

Concept of optical transition in Bulk Semiconductor

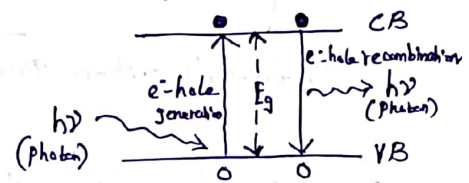
For the optical properties of semiconductor, the photons should interact with the charge carriers. In the process of interaction, two processes occur: (i) absorption & (ii) Recombination. (i) Photons are absorbed (or) emitted & this is important in the case of photonic devices using semiconductor.

Let us see some optical transition in bulk semiconductor

(a) Band to band transition. (Interband transition)

An absorbed photon can result in an electron in the valence band making an upward transition to conduction band.

This results electron-hole pair generation. Followed by this electron-hole recombination can result in the emission of the photon.

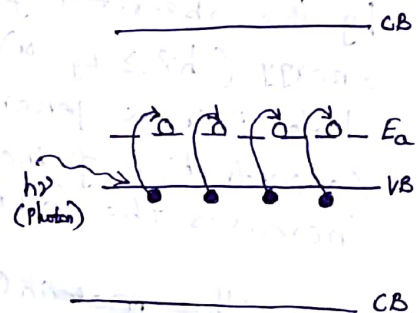


(Eg) Band to Band transition in GaAs, can result in absorption (or) emission of photons of wavelength $\lambda_c = 0.87 \mu\text{m}$ where $E_g = 1.42 \text{ eV}$
 $[\lambda_c = hc/E_g]$

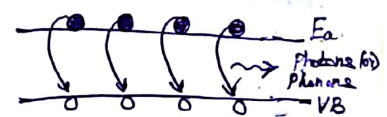
(b) Impurity to Band transition

An absorbed photon can result in a transition between a donor (or) acceptor level and a band in a semiconductor. Mostly observed in doped (N-type or P-type) semiconductors.

If a P-type material is considered, a low energy photon can lift an electron from valence band to acceptor level, where it becomes trapped by an acceptor atom. Thus hole is created in valence band and acceptor atom is ionized.



Similarly a hole may be trapped by an ionized acceptor atom. The result may be the electron decay from its acceptor level to recombine with hole. The energy may be released radiatively (photons) or Non-radiatively (phonons).



(Eg) : In Hg doped Ge $\rightarrow \lambda_c$ for absorption (or) emission between valence band to acceptor level is $14 \mu\text{m}$ $[\lambda_c = hc/E_g]$ where E_g is 0.088 eV

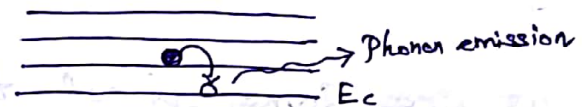
(C) Free - Carrier transition (Intraband transition)

An absorbed photon can impart its energy to an electron in a given band, causing it to move higher level in that band. If a lower level conduction band is considered, by absorbing photon energy the electrons move to next higher energy level in the same conduction band.

Similarly due to thermalization, electron relaxes down to the bottom of conduction band while releasing its energy in the form of phonons (ie) recombination process



Photon - (Absorption process)



Phonon - (Recombination process)

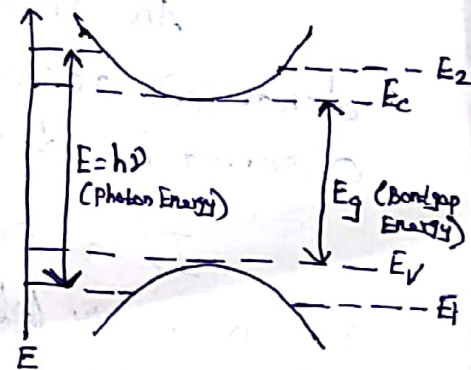
Optical absorption process

Consider direct band to band absorption due to photon in semiconductor. The direct band to band absorption can take place only at frequencies for which photon energy is $h\nu \geq E_g$

Then $\nu = [E_g/h]$, the corresponding wavelength is $\lambda_c = \frac{hc}{E_g}$

(ie) $\lambda_c \propto \frac{1.24}{E_g}$, is called band gap wavelength (or) cutoff wavelength

∴ Electron excitation from the valence to conduction band may be induced by the absorption of a photon of appropriate energy ($h\nu \geq E_g$ (or) $\lambda_c \leq \lambda_g$). Then electron-hole pair is generated. This adds to the concentration of mobile charge carriers and increases the conductivity of the material.



