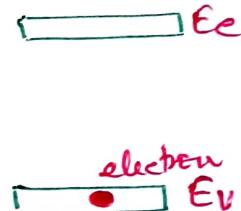
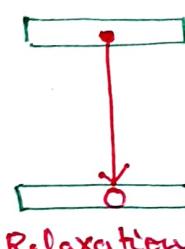
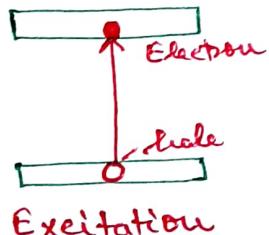
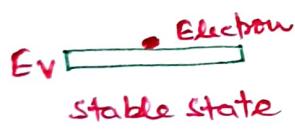


UNIT - III

Concept of Optical Transition in Bulk

Semiconductors :- The process in which an atom or molecules changes its state from one energy state to another energy state by emitting or by absorbing electromagnetic radiation in visible, infrared or UV region is called optical transition.

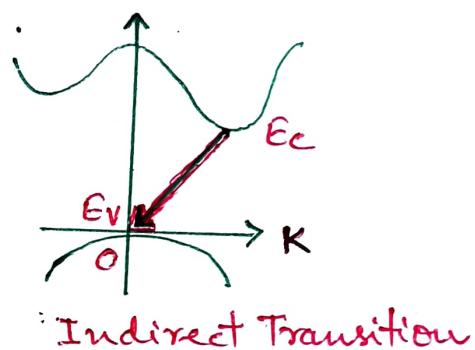
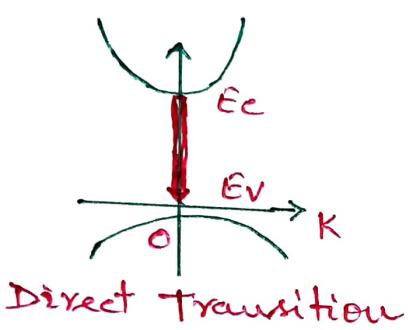
Transition of e^- from low energy state to high energy state are called Excitation, whereas that from high energy state to lower energy states are referred to as relaxations.



The transition of e^- from high energy state to low energy state in semiconductors are taken as recombination of e^- & hole pair, that can be done through radiative and non-radiative emitting process of photons and phonons respectively.

We can also have that e^- are trapped in the defect present in the crystal and transmission of energy is transformed into the other form of energy other than light.

Let us consider the transition from bottom of conduction band to the upper level of valence band. The semiconductor having such condition for transition, placed at a common wave-vector K , is said the direct transition and that with different value of K is said to the indirect - transition.

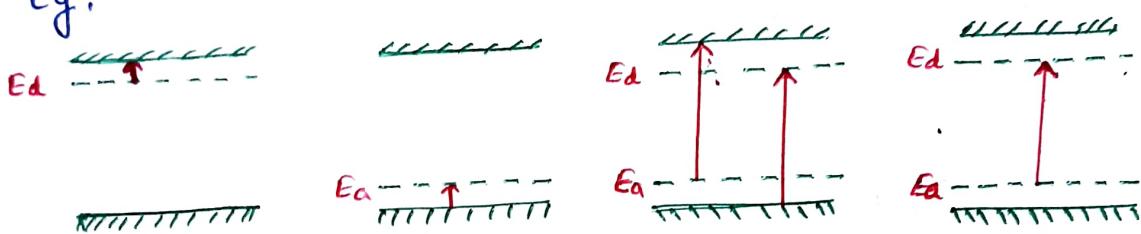


Dr. Mudit P. Srivastava

During the transition of (e^-) electrons, energy and momentum are conserved respectively, so that phonon do not take part in direct transitions, as there wave vector K is much larger than photons. Thus they satisfy the momentum conservation law.

Hence in direct transition the transition probabilities are determined only by e^- transition probabilities. On the other hand, for indirect transition probabilities, determined by the product of e^- transition probabilities and phonon transition probabilities. This result the transition probabilities for direct transition $>$ Indirect transition which gives direct transition semiconductors to be superior than that to the indirect ones for light emitting devices.

Optical Absorption: This process involve a transition of e^- from the valence band to conduction band. This transition takes place between occupied (filled) and unoccupied (un-filled) energy state. These energy states are separated by an energy gap, which is greater than the energy gap Eg.

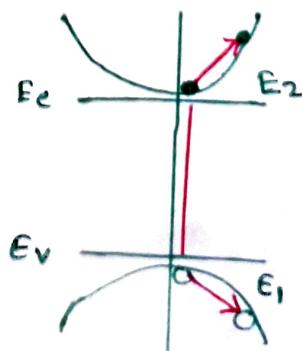
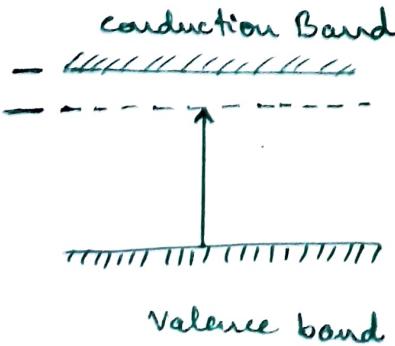


Absorption process takes places when an electron in valence band absorb a photon with energy greater than the band gap energy of semiconductor.

$$\hbar\nu \geq E_g \quad \text{or} \quad \nu \geq (E_g/h)$$

The $\hbar\nu \geq E_g$ are absorbed in a semiconductor. This process usually results in the generation of e-h pair in semiconductor.

Although free-carriers (both e^- & holes) absorb radiations and they make transition into another energy states in same band. This is known as interband transition.



