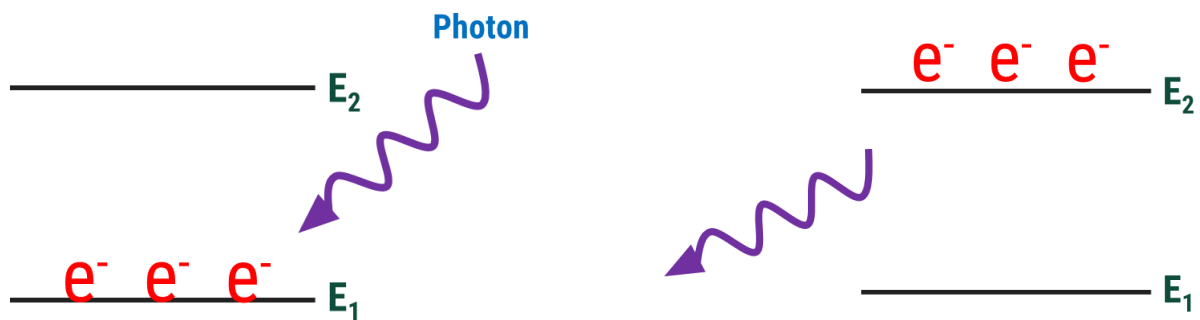


UNIT – 3 (Light Semiconductor Interaction)

3.1 Introduction:

- ✓ Electrons in semiconductors tend to stay in lowest energy state as it is most stable. If additional energy is supplied to electrons by heating, light, or electron beams, it absorbs these energies and jump (transit) to high energy state.
- ✓ Such transitions of electrons from lower to higher energy states by absorbing external energy are called excitations.
- ✓ But higher energy states are unstable therefore to gain stability the electrons in higher energy states transit to lower energy states in certain lifetime. Such transitions of excited electrons from higher energy states to lower energy states are called relaxations.



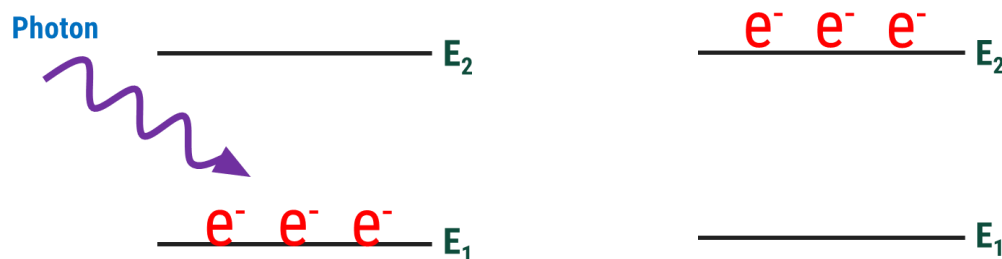
- ✓ In semiconductors, transitions of electrons from higher energy states to lower energy states is also called electron hole recombination.
- ✓ During relaxation electrons release additional energy in form the of light or heat. Therefore electron hole recombinations are of two types : radiative recombination's and non-radiative recombinations.
- ✓ Radiative recombinations emit photons and energies of photons correspond to a difference in the energies between initial and final energy states related to the transitions.
- ✓ In contrast, in the non-radiative recombination, phonons are emitted to crystal lattices or electrons are trapped in the defects, and the transition energy is transformed into forms other than light.

3.2 Optical transitions in bulk semiconductor:

- ✓ According to Einstein, whenever there is interaction between radiation and matter, there can be three main processes than can occur. One is absorption and other two are emissions.

3.2.1 Induced Absorption:

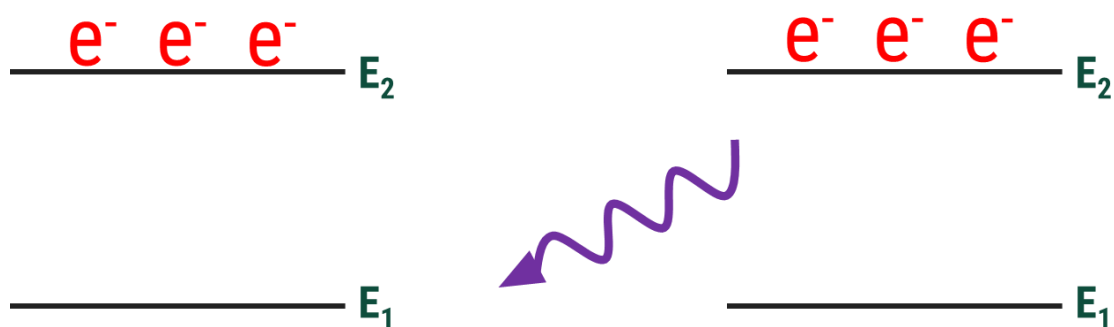
- ✓ Initially an atom is in the ground state (E_1), i.e. all of its electrons possess the lowest possible energy states.
- ✓ If an atom transits from ground state (E_1) to higher energy state (E_2) by absorbing energy of incident photons then the process is called absorption (induced absorption or stimulated absorption).
- ✓ Energy of photon (E) = $h\nu = (E_2 - E_1)$
- ✓ For absorption: **Atom + Photon \rightarrow Atom***



- ✓ The rate of absorption (R_{12}) is directly proportional to the radiation (ρ) and population of lower energy level ($N_1 = \text{No. of atoms in lower energy level}$).
- ✓ i.e. $R_{12} \propto N_1 \rho$
- ✓ i.e. $R_{12} = B_{12} N_1 \rho$
- ✓ where B_{12} is called the Einstein's coefficient (constant) for absorption of radiation.