The material behaves as a photoconductor with a conductivity proportional to photon flux. The effect is used to detect light.

Optical Recombination Process

The operation of all optoelectronic devices is based on creation (or) annihilation of electron-hole pairs

When semiconductor is kept under the illumination of light, by absorbing photon with $(E \geq E_g)$, electron-hole pairs are created. The reverse process of electron-hole annihilation is called Recombination.

Recombination may be radiative (or) Non-radiative. (i.e) when electron is annihilated with hole, energy is released equal to $(E) \geq E_g$ called radiative recombination. Also when electron is annihilated with hole, energy is released $E < E_g$ called Non radiative recombinations. In radiative recombination photon of energy $E = h\nu$ is released and in non radiative recombination phonons are released.

Recombination of electron-hole pair observed in different optical properties:

- 1) Luminescence - Process where e^- -hole pairs are created and recombined radiatively.
- 2) Photoluminescence - e^- -hole pairs recombination occurs radiatively where generation of e^- -hole pairs occurs due to photon absorption.
- 3) Catholuminescence - Another Radiative recombination process where generation of e^- -hole pairs done with electron bombardment.
- 4) Electroluminescence - Process of radiative recombination following injection with p-n Junction (or) similar device.

When semiconductor is under equilibrium, without any incident photon (or) injection of electron, the carrier density can be calculated from an equilibrium Fermi level using Fermi-Dirac statistics.

$$f(E) = \frac{1}{e^{(E-E_F)/kT} + 1}$$

But when light is illuminated, non equilibrium carrier concentration is created and above relation is not valid. Hence Fermi-Dirac distribution functions for electrons & holes in non equilibrium condition are

$$f(E)_n \propto \exp\left(\frac{E_F - E_c}{kT}\right) \text{ for electrons}$$

$$f(E)_p \propto \exp\left(\frac{E_v - E_F}{kT}\right) \text{ for holes}$$

Further, Carrier Concentration is Calculated as

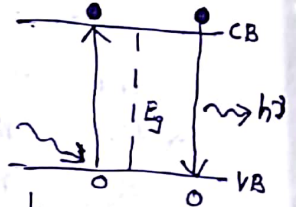
$$n = N_c \exp \left[\frac{E_{Fn} - E_c}{kT} \right] \quad \text{for electron}$$

$$p = N_v \exp \left[\frac{E_v - E_{Fp}}{kT} \right] \quad \text{for holes.}$$

The excess Carriers Created in Semiconductor in non equilibrium Condition must eventually recombine. Then in equilibrium state

$$\text{Generation Rate (G)} = \text{Recombination Rate (R)}$$

Thus Generation / Recombination processes involves transition of Carriers across energy bandgap (E_g). and is different for direct & Indirect bandgap Semiconductor.



The probability of radiative recombination is very high in direct bandgap Semiconductor due to momentum & Energy Conservation.

Recombination rate of Charge Carriers also depends on Life time of Charge Carriers in Semiconductors. In general both radiative and non radiative recombination is considered, the total life time is given by

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

τ_r is radiative life time & τ_{nr} is non-radiative life time of Charge Carriers. Also total Recombination rate is given by

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

Internal quantum efficiency due to recombination Process is

$$\eta_r = \frac{1}{1 + [\tau_r / \tau_{nr}]}$$

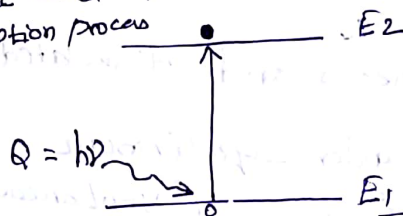
If τ_r / τ_{nr} is small in which τ_{nr} is large as possible, η_r increases leads to high radiative recombination in Semiconductor

Emission Process in Semiconductor

Electron deexcitation from the conduction band to the valence band (electron-hole recombination) may result in spontaneous emission of photons of energy $[h\nu \geq E_g]$ (or) stimulated emission of photons provided that a photon of energy $h\nu \geq E_g$ is initially present.