The e^- density in C.B. can be expressed as

$$E_n = E_c + \frac{\pi^2 k^2}{2 m n^*}$$

[We can take E_2 as E_n
 m^* as m_c^*]

and holes in valence band

$$E_p = E_v - \frac{\pi^2 k^2}{2 m_p^*}$$

[We can take E_1 as E_p
 m^* as m_v^*]

$$\begin{aligned} \text{so } h\nu &= E_n - E_p = E_c - E_v + \frac{\pi^2 k^2}{2 m n^*} + \frac{\pi^2 k^2}{2 m_p^*} \\ &= E_c - E_v + \frac{\pi^2 k^2}{2} \left(\frac{1}{m n^*} + \frac{1}{m_p^*} \right) \end{aligned}$$

$$h\nu = E_g + \frac{\pi^2 k^2}{2 m v^*}$$

$$\left[\frac{1}{m v^*} = \frac{1}{m v^*} + \frac{1}{m_c^*} \right]$$

where $m v^*$ is the reduced mass.

$$\text{Reduced mass } m v^* = \frac{m v^* m_c^*}{m v^* + m_c^*}$$

Using the above eqn. density of final states for c.B. with parabolic band structure as in Fig.

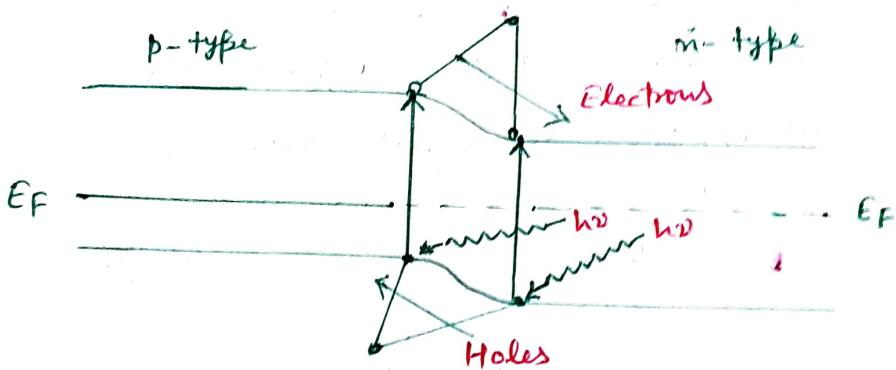
For direct band gap

$$\underline{d_d = A(T)(h\nu - E_g)^{1/2}}$$

d_d = Absorption coefficient

$$\underline{d_i = A'(T)(h\nu - E_g)^2}$$

PHOTOVOLTAIC EFFECT :- When an electromagnetic radiation of frequency ν (with $\nu > E_g$) is incident on a p-n junction, e⁻-hole pairs are produced. The e⁻ diffuse into the n-region while holes diffuse into p-region of crystal as shown in figure. In the absence of an external electric field, the light induced current develops a photovoltage across the p-n junction. This phenomenon is called photovoltaic effect.



The general expression of the net current flowing through the junction under the application of external voltage

$$I_V = I_0 \left[\exp\left(\frac{eV}{KT}\right) - 1 \right] \quad (1)$$

where V may be +ve or -ve represents forward or reverse bias
 I_0 = dark current.

When light is allowed to fall on junction, photocurrent I_L is produced whose direction is opposite to that of I_V . Therefore, the net current in the presence of radiation

$$I = I_L - I_V \quad (2)$$

when no external voltage is applied to junction, then the junction act as a photovoltaic cell & $I=0$, so eqn. (2)

$$I_L + I_0 - I_0 \exp\left(\frac{eV_{ph}}{KT}\right) = 0 \quad (3)$$

where V_{ph} = photovoltage. So eqn. (3) become

$$\exp\left(\frac{eV_{ph}}{KT}\right) = \left(\frac{I_L + I_0}{I_0}\right) = \left(1 + \frac{I_L}{I_0}\right)$$

$$\text{or } \frac{eV_{ph}}{KT} = \log\left(1 + \frac{I_L}{I_0}\right) \text{ or } V_{ph} = \frac{KT}{e} \log\left(1 + \frac{I_L}{I_0}\right) \quad (4)$$

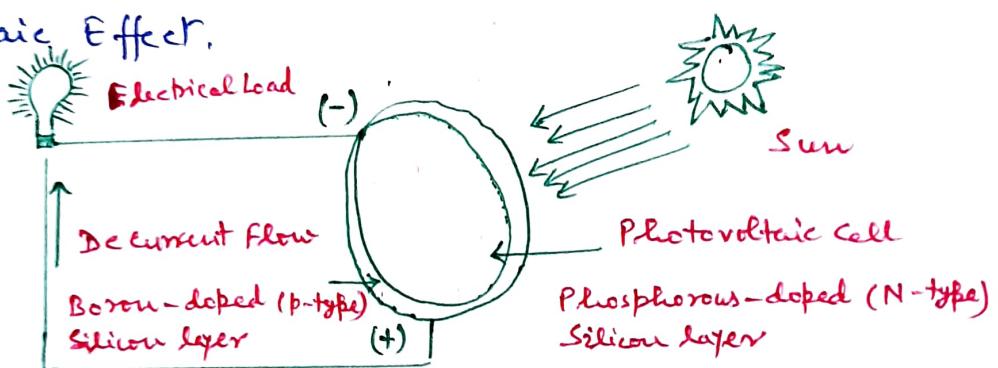
For very high light intensities ($I_L/I_0 \gg 1$), so from (4)

$$V_{ph} = \frac{KT}{e} \log\left(\frac{I_L}{I_0}\right) \quad (5)$$

Thus photovoltage varies logarithmically with the photocurrent and hence the intensity of E.M. radiation.

Application of Photo-voltaic Effect - (Solar Cell):

A voltage is generated across p-n junction semiconductor due to the absorption of light radiation is called photo voltaic Effect.