3.2.2 Spontaneous Emission:

- ✓ “The process of emission of photons when an atom transits from higher energy level to lower energy level without use of external energy (source) is called spontaneous emission.”
- ✓ Suppose an atom is in higher energy level, As this level is unstable, the atom spontaneously returns to lower energy level on its own.
- ✓ It will emit energy, equal to the difference of two energy levels i.e. $h\nu = (E_2 - E_1)$
- ✓ For spontaneous emission: **Atom* \rightarrow Atom + Photon**

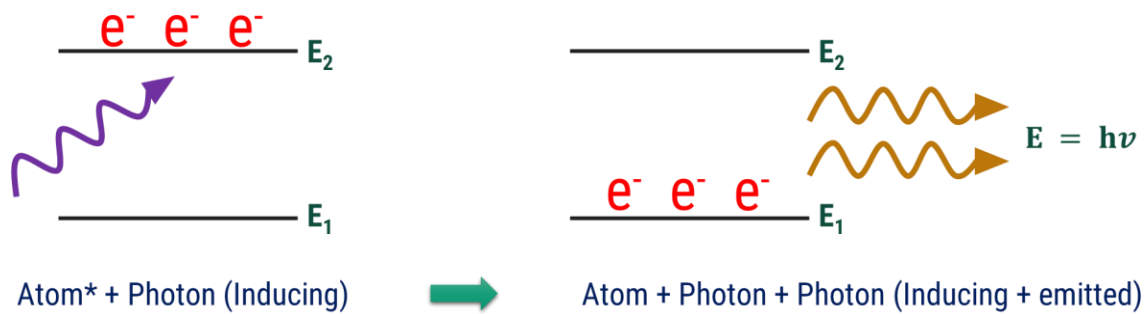


- ✓ The rate of spontaneous emission (R_{21}) is directly proportional to the population of higher energy level ($N_2 = \text{No. of atoms in higher energy level}$).
- ✓ i.e. $R_{21(\text{Sp})} \propto N_2$
- ✓ i.e. $R_{21(\text{Sp})} = A_{21(\text{Sp})} N_2$
- ✓ where A_{21} is called the Einstein's coefficient (constant) for spontaneous emission of radiation.

3.2.3 Stimulated Emission:

- ✓ “The process of emission of photons when an atom transits from higher energy level to lower energy level, with use of external energy (source) is called stimulated emission.”
- ✓ For this process, the atom has to be in higher energy state.

- ✓ Suppose a photon (with energy $E_2 - E_1$) is incident on atom, this incident photon will stimulate the excited atom to transit to lower energy E_1 .



- ✓ Both the inducing and emitted photons will have the same phase, energy and direction.
- ✓ i.e. they will be coherent.
- ✓ This is the process responsible for LASER.
 - ✓ The rate of spontaneous emission $R_{21(st)}$ is directly proportional to the radiation (ρ) and population of higher energy level ($N_2 = \text{No. of atoms in higher energy level}$).
 - ✓ i.e. $R_{21(st)} \propto N_2 \rho$
 - ✓ i.e. $R_{21(st)} = B_{21(st)} N_2 \rho$
 - ✓ where B_{21} is called the Einstein's coefficient (constant) for stimulated emission of radiation.

3.2.4 Difference between spontaneous and stimulated emission

Spontaneous emission	Stimulated emission
Emission of photon take place without inducement.	Emission of photon takes place by inducement.
It is random process.	It is not a random process.
Photons do not get multiplied by chain reaction.	Photons get multiplied by chain reaction.
It is an uncontrollable process.	It is a controllable process.

Intensity is low.	Intensity is high.
Emission takes place in all directions.	Emission takes place in specific direction.
Polychromatic light is emitted.	Monochromatic light is emitted.

3.2.5 Relation between Einstein's coefficient:

- ✓ Einstein obtained a mathematical expression to establish the existence of the two different kinds of emission processes i.e. stimulated and spontaneous.
- ✓ We can't predict which particular atom will make a transition from one state to another at a particular instance, but we can calculate the rate of transmission between the states.
- ✓ Let us assume that an atomic system is in thermal equilibrium i.e. no. of upward transitions is equal to the no. of downward transitions per unit volume per second.
- ✓ Rate of absorption = Rate of emission

$$B_{12} N_1 \rho = A_{21} N_2 + B_{21} N_2 \rho \dots \dots (1)$$

$$\therefore (B_{12} N_1 - B_{21} N_2) \rho = A_{21} N_2$$

$$\therefore \rho = \frac{A_{21} N_2}{(B_{12} N_1 - B_{21} N_2)}$$

Dividing by N_2

$$\therefore \rho = \frac{A_{21}}{(B_{12} \frac{N_1}{N_2} - B)} \dots \dots (2)$$

