21}} = \frac{8\pi hc}{\lambda^5}$$

This ratio shows st is finite also known as einstein relation for stimulated emission

- **Optical Joint DOS**

Optical processes (emission & absorbtⁿ) involve the energy states in VB & in CB.

It tells us the no. of states available for photons to interact simultaneously in the VB & CB

- " Explain Absorption & Emission"

- For given $h\nu$ there are several pairs of $E_2 - E_1$ state available to interact with

- Proof :-

$$E_2 = E_c + \frac{\hbar^2 k^2}{2m_e} \quad \text{— (i)}$$

$$E_1 = E_v - \frac{\hbar^2 k^2}{2m_v} \quad \text{— (ii)}$$

$$h\nu = E_2 - E_1$$

$$h\nu = (E_c - E_v) + \frac{\hbar^2 k^2}{2}\left(\frac{1}{m_c} + \frac{1}{m_v}\right)$$

$$k^2 = (h\nu - E_g)\,\frac{2m_r}{\hbar^2} \quad \text{— (iii)}$$

frm (i) & (iii)

$$E_2 = E_c + \frac{m_r}{m_c}(h\nu - E_g)$$

$$(E_2 - E_c) = \left(\frac{m_r}{m_c}\right)(h\nu - E_g)$$

$$(E_2 - E_c)^{1/2} = \left(\frac{m_r}{m_c}\right)^{1/2}(h\nu - E_g)^{1/2} \quad \text{— (iv)}$$

We have

$$Z_c(E_2)\,dE_2 = Z(\nu)\,d\nu \quad \text{— (v)}$$

$$Z(\nu) = Z_c(E_2)\frac{dE_2}{d\nu} \quad \text{— (vi)}$$

$$\therefore\ Z(\nu) = \left[\frac{1}{2\pi^2}\left(\frac{2m_c}{\hbar^2}\right)^{3/2}(E_2 - E_c)^{1/2}\right] \cdot \frac{dE_2}{d\nu}$$

$$h \cdot \frac{m_r}{m_c}$$

$$Z(\nu) = \frac{1}{2\pi^2}\left(\frac{2m_c}{\hbar^2}\right)^{3/2}(E_2 - E_c)^{1/2} \cdot h \cdot \frac{m_r}{m_c}$$

Substitute eq (iv)

$$Z(\nu) = \frac{1}{2\pi^2}\left(\frac{2m_c}{\hbar^2}\right)^{3/2} \cdot h \cdot \frac{m_r}{m_c} \cdot \left(\frac{m_r}{m_c}\right)^{1/2}(h\nu - E_g)^{1/2}$$

$$= \frac{1}{2\pi^2}\left(\frac{2\cancel{m_c}}{\hbar^2}\right)^{3/2} \cdot h\left(\frac{m_r}{\cancel{m_c}}\right)^{3/2} \cdot (h\nu - E_g)^{1/2}$$

$$= \frac{h}{2\pi^2} \cdot \left(\frac{1}{\hbar^2}\right)^{3/2} \cdot (2m_r)^{3/2} \cdot (h\nu - E_g)^{1/2}$$

$$= \frac{h}{2\pi^2} \cdot \left(\frac{2\pi}{h}\right)^3 \cdot \quad ''$$

$$= \left(\frac{4\pi}{h^2}\right) \times \frac{\pi}{\pi} \cdot \quad ''$$

$$\boxed{Z(\nu) = \frac{1}{\pi \hbar^2} \cdot (2m_r)^{3/2} \cdot (h\nu - E_g)^{1/2}}$$

Drude Model

Obtained by Drude & Lorentz in 1900.

Acc. to this theory, metal contains free e^- responsible for electrical conductivity & metals obey the laws of classical mechanics.

Postulates :-

i) The free e's available in metal ~~are~~ moves in random motion w/o $\vec{E}$ similar to gas molecules in a vessel.

The collisions ($e^- - e^-$ & e^- - ion) are elastic.

The total ~~e~~ energy of e^- is purely KE.

ii) When $\vec{E}$ is applied, e's gain energy & move in one direction.

e's ~~g~~ acquire const. velocity called drift velocity & collisions are inelastic.

~~Collisio~~ Relaxation time is time b/w two collisions.

Electrical Conductivity.

$J \rightarrow$ current density
$E \rightarrow$ electric field
$\sigma \rightarrow$ electrical conductivity.