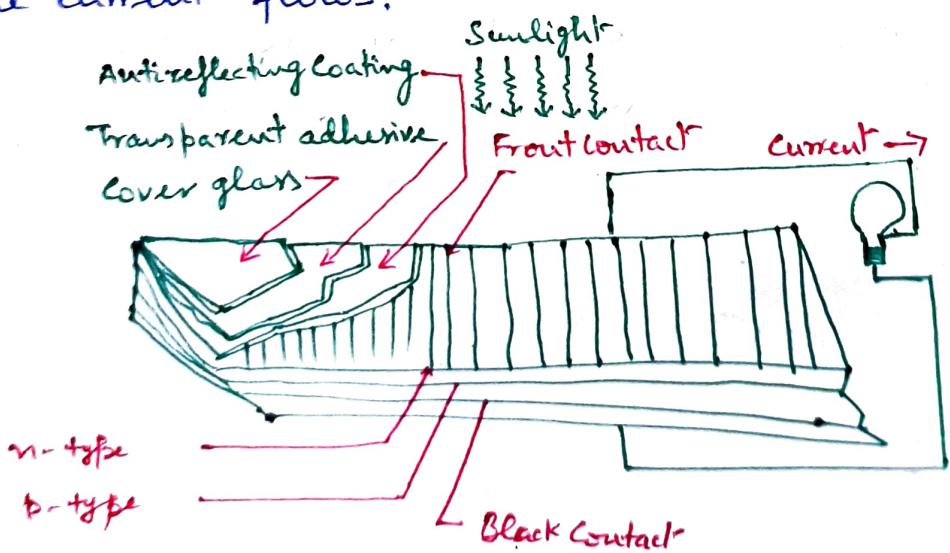


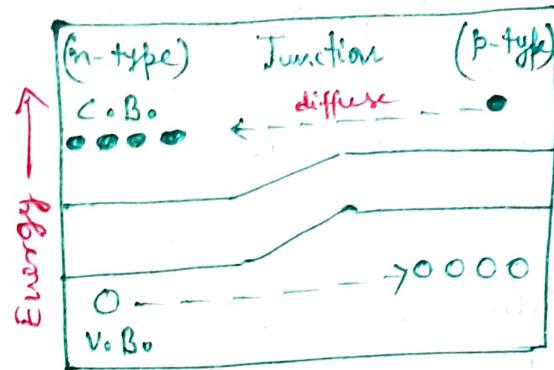
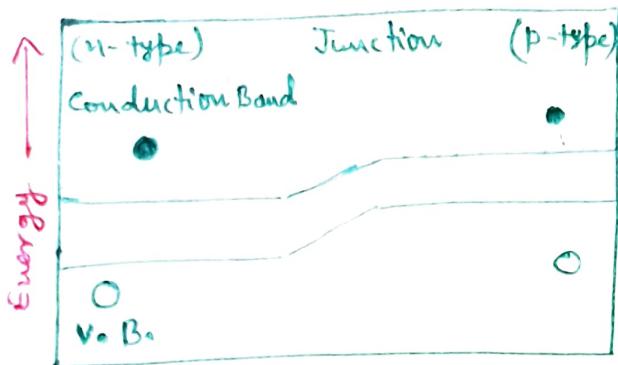
Construction:- The majority of Solar cells in use are the single crystal silicon (Silica-SiO₂) type. A single Solar cell is composed of an ultra-thin layer of phosphorus-doped (N-type) silicon (or emitter) on top of a thicker layer of boron doped (P-type) Silicon (or base). The surface exposed to Sunlight is coated with anti-reflecting coating to avoid loss of incident light. Metal contacts are made on n-type and p-type side of the semiconductor for electrical conduction.

Working Mechanism :- When a solar panel is exposed to sunlight, the photons are absorbed by the semiconductor materials. Those photons whose energy is greater than of band gap can only be converted into electricity by solar cell. When such photon enter into the semiconductor it may be absorbed and transfer an e^- from V.B. to C.B. Since holes are left in V.B. the absorption process generates e^- -hole pairs. The e^- remain at higher energy (C.B.) only for short time before returning to their original energy position. This can be done by using P-N junction (one side by p-type & other type by n-type).

The Working is as follows !

- The absorption of photons through generation of e^- -hole pairs in a semiconductor.
- The separation of e^- and holes so that their recombination is prevented.
- Collection of e^- & holes separately.
- When P-N junction is connected to the external circuit the current flows.





As e^- continues to diffuse, more no. of negative charge on the emitter side and more no. of holes on the base side as shown in fig. When external circuit is connected across the p-n junction, current flows.

The Photovoltaic cell are connected electrically in series or parallel to circuit to produce higher voltage & current. The PV cell produces about 0.5-1 volt D.C. The current and the power output of a PV cell depends on its efficiency and size (surface area) and is proportional to intensity of sunlight striking the surface of cell.

A photovoltaic response of single-junction cell is limited to the portion of Sun's spectrum whose energy is above than band-gap. This can be improved by using two (or more) different cell with more than one band gap and more than one junction, to generate a voltage.
(Multijunction),

* Optical gain in a semiconductor \Rightarrow

The optical joint density of states takes into account the no. of states available in both the C.B and the valence bands with which a photon of energy $h\nu$ can interact and is given by

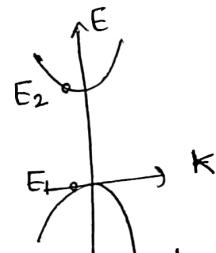
$$\rho(v) = \frac{(2m_r)^{3/2}}{\pi h^2} (h\nu - E_g)^{1/2}; \quad h\nu > E_g \quad (1)$$

Note that only photons with energy $h\nu > E_g$ can participate in the emission and absorption process.