- ✓ N_1 and N_2 is the no. of atoms in ground and excited state, in thermal equilibrium
- ✓ So as per Boltzmann distribution law,

$$N = N_0 \cdot e^{\frac{-E}{k_B T}}$$

- ✓ We can write,

$$N_1 = N_0 \cdot e^{\frac{-E_1}{k_B T}} \text{ and } N_2 = N_0 \cdot e^{\frac{-E_2}{k_B T}} \dots \dots (3)$$

- ✓ Where N_0 is the total no. of atoms

✓ k_B is the Boltzmann constant

✓ From equation no. (3)

$$\therefore \frac{N_1}{N_2} = \frac{N_0 \cdot e^{\left(\frac{-E_1}{k_B T}\right)}}{N_0 \cdot e^{\left(\frac{-E_2}{k_B T}\right)}}$$

$$\therefore \frac{N_1}{N_2} = e^{\left(-\frac{E_2 - E_1}{k_B T}\right)}$$

✓ We know $E_2 - E_1 = h\nu$

$$\therefore \frac{N_1}{N_2} = e^{\left(-\frac{h\nu}{k_B T}\right)}$$

$$\therefore \frac{N_2}{N_1} = e^{\left(\frac{h\nu}{k_B T}\right)} \dots \dots \dots (4)$$

$$\therefore \rho = \frac{A_{21}}{(B_{12} e^{\left(\frac{h\nu}{k_B T}\right)} - B_{21})}$$

$$\therefore \rho = \frac{A_{21}}{B_{21}} \frac{1}{\frac{B_{12}}{(B_{21}) e^{\left(\frac{h\nu}{k_B T}\right)} - 1}} \dots \dots \dots (5)$$

✓ From Planck's theory of radiation,

$$\therefore \rho = \frac{8\pi h\nu^3}{c^3} \left[\frac{1}{e^{\left(\frac{h\nu}{k_B T}\right)} - 1} \right] \dots \dots \dots (6)$$

✓ Comparing equation (5) & (6)

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \text{ and } B_{12} = B_{21}$$

✓ From equation (7), we can say that probability of absorption is equal to the probability of stimulated emission.

✓ Also, from equation (7), the ratio of spontaneous and stimulated emission is proportional to ν^3 .

i.e. Spontaneous emission dominates over stimulated emission.

3.2.6 Ratio of spontaneous and stimulated emission:

$$\frac{R_{21}(\text{St})}{R_{21}(\text{Sp})} = \frac{B_{21}N_2 \rho}{A_{21}N_2}$$

$$\frac{R_{21}(\text{St})}{R_{21}(\text{Sp})} = \frac{B_{21} \rho}{A_{21}} \dots \dots (1)$$

$$\frac{B_{21} \rho}{A_{21}} = \frac{1}{\frac{B_{12}}{B_{21}} \left(e^{\frac{h\nu}{k_B T}} - 1 \right)}$$

But $B_{12} = B_{21}$

$$\frac{B_{21} \rho}{A_{21}} = \frac{1}{e^{\frac{h\nu}{k_B T}} - 1} \dots \dots (2)$$

Excited state (N_2) $\xrightarrow{\hspace{1cm}}$ E_2

ground state (N_1) $\xrightarrow{\hspace{1cm}}$ E_1

- ✓ From equation (1) & (2) we can write

$$\frac{R_{21}(\text{Sp})}{R_{21}(\text{St})} = e^{\frac{h\nu}{k_B T}} - 1 \dots \dots (3)$$

- ✓ From above equation, we can say that Spontaneous emission far exceeds the no. of stimulated emission. So, laser action is not possible.
- ✓ In order to achieve more stimulated emission as compared to spontaneous emission, the population of excited state (N_2) should be made larger as compared to the population of ground state (N_1). This is what we call "Population inversion".

3.3 LASER:

Basic used terms in Laser:

- ✓ Population Inversion:
The state of achieving more no. of atoms in excited state as compared to ground state is called population inversion.
 $E_2 > E_1$ and $N_2 > N_1$

✓ **Pumping:**

The mechanism of exciting atoms from lower energy state to higher energy state by applying energy from external source is called pumping.

✓ **Active medium:**

The medium in which population inversion is achieved for Laser.

✓ **Optical resonator:**

A pair of reflecting surfaces (mirrors), of which one is perfect and other is a partial reflector is called optical resonator.

Principal of Laser:

✓ The working of Laser is based on the principle of stimulated emission along with light amplification.

✓ For stimulated emission to take place, population of higher energy atoms should be more than population of lower energy atoms.

✓ This is achieved by pumping, Depending on the active medium, the pumping types can be optical pumping or electrical pumping or direct conversion pumping.

✓ Light amplification is achieved by photon multiplication within optical resonator cavity.

✓ The first step is to achieve population inversion in the active medium.

