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SRM INSTITUTE OF SCIENCE AND TECHNOLOGY

18PYB103J –Semiconduuctor Physics

Concepts of Optical Recombination and emission process

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- When a semiconductor is illuminated with light an electron in the valence band making an upward transition to conduction band.
- This results electron-hole pair generated, the reverse process of electron-hole annihilation is called recombination.
- Recombination process may be radiative or non- radiative
  1. If electron annihilated with hole energy is relased equal to E $\geq$ Eg called radiative recombination, in this process a photon of energy E= hv is released
  2. If electron annihilated with hole energy is relased equal to E < Eg called non radiative recombination, in this process phonons are released

Recombination electron – hole pairs observed in different optical process

- Luminescence: Process where electron hole pairs created and recombined radiatively
- Photoluminescence: electron- hole pairs are generated due to absorption of light and recombination occurs raidiatively
- Cathodluminescence: electron – hole pairs are generated by the electron bombardment, and radiative recombination occurs
- Electroluminescence: process of radiative recombination following injection with pn-junction or similar device.

When a 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

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

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

$$f(E)_n \approx \exp\left(\frac{E_{Fn} - E_c}{kT}\right) \quad \text{for electrons}$$

$$f(E)_p \approx \exp\left(\frac{E_v - E_{Fp}}{kT}\right) \quad \text{for holes}$$

Further carrier concentration is calculated as

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

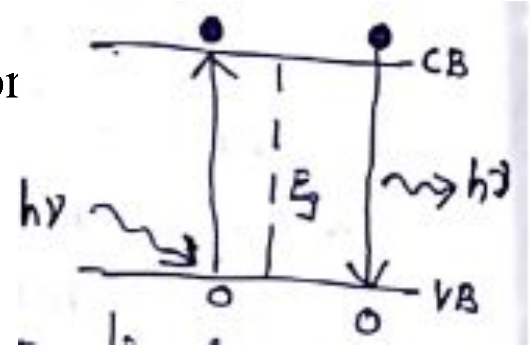
$$p = N_v \exp\left[\frac{E_v - E_{Fp}}{kT}\right] \quad \text{for holes}$$

The excess carriers generated in semiconductor at non equilibrium condition must eventually recombine

Generation rate (G) = recombination rate (R)

The generation recombination process involves transition of charge carriers across the energy bandgap and is different for direct & indirect bandgap semiconductor materials.

The probability of radiative recombination is very high and direct bandgap semiconductor due to momentum & energy conservation



Recombintaion rate of charge carriers is depends upon the lifetime charge carriers

In general both radiative and noradiative recombinations are considered, the total life time is given as

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

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

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

Internal quantum efficiency due to recombination Process is

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

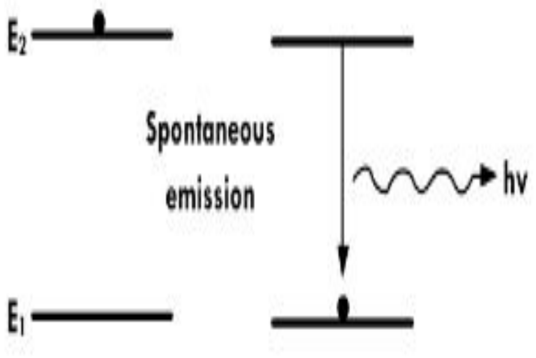
If τ_r/τ_{nr} is small in which τ_{nr} is large as possible, η_r increases leads to high radiative recombination in Semiconductor

Emission process:

Generally the emission process are takes place in two types in optical devices

1. Spontaneous emission
2. Stimulated emission

Spontaneous emission: spontaneous emission, this process requires a conduction band energy state occupied by an electron and an empty valence band energy state. The electron Itself transit from conduction band to valence band spontaneously by releasing a photon.



This photon has a random direction and phase.

This is the opposite of the common situation in equilibrium, but at a finite temperature there will be a small number of full states in the conduction band and empty states in the valence band. Also, electrons and holes can be created via optical absorption and other pumping mechanisms.