If $h\nu = E_2 - E_1$ is the energy of an incident photon then for absorption of the photon an electron should be present in the state with energy E_1 in the V.B. and there should be an unoccupied allowed state at energy E_2 in the C.B.. Thus, the probability of absorption is given by (in quasi-equilibrium),

$$P_a(v) = f_c(E_1) [1 - f_c(E_2)] \rightarrow \text{Probability that a state with energy } E \text{ remains unoccupied.}$$

\downarrow
Prob. of occupation of a state E



Similarly for emission of photon, it requires that an electron exists at energy level E_2 in the C.B and there exists a hole at energy level E_1 in the V.B. Therefore, the probability of emission -

$$P_e(v) = f_c(E_2) [1 - f_c(E_1)] \quad (3)$$

for net emission, we must have, $P_e(v) > P_a(v)$

$$\text{or } f_c(E_2) [1 - f_c(E_1)] > f_c(E_1) [1 - f_c(E_2)] \quad (4)$$

$$P_e(v) = \left[\frac{1}{e^{(E_2 - E_{Fv})/KT} + 1} \right] \left[\frac{e^{(E_1 - E_{Fv})/KT}}{e^{(E_1 - E_{Fv})/KT} + 1} \right] \quad (5)$$

$$\text{and } P_{al(\nu)} = \left[\frac{1}{1 + e^{(E_1 - E_{FV})/KT}} \right] \left[\frac{e^{(E_2 - E_{Fc})/KT}}{1 + e^{(E_2 - E_{Fc})/KT}} \right] \quad (6)$$

from equ. (5) and (6) =

$$\Rightarrow e^{(E_1 - E_{FV})/KT} > e^{(E_2 - E_{Fc})/KT}$$

$$\Rightarrow \text{or } E_1 - E_{FV} > E_2 - E_{Fc}$$

$$\text{or } E_{Fc} - E_{FV} > E_2 - E_1 = h\nu$$

$$E_{Fc} - E_{FV} > E_g \quad (7)$$

when the separation between the quasi-fermi levels in a SC exceeds the bandgap, then for all frequencies ν that satisfy equ (7), it is possible to have light amplification or overall optical gain:

The gain coefficient for amplification of radiation of frequency ν by stimulated emission in a S.C. is given by

$$\gamma(\nu) = \frac{(c/n)^2}{\sigma \tau_r} \frac{P(\nu)}{\nu^2} \Delta P \quad (8)$$

where $\tau_r \rightarrow$ recombination time
 $P(\nu) \rightarrow$ joint density of stat

$$\Delta P = P_e(\nu) - P_{al(\nu)}$$

for amplification, $\gamma(\nu) > 0$ which requires $\Delta P > 0$
 i.e. the probability of emission has to be greater than
 the probability of absorption.

Optical loss or Absorption coefficient in thermal equilibrium:

A semiconductor in thermal equilibrium has only a single fermi level i.e. $E_F = E_{Fc} = E_{FV}$

and the carrier distribution is given by the fermi function and therefore both $f_e(E_1)$ and $[1 - f_e(E_2)]$ are

much larger than $f_v(E_2)$ and $[1 - f_v(E_1)]$. Thus,

$$P_e(v) < P_a(v)$$

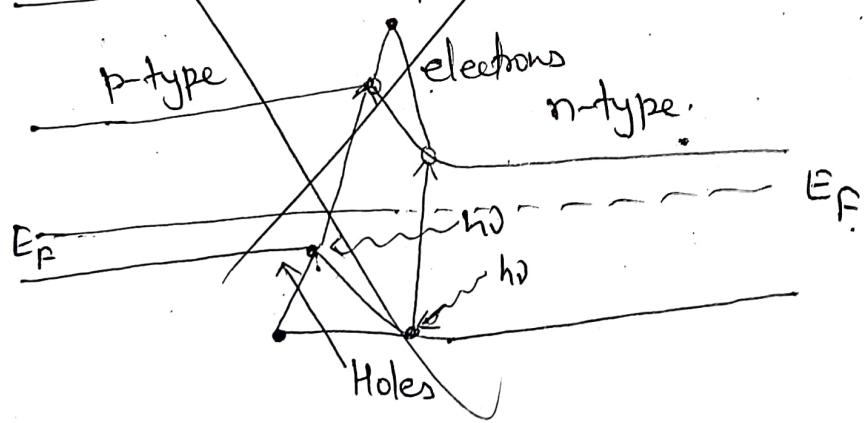
also $\Delta P = P_e(v) - P_a(v) = -ve$

Therefore, the gain coefficient $\gamma(v)$ in eqn (8) is always negative. (since $E_2 > E_1$).

Thus, a semiconductor in thermal equilibrium, whether it is intrinsic or doped, always attenuates light and we have the overall optical loss in S.C.

$$X \longrightarrow X$$

Photovoltaic Effect (contd.)



Fermi Golden Rule : \Rightarrow The fermi golden rule provides one way to calculate the transition rate (probability of transition per unit time) between two certain quantum mechanically defined states.

It gives the rate of any decay process. It can be given as

$$W_{if} = \frac{4\pi^2}{h} |M|^2 \frac{dn_f}{dE} \quad (1)$$

where W_{if} = rate of transition from initial states Ψ_i to final state Ψ_f .

M = Matrix element

$M = \int \Psi_f^* H_{int} \Psi_i dv$ for all the transition and H_{int} is the interaction responsible for it.

Also $M = \langle f | H_{int} | i \rangle$

So eqn.(1) becomes

$$W_{if} = \frac{4\pi^2}{h} |\langle f | H_{int} | i \rangle|^2 \frac{dn_f}{dE}$$

Here $\frac{dn_f}{dE}$ = density of states.

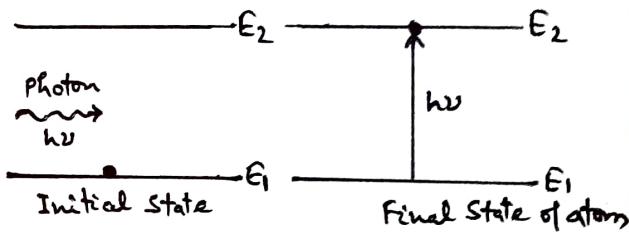
Laser

Absorption of Radiation \Rightarrow When the photon of light having energy $h\nu$ is incident on atom, the atom in the ground state E_1 may absorb the photon and jumped to the excited state or higher state E_2 . This process is called the absorption of radiation.