✓ A spontaneous emitted photon of an excited atom stimulates another atom in its path to release a second photon. These two coherent photons in turn stimulate two other atoms to release two more photons. So, there are four coherent photons.

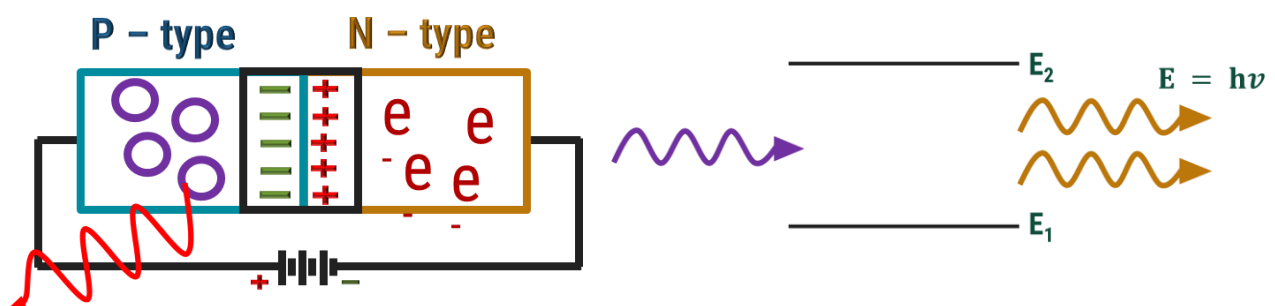
✓ The photons thus get multiplied like a chain reaction, thereby producing an amplified light, resulting in an intense Laser beam.

Semiconductor Laser:

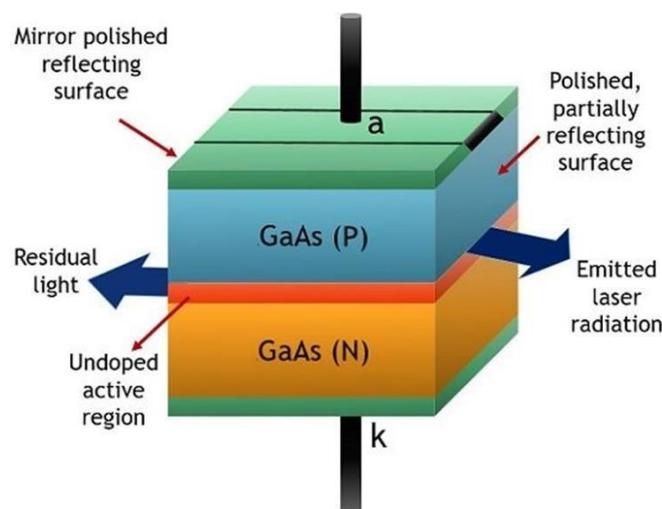
✓ It is a specially fabricated p-n junction diode that emits Laser light when it is forward biased.

Working Principal:

- ✓ When a p-n junction is forward biased, the electrons from n-region and holes from p- region cross the junction and recombine with each other.
- ✓ During this recombination, the energy is released in the form of photons.
- ✓ The photons emitted during recombination stimulated other electrons and holes to recombine as a result of which stimulated emission takes place.
- ✓ The basic principle of semiconductor Laser is Electroluminescence.



- ✓ Based on the materials used for fabricating the p-n junctions, the semiconductor Laser can be classified into 'Homo-junctions' (having same semiconductor materials with equal bandgaps on both sides, but different doping) and 'Hetero-junctions' (having different semiconductor materials with different bandgap on both sides).
- ✓ Semiconducting Laser is also called Laser diode or Injection laser diode.



- ✓ A homo-junction GaAs semiconductor diode is given in Figure. The p-n junction is fabricated using a single semiconductor material.

- ✓ The active medium here, is a p-n junction made from GaAs. The p-type and N-type are doped by Germanium and Tellurium respectively.
- ✓ The thickness of p-n junction layer is made very thin, of an order of few microns and the end faces are made reflecting, that form the optical resonator cavity.
- ✓ Current is supplied to the p-n junction through metal electrodes, fixed at the upper and lower faces.

Working:

- ✓ Population inversion here is achieved by injecting electrons across the junction from n-type to p-type semiconductor, by means of forward biasing voltage applied across it.
- ✓ The recombination of electrons and holes in the p-n junction region, results in emission of photons.
- ✓ The process is spontaneous and the laser radiation is random and incoherent.
- ✓ The photon triggers the stimulated emission of photons to get generated by increasing the rate of recombination of electrons and holes.
- ✓ If the current density is increased, the emission becomes more and more coherent and radiation intensity increases.
- ✓ The wavelength of the emitted radiation, depends on the concentration of donor and acceptor atoms and energy gap of semiconductor.
- ✓ Band gap of GaAs is 1.44 eV.

$$h\nu = \frac{hc}{\lambda} = E_g$$

$$\lambda = \frac{hc}{E_g}$$

$$\lambda = \frac{6625 \times 10^{-34} \times 3 \times 10^8}{1.44 \times 1.6 \times 10^{-19}}$$

$$\lambda = 8628 \text{ \AA} \quad \text{Wave-length of emitted radiation (IR).}$$

Advantages:

- ✓ Modulation of output is possible by controlling the junction current.
- ✓ It is small compact and has higher efficiency.
- ✓ The fabrication is simple and the output is continuous.
- ✓ Low power consumption and less costly.