Spontaneous Emission is underlying phenomena on which LED is designed & Stimulated emission is responsible for the operation of Semiconductor optical amplifier and Laser diode.

Let us consider two energy levels in semiconductor E_1 and E_2 where E_1 corresponds to ground state and E_2 to excited state. At room temperature most of the electrons are in ground state. When photons of energy greater than/equal to $h\nu = E_2 - E_1$ is incident on system, an electron by absorbing this energy moves to excited state and thus create electron-hole pair in system and this is called absorption process.



$$N_{ab} \propto Q N_1 \Rightarrow \boxed{N_{ab} = B_{12} Q N_1}$$

Where $N_{ab} \rightarrow$ (Number of atoms undergoing absorption process)/Vt

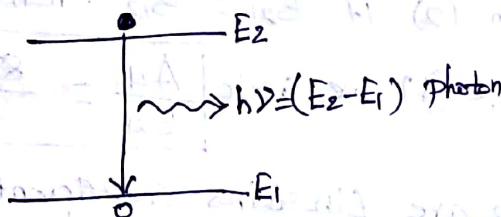
$N_1 \rightarrow$ (Number of atoms in E_1)/V

$Q \rightarrow$ Energy density of incident radiation

$B_{12} \rightarrow$ Proportionality constant

Spontaneous emission - (Explanation)

When electron-hole pairs are generated by absorption process after a short time without any external stimulus, the electron comes back to the ground state (E_1) from unstable excited state (E_2) by emitting photon of energy $(h\nu) \geq (E_2 - E_1)$. This process is called spontaneous emission.



$$\text{Then } N_{sp} \propto N_2 \Rightarrow \boxed{N_{sp} = A_{21} N_2}$$

N_{sp} is number of atoms undergoing spontaneous process/Vt, N_2 is the number of atoms in E_2 /V, A_{21} is proportionality constant.

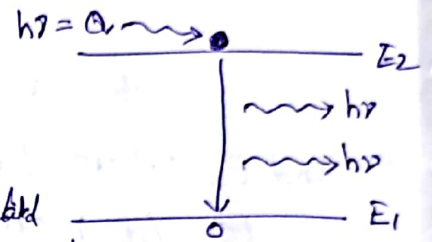
(ii) Stimulated Emission - (Explanation)

On the other hand, if a photon of energy ($h\nu$) impinges on electron while it is in excited state (E_2), the electron can be stimulated back to Ground state (E_1) with emission of photons ($h\nu$) $\geq (E_2 - E_1)$ which is in phase with incident radiation. This is called stimulated emission.

In stimulated emission e^- are stimulated back before their life time from excited state (E_2) whereas in spontaneous emission electron returns back to ground state (E_1) from excited state (E_2) after completing life time.

$$N_{st} \propto N_2 \propto B_{21}$$

where N_{st} is number of atoms involving stimulated emission / vt , N_2 is the number of atoms in E_2/v and B_{21} is constant of proportionality.



Ratio between Spontaneous and Stimulated Coefficient

For a given system under equilibrium

$$\text{Absorption} = \text{Emission (Spontaneous + Stimulated)}$$

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

$$\text{Then } Q = \frac{A_{21}}{\left[\frac{N_1}{N_2}\right] B_{12} - B_{21}} \rightarrow (1)$$

From Boltzmann distribution law, at a given temperature (T), the ratio of population of two levels is given by

$$\frac{N_1}{N_2} = e^{(E_2 - E_1)/KT} = e^{h\nu/KT} \Rightarrow Q = \frac{A_{21}}{e^{h\nu/KT} B_{12} - B_{21}} \rightarrow (2)$$