If E_1 and E_2 are the energies of electron in initial and final state and ν is the frequency absorbed then

$$E_2 - E_1 = h\nu$$

$$\text{or } \nu = \frac{E_2 - E_1}{h}$$



In absorption of radiation the rate transition $1 \rightarrow 2$ depends on the properties of states 1 and 2 and is proportional to the energy density $u(\nu)$ of incident radiation with freqy.

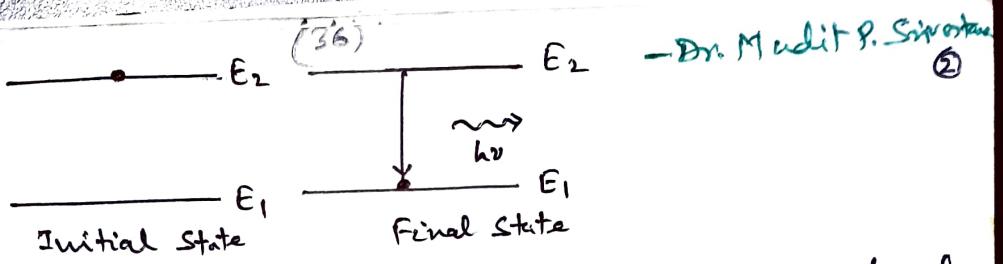
$$P_{12} = B_{12} u(\nu)$$

where B_{12} is the constant of proportionality depends upon property of state 1 and 2 is called Einstein's coefficient of radiation.

Spontaneous Emission of Radiation \Rightarrow When the atom is in excited state E_2 , the atom in excited state can stay for about 10^{-8} sec. After that atom automatically decays to ground state E_1 by emitting a photon of energy $h\nu$. This process is called spontaneous emission of Radiation.

If atom is in excited state 2, then it spontaneously jump to state 1 emitting a photon of frequency ν

$$\nu = \frac{E_2 - E_1}{h}$$



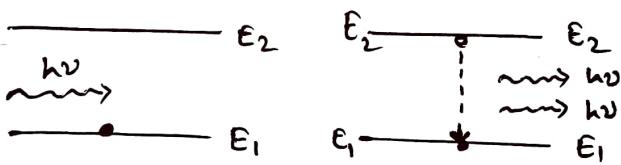
The probability of spontaneous emission $2 \rightarrow 1$ depends only on properties of state 1 and 2.

$$P_{(21)} \text{ spontaneous} = A_{21}$$

This is called Einstein's coefficient of spontaneous emission.

Stimulated or Induced Emission of Radiation \Rightarrow

If the atom is in excited state E_2 and a photon of energy $E_2 - E_1$ is incident on it. The incident photon interact with the atom and then it stimulate the atom to come down to ground energy state E_1 . A fresh photon is emitted in the process. This is called Stimulated emission.



It has following properties

- (1) For each incident photon, there are two outgoing photons moving in same direction.
- (2) Additional The emitted photon has exactly the same phase, energy and direction as incident photon.
- (3) The rate of stimulated emission to lower energy state is directly proportional to no. of atoms left in excited state E_2 and energy density.

The probability of stimulated emission from energy state E_2 to energy state E_1 depends on the energy density of incident ~~photons~~ radiation as well as on the properties of two energy state involved.

$$P_{21} \text{ stimulated} = B_{21} u(v) \quad - \text{Dr. Mudgil}$$

where B_{21} is Einstein's Coefficient of Stimulated emission of radiation.

Relation between Einstein's Coefficient A and B \Rightarrow

Let us consider an assembly of atoms in thermal equilibrium at temperature T with radiation of frequency v and energy density $u(v)$. Let N_1 and N_2 be the no. of atoms in energy state 1 and 2. The probability of absorption for transition $1 \rightarrow 2$ is

$$P_{12} = B_{12} u(v) \quad - ①$$

Now the no. of atoms in state 1 that can absorb a photon and give rise to absorption per unit time

$$= N_1 P_{12} = N_1 B_{12} u(v) \quad - ②$$

The probability of spontaneous emission for transition $2 \rightarrow 1$

$$(P_{21})_{\text{spontaneous}} = A_{21} \quad - ③$$

The probability of stimulated emission for transition $2 \rightarrow 1$

$$(P_{21})_{\text{stimulated}} = B_{21} u(v) \quad - ④$$

Net Probability of emission from state $2 \rightarrow 1$ is

$$P_{21} = A_{21} + B_{21} u(v) \quad - ⑤$$

The no. of photons in state 2 that can cause emission process (spontaneous + stimulated) per unit time

$$N_2 P_{21} = N_2 [A_{21} + B_{21} u(v)]$$

For equilibrium the absorption and emission rates must be equal i.e.,

$$N_1 P_{12} = N_2 P_{21}$$

$$\text{or } N_1 B_{12} u(v) = N_2 [A_{21} + B_{21} u(v)]$$

$$= N_2 A_{21} + N_2 B_{21} u(v)$$

$$u(v) [N_1 B_{12} - N_2 B_{21}] \stackrel{(38)}{=} N_2 A_1$$

- Dr. Mudgil (4)

$$u(v) = \frac{N_2 A_{21}}{N_1 B_{12} - N_2 B_{21}}$$

$$= \frac{A_{21}}{B_{21}} \cdot \frac{1}{\frac{N_1}{N_2} \left(\frac{B_{12}}{B_{21}} \right) - 1} \quad - (6)$$

According to Boltzmann distribution Law the no. of atom N_1 and N_2 in energy state E_1 and E_2 in thermal equilibrium at temperature T

$$N_1 = N_0 e^{-E_1/kT} \quad \text{and} \quad N_2 = N_0 e^{-E_2/kT}$$

where N_0 = total no. atom and k = Boltzmann Constant.