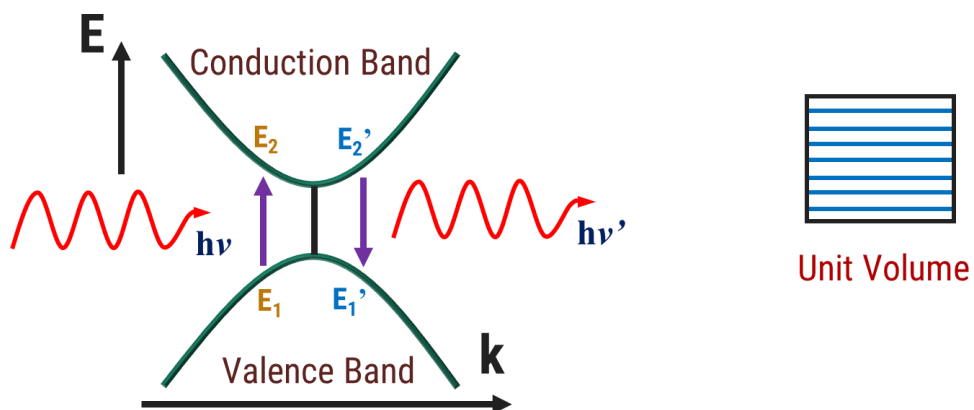
Disadvantages:

- ✓ Output is in the form of wide beam.
- ✓ Threshold current density is large.
- ✓ Monochromaticity and coherence is poor as compared to other Laser.
- ✓ Temperature affects output of Laser.

Applications:

- ✓ They are used in long haul communication.
- ✓ Used in optical communication in PC or mobile phones.
- ✓ Used in Laser printers.
- ✓ Used in Laser microscopes, line Laser.

3.4 Joint density of states:



- ✓ We know that density of states defines the number of allowed energy states per unit volume.
- ✓ To know or find the number of transitions or emissions (because that gives the no. of photons emitted) we need to know the emissions per unit volume.
- ✓ This can also give an idea of the power emitted.
- ✓ The number of emissions per unit volume can be found by multiplying density of states and probability of occupations.

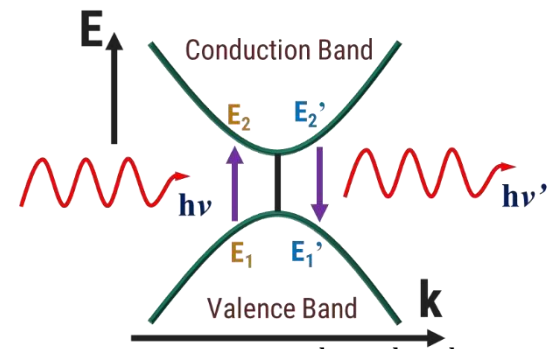
i.e. no. of emission/unit volume = density of states \times probability of occupation.

- ✓ Concentration of electrons in conduction band is given by:

$$n_e = \int Z_c(E) \cdot dE \cdot f(E)$$

- ✓ Concentration of holes in valence band is given by:

$$n_h = \int Z_v(E) \cdot dE \cdot [1 - f(E)]$$



- ✓ Suppose a radiation of energy $h\nu$ is incident on an electron sitting at certain level in valence band (E_1), it makes a transition to a vacant state in conduction band (E_2).
- ✓ This means that absorption involves a certain energy level in valence and a corresponding vacant level in conduction band.
- ✓ Similarly, if there is an electron at certain energy level (E_2') in conduction band and it makes a transition at a vacant level (E_1') in valence band, a photon with energy $h\nu'$ is emitted.
- ✓ We can thus say that absorption and emission involve a state in valence band and conduction band.
- ✓ For a photon interaction, we have one state in valence band and one state in conduction band and so we define joint density of states that takes care of number of states for a given energy $h\nu$.
- ✓ For a fixed incident energy $h\nu$, if E_2 is fixed then E_1 will also be fixed.

- ✓ For a given energy $h\nu$ there are several pairs of $E_2 - E_1$ and so there are number of pairs of states available for a photon of energy $h\nu$ to interact and this is given by density of states.
- ✓ Since the absorption or emission takes place from the top of valence band and bottom of conduction band respectively, we can have a parabolic approximation as,

$$\therefore E_2 = E_c + \frac{\hbar^2 k^2}{2m_c} \dots \dots \dots (1) \text{ for any level in conduction band}$$

$$\therefore E_1 = E_v - \frac{\hbar^2 k^2}{2m_v} \dots \dots \dots (2) \text{ for any level in valence band}$$