$J \propto E$

$J = \sigma E$

when $E = 0$, $V_d = 0$, electric current is zero

when $E \neq 0$,

free e^- force $(F) = eE$

$ma = eE$

$-a = \frac{eE}{m}$

Also, $a = \frac{V_d}{\tau}$

$\therefore \frac{V_d}{\tau} = \frac{eE}{m}$

$V_d = \left(\frac{eE}{m}\right)\tau$

$J = neV_d$

$= ne\left(\frac{eE}{m}\right)\tau = \frac{ne^2E\tau}{m} = \underbrace{\left(\frac{ne^2\tau}{m}\right)}_{\sigma} E$

$J = \sigma E$

$F = eE$

$ma = eE$

$a = \frac{eE}{m}$

$a = V_d/\tau$

$\frac{V_d}{\tau} = \frac{eE}{m}$

$V_d = \frac{eE\tau}{m}$

$J = \frac{ne^2\tau E}{m}$

$\sigma = \frac{ne^2\tau}{m}$

we know, $J \propto E \Rightarrow J = \sigma E$

$\therefore \sigma = \left[\frac{ne^2\tau}{m}\right]$

$\rho = \frac{1}{\sigma} = \frac{m}{ne^2\tau}$ electrical resistivity.

Photon DOS

DOS of photons is the total no of allowed states per unit vol in the energy range of E to E + dE

DOS : $g(E) = \frac{1}{V} \times \frac{dN(E)}{dE}$

We can calc. DOS by counting states in k- space by integrating over a vo

* The total no of states below a given 'k' can be determined by integrating a sphere with r=k and obtain 'k' space vol. , then dividing vol. of single state

to calc N(E)

Vol of sphere in k- space $= \frac{4}{3}\pi k^3$

Vol in single state in k- space $= \left(\frac{2\pi}{L}\right)^3 = \frac{8\pi^3}{V}$

$$\therefore N(E) = \frac{\frac{4}{3}\pi k^3}{8\pi^3/V} = \frac{4}{3}\cancel{\pi}k^3 \times \frac{V}{8\pi^{3}}$$

$$N(E) = \frac{V k^3}{6\pi^2}$$

$$\frac{dN(E)}{dE} = \frac{3V}{6\pi^2} k^2 \frac{dk}{dE}$$

$$\therefore g(E) = \frac{1}{\cancel{V}} \times \frac{1}{2}\frac{\cancel{V}}{\pi^2} k^2 \cdot \frac{dk}{dE}$$

for photons: $E = \hbar\omega = \hbar(ck)$ light speed

$$\therefore \frac{E}{\hbar c} = k$$

$$\frac{1}{\hbar c} = \frac{dk}{dE}$$

$$\therefore \; g(E) = \frac{1}{2\pi^2} \cdot \left(\frac{E}{\hbar c}\right)^2 \times \frac{1}{\hbar c}$$

$$g(E) = \frac{1}{2\pi} \frac{E^2}{(\hbar c)^3}$$

- Fermi Golden Rule

FGR is a simple expression for the transition rates b/w states of quantum system

The rates are calculated from probablities determined by transition matrix elements in quantum mechanical.

density of final states

$$\boxed{\text{Transition Probablity } \lambda_{if} = \frac{2\pi}{\hbar} |M_{if}|^2 \rho_f} \rightarrow \delta(E_a - E_b + \hbar\omega)$$

$|M_{if}|^2 = |\langle b | H'(r) | a \rangle|^2$

matrix element

i) Upward transition rate

$$W_{a\to b} = \frac{2\pi}{\hbar} |\langle b | H(r)_{ab} | a \rangle|^2 \delta(E_a - E_b - \hbar\omega)$$

Total rate per unit V $= 2/V \times$

$$R_{a\to b} = \frac{2}{V} \sum_{k_a} \sum_{k_b} \frac{2\pi}{\hbar} |H'_{ab}|^2 \delta(E_a - E_b - \hbar\omega) f_a (1 - f_b)$$

ii) Downward transition rate

$$W_{b\to a} = \frac{2\pi}{\hbar} |\langle a | H'(r)_{ba} | b \rangle|^2 \delta(E_b - E_a + \hbar\omega)$$

$$R_{b\to a} = \frac{2}{V} \sum_{k_a} \sum_{k_b} \frac{2\pi}{\hbar} |H'_{ba}|^2 \delta(E_b - E_a + \hbar\omega) f_b (1 - f_a)$$