Also, from Planck's body radiation theory

$$Q = \frac{8\pi hc}{\lambda^5} \times \left[\frac{1}{e^{h\nu/KT} - 1} \right] \rightarrow (3)$$

$$\text{In equation (2) if } B_{21} = B_{12} \text{ then } Q = \frac{A_{21}}{B_{21}} \times \left[\frac{1}{e^{h\nu/KT} - 1} \right] \rightarrow (4)$$

$$\text{Comparing (3) \& (4) we write } \boxed{\frac{A_{21}}{B_{21}} = \frac{8\pi hc}{\lambda^5}}$$

Here A & B are Einstein's Coefficients which gives values for ratio of Spontaneous and Stimulated emission.

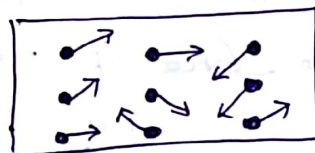
Drude model

In solids, electrons in the outermost orbit of atom determines its electrical properties which is explained through free Electron theory. The free electron theory is applicable to both metals and non-metals to explain electrical conductivity, magnetic thermal properties & structure. This is developed in three stages and first stage is Drude model.

Drude model of free electron theory is also called Classical free electron theory developed by Drude & Lorentz in the year 1900. According to this theory metals contains free electrons which are responsible for electrical conductivity and metals obey the laws of classical mechanics.

Postulates of Drude model

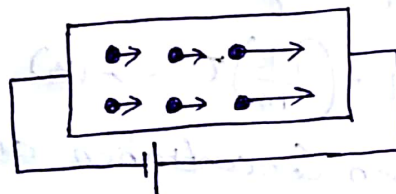
1) The free electrons (or) electron gas available in metal undergoes random motion in absence of Electric field similar to the gas molecules in a vessel



Electron movement in metal in absence of Electric field.

These collisions (electron-electron) & (electron-ion) were considered as elastic collision. The total energy of electron is assumed to purely kinetic energy.

2) Suppose an electric field is applied to metal, the free electrons gain some energy and are directed to move towards a higher potential.



Electron movement in metal - presence of Electric field

In presence of electric field, electron acquire constant velocity known as drift velocity & collisions (electron-electron) & (electron-ions) considered as Inelastic. Also time of collision is said to be relaxation time.

Note

Drift velocity - Average velocity acquired by free electron in a particular direction in presence of Electric field

Relaxation time - Time taken by free electron to reach equilibrium position after undergoing collision with other electron or immobile positive ions.

Expression for Electrical Conductivity

Consider a conductor which is subjected to an electric field of strength E , the current density (J) is given by

$$J \propto E$$
$$\boxed{J = \sigma E}$$

Here σ refers Electrical conductivity

When $E = 0$ (ie) no Electric field is applied to Conductor

Free Electrons will have random motion. Therefore Drift velocity is zero & so Electric current is zero.

When $E \neq 0$ (ie) when Electric field is applied to Conductor

Free Electron experience force $(F) = eE$

$$ma = eE \quad (\because F = ma)$$

$$\text{Acceleration acquired by } e^- (a) = \frac{eE}{m} \rightarrow (1)$$

If V_d is drift velocity of electron & collision time is τ then

$$\text{Acceleration acquired by } e^- (a) = \frac{V_d}{\tau} \rightarrow (2)$$

$$(1) = (2) \Rightarrow \frac{eE}{m} = \frac{V_d}{\tau}$$

$$V_d = \left(\frac{eE}{m} \right) \tau \rightarrow (3)$$

If ' n ' is electron Concentration and e is electronic charge then current density $J = neV_d \rightarrow (4)$

$$\text{Then } J = ne \left(\frac{eE\tau}{m} \right) = \frac{ne^2\tau}{m} E$$

If n, e, m, τ are constant $J \propto E \Rightarrow J = \sigma E$

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

where σ = Electrical conductivity of metal

As we know $\rho = \frac{1}{\sigma} = \frac{m}{ne^2\tau}$ which is Electrical resistivity

Then Electrical resistivity is given by