$$\frac{N_2}{N_1} = \frac{e^{-E_2/kT}}{e^{-E_1/kT}} = e^{-(E_2 - E_1)/kT}$$

But $E_2 - E_1 = h\nu$ (energy of photon emitted or absorbed)

$$\frac{N_2}{N_1} = e^{-h\nu/kT}$$

$$\text{ie} \quad \frac{N_1}{N_2} = e^{+h\nu/kT}$$

Substituting this value in eqn. (6) we get

$$u(v) = \frac{A_{21}}{B_{21}} \cdot \frac{1}{e^{h\nu/kT} \cdot \frac{B_{12}}{B_{21}} - 1} \quad - (7)$$

Comparing with Planck's radiation formula

$$u(v) = \frac{8\pi h\nu^3}{c^3} \cdot \frac{1}{e^{h\nu/kT} - 1} \quad - (8)$$

Equating eqn (7) to (8) we get

$$\boxed{\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}}$$

$$\text{and} \quad \boxed{\frac{B_{12}}{B_{21}} = 1}$$

Joint density of states in Semiconductor:-

density of state for a semiconductor is defined the same way as for any material: (no. of energy states per unit volume in energy range E to $E+dE$). For a semiconductor, however two or more bands can play role, electrons in the conduction band and holes in the valence band. So, for a semiconductor, we used to calculate the joint density of states, i.e. the density of states in conduction band and the density of states in valence band.

Density of states is calculated for electron-hole pair having same wave vector ($\vec{r}e\vec{K}$) which means only allowed transitions are considered. (not oblique.)

By using parabolic approximation,

$$E_2 = E_c + \frac{\hbar^2 K^2}{2m_c^*} \quad \text{--- (1)}$$

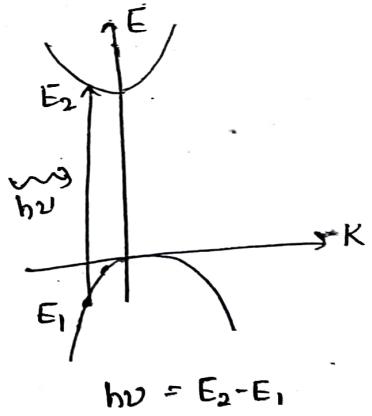
$$E_1 = E_v - \frac{\hbar^2 K^2}{2m_v^*} \quad \text{--- (2)}$$

where, $E_c \rightarrow$ bottom edge of C.B. (Note \rightarrow free e⁻ energy $E = P^2/2m = \frac{\hbar^2 K^2}{2m}$)

$E_v \rightarrow$
 m_c^* and $m_v^* \rightarrow$

so from eqn. (1) and (2)

$$\begin{aligned} h\nu &= E_2 - E_1 = E_c + \frac{\hbar^2 K^2}{2m_c^*} - E_v + \frac{\hbar^2 K^2}{2m_v^*} \\ &= (E_c - E_v) + \frac{\hbar^2 K^2}{2} \left(\frac{1}{m_c^*} + \frac{1}{m_v^*} \right) \end{aligned} \quad \text{--- (3)}$$



$$\therefore E_c - E_v = Eg$$

and $\omega_0 = \frac{1}{m_r^*} + \frac{1}{m_v^*} = \frac{1}{m_{re}^*} \rightarrow \text{reduced mass}$

So, eqn (3) =

$$h\nu = Eg + \frac{\hbar^2 K^2}{2m_{re}^*}$$

$$\text{or } (h\nu - Eg) = \frac{\hbar^2 K^2}{2m_{re}^*}$$

$$\text{or } K^2 = \frac{2m_{re}^*}{\hbar^2} (h\nu - Eg)$$

Putting the value of K^2 in eqn (1), we have

$$E_d = E_c + \frac{\hbar^2}{2m_c^*} \cdot \frac{6m_r^*}{\hbar^2} (h\nu - Eg)$$

$$E_d = E_c + \frac{m_r^*}{m_c^*} (h\nu - Eg) \quad (4)$$

So, the no. of states per unit volume in a range E_2 to $E_2 + dE_2$ can be written as (in conduction band)

$$g_c(E_2) dE_2 = g(v) d\nu \rightarrow \text{no. of states per unit volume for photons of energy between } h\nu \text{ & } h(v+d\nu) \text{ to interact with}$$

$$\text{So, } g(v) = g_c(E_2) \frac{dE_2}{d\nu} \quad (5)$$

$$\text{Hence } g_c(E_2) = \frac{1}{2\pi^2} \left(\frac{2m_c^*}{\hbar^2} \right)^{3/2} (E_2 - E_c)^{1/2} \quad (6)$$

$$\text{So, eqn (5)} \Rightarrow g(v) = \frac{1}{2\pi^2} \left(\frac{2m_c^*}{\hbar^2} \right)^{3/2} (E_2 - E_c)^{1/2} \cdot \frac{dE_2}{d\nu}$$

$$\text{from eqn (4)} \Rightarrow \frac{dE_2}{d\nu} = 0 + \frac{m_r^*}{m_c^*} \cdot h$$

$$\text{So, } g(v) = \frac{1}{2\pi^2} \left(\frac{2m_c^*}{\hbar^2} \right)^{3/2} (E_2 - E_c)^{1/2} \cdot h \frac{m_r^*}{m_c^*}$$

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

$$g(v) = \frac{1}{\pi \hbar^2} (2m_r^*)^{3/2} (h\nu - Eg)^{1/2}$$

— Dr. Mudli — (17)

The downward transition rate per unit volume ($s^{-1}cm^3$) is

$$R_{b \rightarrow a} = \frac{2}{V} \sum_{k_a} \sum_{k_b} \frac{2\pi}{h} |H'_{ba}|^2 \delta(E_a - E_b + \hbar\omega) f_b(1-f_a) \quad (17)$$