- ✓ The energy of photon $h\nu$ is given as:

$$\therefore h\nu = E_2 - E_1$$

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

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

$$\therefore h\nu = E_g + \frac{\hbar^2 k^2}{2} \left(\frac{1}{m_r} \right)$$

- ✓ Where, E_g = forbidden gap & m_r = reduced mass

$$\therefore h\nu = E_g + \frac{\hbar^2 k^2}{2m_r}$$

$$\therefore k^2 = (h\nu - E_g) \frac{2m_r}{\hbar^2} \dots \dots \dots (3)$$

- ✓ Substituting this value of k^2 in equation (1) and (2)

$$E_2 = E_c + \frac{\hbar^2}{2m_c} (h\nu - E_g) \frac{2m_r}{\hbar^2}$$

$$\therefore E_2 = E_c + \frac{m_r}{m_c} (h\nu - E_g) \dots \dots \dots (4)$$

- ✓ In the above equation E_c, m_r, m_c, E_g are constants, only E_2 and ν are variables.

$$E_1 = E_v - \frac{\hbar^2}{2m_v} (h\nu - E_g) \quad \frac{2m_r \hbar^2}{m_v}$$

$$\therefore E_1 = E_v - \frac{m_r}{m_v} (h\nu - E_g) \dots \dots \dots (5)$$

- ✓ i.e. there is 1-1 correspondence between $(E_2 \& E_1)$ and ν , Hence we have,

$$Z_c(E_2) dE_2 = Z(\nu) d\nu \dots \dots \dots (6)$$

- ✓ Where $Z(\nu) d\nu$ is the number of states per unit volume available for photons of energy between $h\nu$ and $h(\nu + d\nu)$ to interact (either absorb or emit).
- ✓ Once we found out $Z(\nu) d\nu$, i.e. density of states available for interaction and multiply it by probability of emission or absorption, we can obtain total number of emission or absorption per unit volume.

- ✓ From equation (6)

$$Z(\nu) = Z_c(E_2) \frac{dE_2}{d\nu} \dots \dots \dots (7)$$

- ✓ From equation (4)

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

$$\therefore (E_2 - E_c)^2 = \left(\frac{m_r}{m_c} \right)^2 (h\nu - E_g)^2 \dots \dots \dots (8)$$

- ✓ Optical joint density of states gives the number of states available for photons to interact with from equation (7), we have

$$Z(\nu) = Z_c(E_2) \frac{dE_2}{d\nu} \dots \dots \dots (7)$$

$$\therefore Z(\nu) = \frac{\pi}{2 h^3} \left(\frac{m_r}{m_c} \right)^2 (E_2 - E_c)^2 \frac{1}{m_c} h \dots \dots \dots (9)$$

- ✓ From equation (8)

$$\therefore Z(\nu) = \frac{\pi}{2 h^3} (m_c)^2 \left(\frac{m_r}{m_c} \right)^2 \frac{1}{m_c} (h\nu - E_g)^2 \frac{1}{m_c} h \dots \dots \dots (9)$$

$$\therefore Z(\nu) = \frac{\pi}{2h^2} (8m_c)^2 \left(\frac{3}{m_c} \right)^2 (h\nu - E_g)^2$$

$$\therefore Z(\nu) = \frac{\pi}{2h^2} (8m_r)^2 (h\nu - E_g)^2$$

$$\therefore Z(\nu) = \frac{\pi}{2h^2} (2 \times 2^2 m_r)^2 (h\nu - E_g)^2$$

$$\therefore Z(\nu) = \frac{8\pi}{2h^2} (2m_r)^2 (h\nu - E_g)^2$$

$$\therefore Z(\nu) = \frac{4\pi}{h^2} (2m_r)^2 (h\nu - E_g)^2$$

- ✓ This is expression for optical joint density of states.

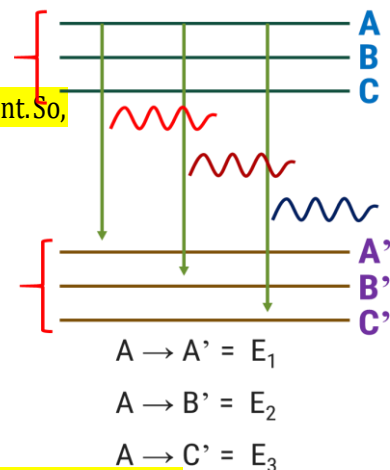
3.5 Transition Rate (Fermi's Golden rule)

Just for information:

- ✓ In each transition the $E = h\nu$ (energy of photon) will be different. So, if frequency ν changes then wavelength λ changes.

$$\nu = \frac{1}{\lambda}$$

- ✓ In this transition Bohr successfully explained the energy spectra. But couldn't explain the intensity or brightness of spectra.
- ✓ So it was explained by the use of Fermi's Golden rule. By the use of transition rate.



- ✓ In quantum physics, Fermi's golden rule is used to calculate transition rates. The transition rate depends upon the strength of coupling between the initial and final state of a system and upon the number of ways the transition can happen (joint density of states).