Absorption:

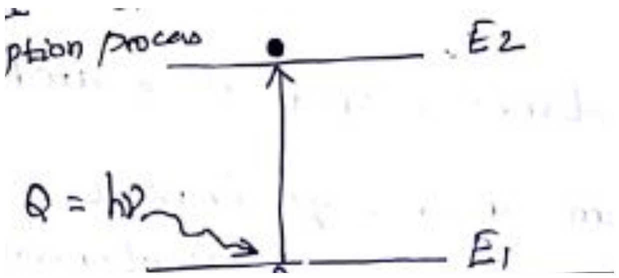
Let us consider two energy levels in semiconductor E_1 & E_2

where E_1 corresponds to ground state

E_2 corresponds to exited state

At room temperature most of the electrons are in ground state

When photons of energy grater or equal to bandgap incident on Semiconductor electron hole pairs are generated, this process is Called absorption



$$N_{ab} \propto QN_1 \Rightarrow N_{ab} = B_{12}\, Q\, N_1$$

N_{ab} □ number of atoms undergoing absorption process/Vt

N_1 □ number of atoms in E_1 / V

Q □ energy density of incident radiation

B_{12} □ proportionality constant

Spontaneous emission:

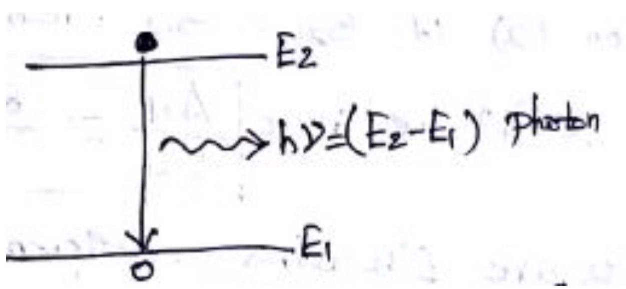
When electron hole pairs are generated due to the absorption of incident radiation.

After a short time without any external stimulus the electron come back from

Unstable exited to state (E_2) to ground state (E_1) by emitting a photon of energy

$h\nu \geq E_2 - E_1$

This process is called spontaneous emission



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

N_{sp} □ is the number of atoms undergoing spontaneous emission process/vt

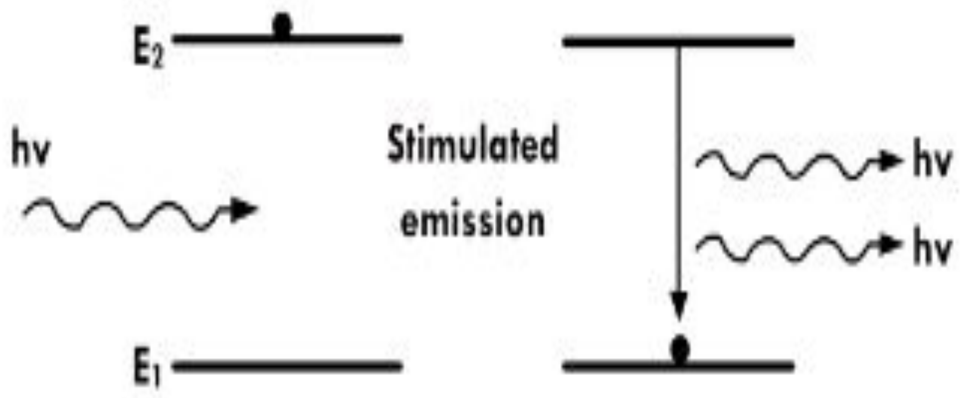
N_2 □ number of atoms in E_2 / V

A_{21} □ proportionality constant

Stimulated emission:

An incident photon causes an upper level atom to decay, emitting a “stimulated” photon whose properties are identical to those of the incident photon.

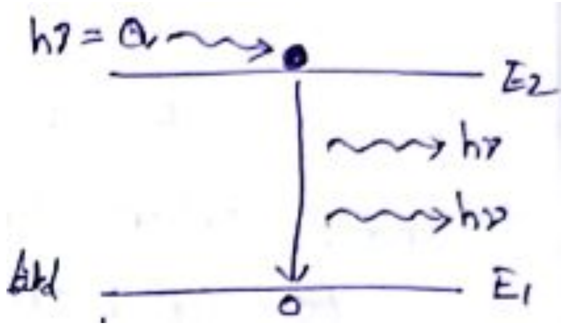
The term “stimulated” underlines the fact that this kind of radiation only occurs if an incident photon is present



Stimulated emission:

If a photon of energy ($h\nu$) impinges on the electron which is presented in Exited state (E_2).

The electron stimulated back to the ground state by releasing the energy $h\nu \geq E_2$-E_1 which is phase with the incident radiation this process is called stimulated emission.



$$N_{st} = B_{21}\, Q\, N_2$$

N_{st} □ number of atoms undergoing stimulated process/Vt

N_2 □ number of atoms in E_2 / V

Q □ energy density of incident radiation

B_{21} □ proportionality constant

Ratio between spontaneous and stimulated Coefficient

For a given system under equilibrium

Absorption = Emission (spontaneous + stimulated)

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

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 planks body radiation theory

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

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

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

Here A & B are Einsteins Coefficients which gives value for ratio of spontaneous and stimulated emission.