Using the even property of delta function

$\delta(-x) = \delta(x)$ & $|H'_{ba}| = |H'_{ab}|$, the net upward transition rate per unit volume can be written as

$$\begin{aligned} R &= R_{a \rightarrow b} - R_{b \rightarrow a} \\ &= \frac{2}{V} \sum_{k_a} \sum_{k_b} \frac{2\pi}{h} |H'_{ba}|^2 \delta(E_b - E_a - \hbar\omega) (f_a - f_b) \end{aligned} \quad (18)$$

DENSITY OF STATE FOR PHOTONS

Consider the periodic boundary condition that the wave function should be periodic in the x, y, z directions with a period L . Therefore,

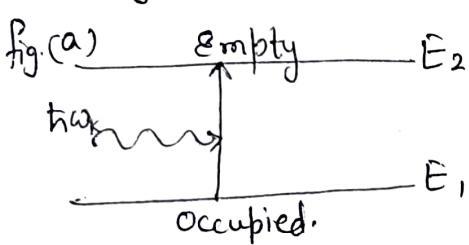
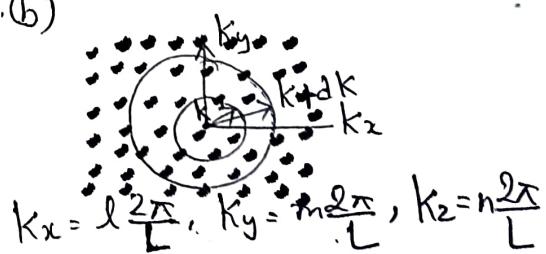


fig.(b)



fig(a) - Photon incident on a discrete two-level system where level 1 is occupied and level 2 is empty.

(b) K-space diagram for the density of photon states.
Dot represents one state with two possible polarizations.

$$k_x = l \frac{2\pi}{L}, \quad k_y = m \frac{2\pi}{L} \quad \text{and} \quad k_z = n \frac{2\pi}{L} \quad (1)$$

The volume of a state in the k-space is therefore $(2\pi/L)^3$, fig(b). Using the dispersion relation for the photon

$$\omega_k = kc/n_r \quad \text{--- (2)}$$

where c/n_r = speed of light in the medium with refractive index n_r . We can change the sum over the k vector to an integral.

Let us look at the integral using the number of states with a differential volume in the k-space $\frac{d^3k}{(2\pi/L)^3} = \frac{k^2 dk d\Omega}{(2\pi/L)^3}$, $d\Omega$ = differential solid angle.

$$N(E_{21}) = \frac{2}{V} \sum_k \delta(E_2 - E_1 - E_k) = 2 \int \frac{k^2 dk d\Omega}{L} \delta(E_2 - E_1 - E_k) \quad \text{--- (3)}$$

where V = volume of the space.

$$E_k = \hbar\omega_k = \frac{\hbar k c}{n_r} \quad \text{--- (4)}$$

is the photon energy, & the integration over the solid angle is 4π . We find,

$$N(E_{21}) = \frac{8\pi n_r^3 E_{21}^2}{h^3 c^3} = \frac{n_r^3 E_{21}^2}{\pi^2 \hbar^3 c^3} \quad \text{--- (5)}$$

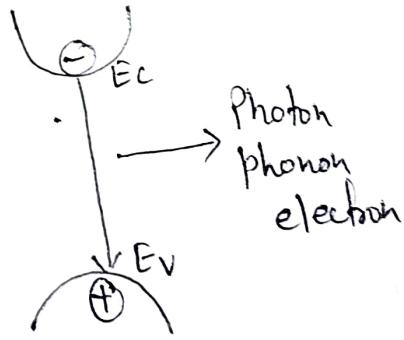
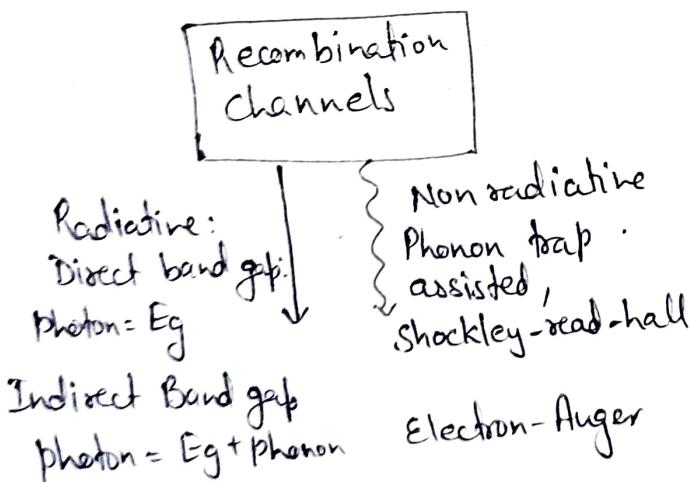
which is the number of states with photon energy E_{21} per unit volume per energy interval $\text{cm}^{-3}(\text{eV})^4$. and $E_{21} = E_2 - E_1$ is the energy spacing between two levels.

RECOMBINATION PROCESS (HIT 50) with the base of all previous theories - ①

Till now, we have come to know about the e-hole pair generation. Now we will come to know about the recapturing of e with a hole.

Classification:

- (i) Band-to-Band recombination giving a photon (radiative)
- (ii) recombination by means of simply giving away energy to the phonons. (SRH-recombination)
- (iii) recombination by transferring kinetic energy to another e- and knocking out into higher energy levels. (Auger recombination)



When the e^- moves from its conduction band state to empty valence band state associated with the hole.

Generation and recombination rates are interested as both processes follow the same path.

Recombination rate \dot{N}_r is given by -

$$\dot{N}_{rem} = \frac{e^2 n_r}{6\pi \epsilon_0 m_0 c^3 h} \left(\frac{2 P_e v}{m_0} \right) t_{rec} \text{ and the}$$

recombination time is given as $T = 1/\dot{N}_{rem}$.

Radiative recombination can be both spontaneous (initial and final photon are incoherent) and stimulated (both photons are in phase).