- ✓ The transition probability is given by:

$$\lambda_{if} = \frac{2\pi}{\hbar} |M_{if}|^2 Z_f$$

- ✓ Where λ_{if} is transition probability, $|M_{if}|^2$ is matrix element for interaction and Z_f is joint density of final state.
- ✓ The above equation is known as fermi's golden rule.
- ✓ The transition probability λ is called the decay probability and is related to mean lifetime τ of the state.

$$\lambda = \frac{1}{\tau}$$

- ✓ The general form of fermi's golden rule can be applied to atomic transitions. Nuclear decay and scattering.
- ✓ The transition can proceed more rapidly if coupling between initial and final states is stronger.
- ✓ This coupling term is traditionally called the matrix element for the transition.
- ✓ This matrix element can be placed in the form of an integral, where the interaction (that causes transition) is expressed as a potential v that operates on initial state wave function.
- ✓ The transition probability is proportional to the square of integral of interaction over all of the space appropriate to the problem.

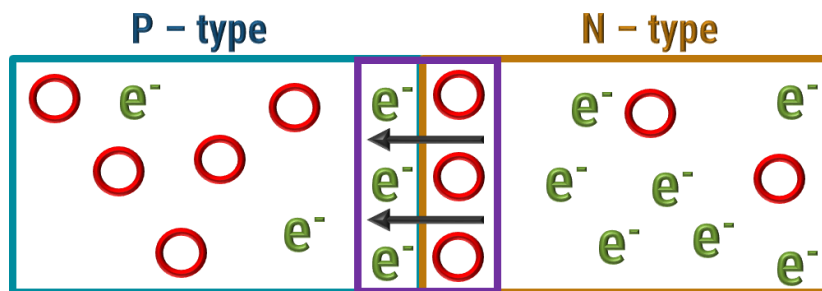
$$M_{if} = \int \psi_f^* V \cdot \psi_i dv$$

- ✓ Where V is operator for physical interaction that couples initial and final states,
- ✓ ψ_f^* is wave function for final state and
- ✓ ψ_i is wave function for initial state.

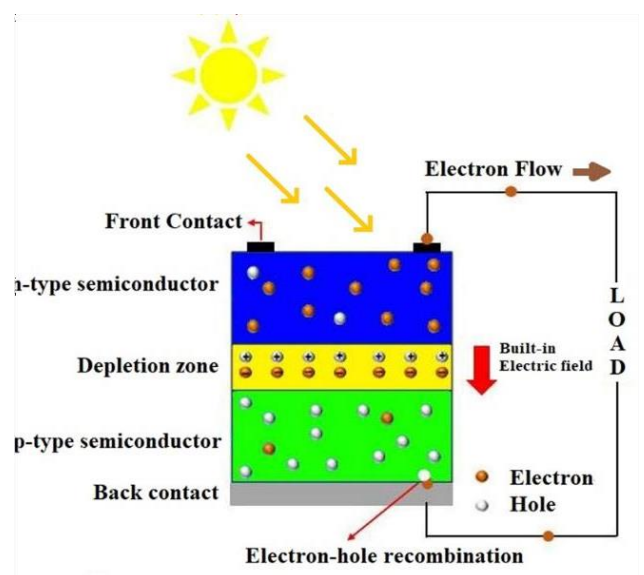
3.6 Photovoltaic effect

- ✓ "The effect due to which light energy is converted into electrical energy is called photovoltaic effect."
- ✓ It was first discovered by Edmund Becquerel in 1839.
- ✓ The photovoltaic effect occurs in solar cells that are composed of two different types of semiconductors,

- ✓ p-type and n-type joined together to form a p-n junction.
- ✓ Whenever these semiconductors are joined, an electric field is formed in the region as electrons move to p-side and holes move to n-side.
- ✓ This movement of electron creates an electron hole pair so, free electrons from n-type region try to diffuse to p-type region and holes in p-type region try to diffuse to n-type region in the crystal.



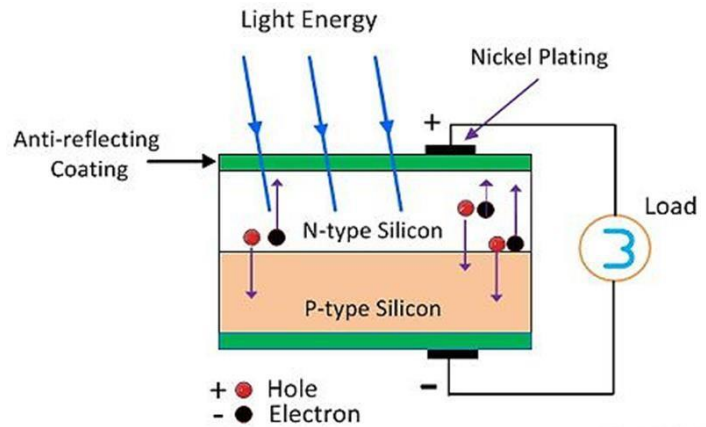
- ✓ Each free electron of n-type region while comes to the p-type region due to diffusion, it leaves a positive donor ion behind it in the n-type region.
- ✓ These positive and negative ions concentration layer creates an electric field across the junction which is directed from positive to negative that is from n-type side to p-type side.
- ✓ Due to this electric field (E) electrons experience a drift in the direction of field and generates drift current.
- ✓ In normal thermal equilibrium condition, the diffusion of charge carrier is equal and opposite of drift of charge carriers, hence the thickness of potential barrier remains fixed.
- ✓ Now the n-type surface of the silicon crystal is exposed to the sunlight. So, when light of suitable wavelength is incident on these cells, energy from the photons is transferred to the semiconducting materials in the p-n junction.
- ✓ This energy causes electrons to jump to a higher energy level (conduction band), leaving behind a hole in the valence band.