Net Transition Rate

$$R_n = R_{a\to b} - R_{b\to a}$$

$$R_n = \frac{2}{V} \sum_{k_a} \sum_{k_b} \frac{2\pi}{\hbar} |H'_{ba}|^2 \delta(E_b - E_a - \hbar\omega) (f_a - f_b)$$

- **Optical Gain & Loss**

i) **Gain**
  └ Emission

When light is emitted during transition from CB to VB

Cond^n : Net SE > Absorption

ii) **Loss**

Absortion of light during transition from VB to CB

Cond^n : Net Absorp > Emi

Note :-

$E_g < \hbar\omega < E_e - E_h \rightarrow$ Gain

$E_g < \hbar\omega < E_e - E_h \rightarrow$ Inversion

$E_g > \hbar\omega$, $E_e - E_h \rightarrow$ Lose

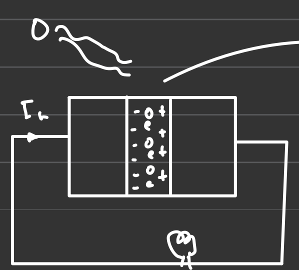
- **Photovoltaic Cell**

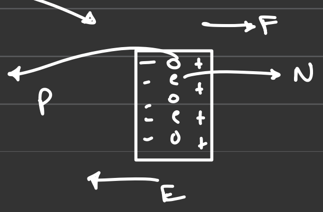
Composed of two types of semi (P N type) forming PN Junc.

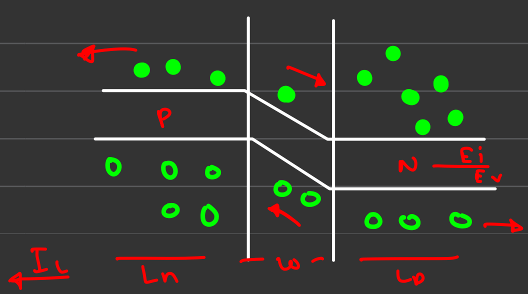
When photon is absorbed then a generation of e- hole pair take place, they will be swept away due to the electric field when away due to the electric field, when applied (e- towards N-region & holes towards P- region)

Net +ve on P - side
Net -ve on N - side

This causes a pot diff to appear at PN Junc called photo voltage which drive photo current







The photo curr I_L in RB directⁿ produces Voltage drop which FB's the pn Junc. , the FB pn junc product I_F

∴ Net Current :

$$I = I_L - I_F = I_L - I_S \left[\exp\left(\frac{eV}{kT}\right) - 1 \right]$$

- The limiting Cases :-

SC condⁿ ($R = 0$, $V = 0$)

$$I = I_{sc} = I_L$$

OC condⁿ ($R \to \infty$, V_{max} / V_{oc})

$$I = 0 = I_L - I_s \left[\exp\left(\frac{eV_{oc}}{kT} - 1\right)\right]$$

$$V_{oc} = \frac{nkT}{e} \ln\left(1 + \frac{I_L}{I_s}\right)$$

$$V_{oc} = V_t \ln\left(1 + \frac{I_L}{I_s}\right)$$

- Power delivered

$$P = VI = I_L V - I_s \left[\exp\left(\frac{eV}{kT} - 1\right)\right] V$$

max P : $\frac{dP}{dV} = 0$

$$\frac{dP}{dV} = 0 = I_L - I_s\left(\exp\left(\frac{eV}{kT} - 1\right)\right) - I_s \frac{V(ev)}{kT} \cdot \exp\left(\frac{ev}{kT}\right)$$

$$\therefore \left(1 + \frac{V}{V_t}\right) \exp\left(\frac{eV}{kT}\right) = 1 + \frac{I_L}{I_s}$$

- Efficiency :-

It is the ratio of energy output from solar cell to input energy from sun

$$\eta = \frac{P_{mx}}{P_{in}} \times 100$$

$$\therefore \eta = \boxed{\frac{V_{oc} I_{sc} FF \times 100}{P_{in}}}$$

$$P_{mx} = V_{oc} I_{sc} FF$$

I_{sc} (SC Current): Current when V across Solar Cell = 0

$$I_{sc} = -I_L$$

I_{oc} (OC current): Max V at 0 I

$$V_{oc} = V_t \ln\left(1 + \frac{I_L}{I_s}\right)$$

FF (Fill factor) :-

Power of a Solar Cell

$$\boxed{FF = \frac{P_m}{I_{sc} V_{oc}} = \frac{I_m V_m}{I_{sc} V_{oc}}}$$