→ Non-Radiative Recombination (Shockley-Read-Hall Process) - SRH

→ Electron in transition bands passes through a new energy state created within the band gap by impurity in the crystal lattice

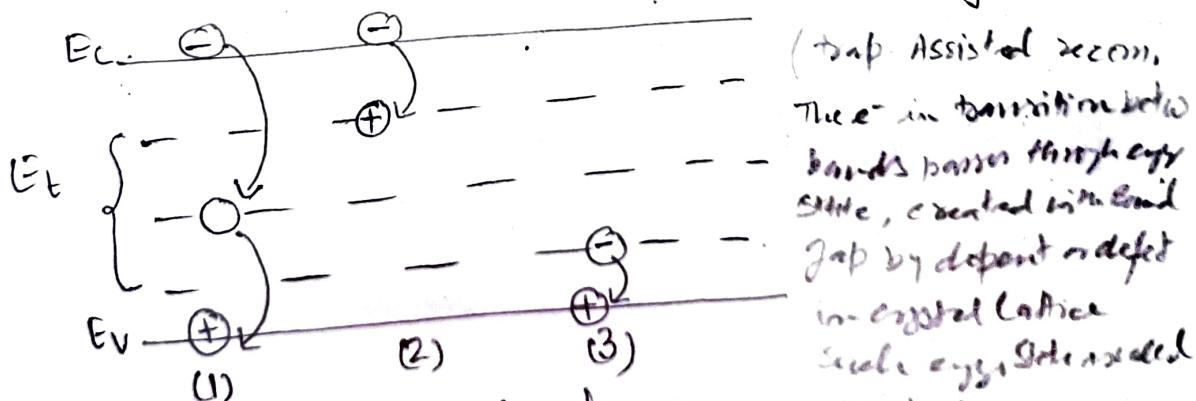


Fig- Non-radiative recombination processes traps.

(1) Recombination center (2) e- electron (3) hole trap.

(3)

As it's discussed that, in this process, e- recombines with hole without any emission and simply gives out its energy. It competes with radiative one. This usually takes via surface states or bulk defects and traps.

The total life times $\tau (\frac{1}{R_{\text{total}}})$

$$R_{\text{total}} = R_{\text{radiative}} + R_{\text{non-radiative}} \quad \rightarrow (1)$$

This kind of radiation is important for both the & -ve importance

Eg - for LED it is undesirable.

- for p-n diodes, it is highly essential to increase the speed of device.

Rate of change of carrier concentration (e- & holes)

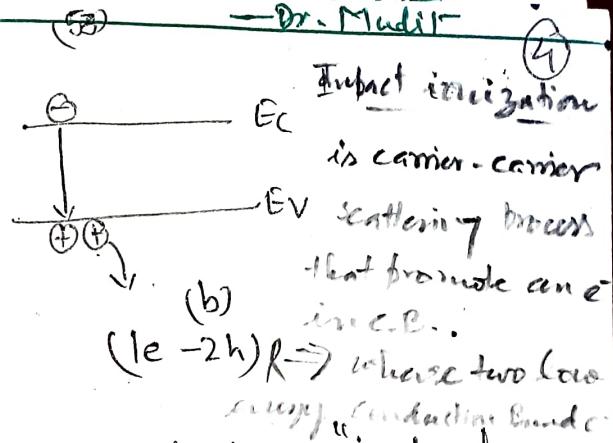
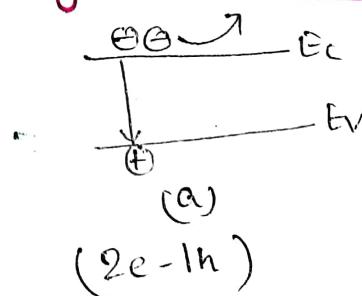
$$R_t = \frac{dn}{dt} = \frac{dp}{dt} \quad \rightarrow (2)$$

$$\text{or } R_t = \frac{np}{T_{nr}(n+p)} \quad \rightarrow (3) \quad \begin{array}{l} \text{for low-level injection} \\ \text{n-type semiconductor } (n \gg p) \end{array}$$

$$\text{or } R_n = \frac{p - p_0}{T_{nr}} \quad \rightarrow (4) \quad \begin{array}{l} \text{respectively} \\ \text{where } p \text{ & } p_0 \text{ are non-} \end{array}$$

equilibrium and equilibrium hole-e- concentrations (similarly for holes). Hence the decay rates are due to minority carriers.

Auger Recombination (2)



We know the physical process called as "impact ionization", Auger is opposite to this. It says that the excess energy given off by an e- recombining with a hole is given to sec. electron (in either band) instead of emitting the energy as photon. The newly excited e- then gives up its additional energy in a series of collision with the lattice, relaxing back to the edge of the band.

This effect is a result of interactions between multiple ~~e-~~ particles, including multiple e- and hole. Its probability increases with a higher concentration of charge carriers.

For e- holehole process, the reaction mechanism is proportional to $p^2 n$ & that for ~~e-~~ electron-electron-hole process it is process to $n^2 p$ where n & p are the e- & hole concentrations respectively.

$$R_E = B n^2 p \quad \text{recombination rate for e-}$$

$$R_H = B p^2 n \quad \text{recombination rate for holes.}$$

B = Auger Coefficient.

life time of Auger for e⁻ as $T_{e, \text{Aug}}^{(5)} = \frac{P}{R_E} = \frac{1}{Bn^2}$ or $\frac{P}{Bn^2 P} \quad (5)$

$$T_{h, \text{Aug}} = \frac{N}{R_H} = \frac{1}{Bp^2} \quad (\text{for holes})$$

Further $\Rightarrow T_{e, \text{Aug}} = \frac{1}{Bn^2 + C_{np}}$

$$T_{h, \text{Aug}} = \frac{1}{Bp^2 + C_{np}}$$

From the minority carrier band

where C = constant depending on material.

The term describing majority carrier behaviour has a squared term indicating effectiveness at very high doping levels. This recombination limits solar efficiency because of short carrier lifetimes.

X — X — X