- ✓ So, it is this movement of electrons creates an electron hole pair, leading to a flow of current in the cell.

Construction of solar cell:

- ✓ P-N junction is one of the essential requirement in the construction of solar cell.
- ✓ This P-N junction is constructed by using semiconducting materials such as germanium silicon, gallium arsenide, cadmium arsenide, etc.
- ✓ The P-N junction is packed in a cylindrical metal container with a glass window on top so that light may fall on both P- and N-type materials uniformly.
- ✓ In order to avoid recombination of generated electrons in the P- and N-regions, their thickness is kept very small.
- ✓ For the generation of more number of charge carriers under the influence of incident light, heavily doped P- and N-type of materials are used.
- ✓ Thus, the use of heavily doped P- and N-regions gives a large photo voltage.
- ✓ Nickel plated metal ring around P-type layer acts as the positive output terminal and the metal contact at the bottom serves as the negative output terminal.



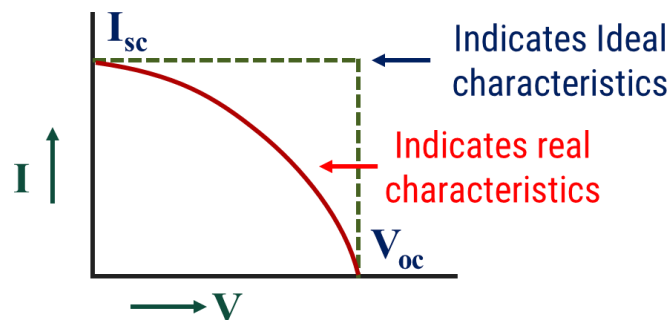
Working of solar cell:

- ✓ When the photons of suitable energy allowed to incident on P-N junction, photons impart sufficient energy to the valence electrons and remove them from their parent atoms.
- ✓ Hence, electron-hole pairs are generated in both P-region and N-region of the junction (as shown in Figure).
- ✓ These newly generated charge carriers reach the depletion region by diffusion where they are separated by a strong potential barrier existing there.

- ✓ At the same time, the minority charge carriers (electrons in P-region, holes in N-region) are supported by the existing potential barrier at the junction for their flow across the junction.
- ✓ Flow of minority charge carriers across the junction constitute the minority current, which is directly proportional to the illumination and also depends on the surface area being exposed to the light.

Parameters of solar cell:

- ✓ The I-V characteristics can be studied with the help of below diagram.



- ✓ The output voltage from solar cell when load impedance is very high, $R_L \rightarrow \infty$ is called open circuit voltage (V_{oc}).
- ✓ The current output when the load impedance is very small i.e. $R_L \rightarrow 0$ is called the short circuit current (I_{sc}).
- ✓ The product of open circuit voltage (V_{oc}) and short circuit (I_{sc}) gives the ideal power output from the solar cell, i.e. $P_{ideal} = V_{oc} \times I_{sc}$.
- ✓ But the actual power output is less than the ideal output, i.e. $P_{max} = I_m \times V_m$.
- ✓ The fill factor (FF) of solar cell is defined as the maximum useful power w.r.t. ideal power.

$$\text{i.e. FF} = \frac{P_{max}}{P_{ideal}} = \frac{I_m \times V_m}{I_{sc} \times V_{oc}}$$

- ✓ Efficiency ' η ' of solar cell is given by:

$$\eta = \frac{I_m \times V_m}{\text{Incident light power}}$$

-
- ✓ The voltage developed by every cell is of an order of 0.5 to 0.6 V and efficiency is around 15 – 20 % for silicon cells.

Merits:

1. For this type of conversion, the input energy i.e. solar energy is available at no cost.
2. Such a process is free from pollution like chemical, thermal and radioactive.

Demerits:

1. The input solar energy is not always constant. It changes with time of day and also with
2. seasons. So, output is not constant energy.
3. Solar cells have low efficiency: The energy generated during daytime can be stored and used, whenever required. But the storage mechanisms are very expensive.
4. The modules require a large area to be installed.

Application of solar cell:

1. Communication
2. Electricity for Remote areas
3. Water pumping
4. Refrigeration
5. Medical Application
6. Signal System
7. Charging Vehicle batteries
8. Public Utilities
9. Science and Research

3.6.1 Optical loss:

- ✓ Optical losses in solar cell, mainly affects the power output, by lowering the short circuit current (I_{sc}), thus reducing the efficiency.

The efficiency of solar cell can be reduced by following reasons:

- ✓ Mismatch of band gap of materials with the solar spectrum.
- ✓ Total spectrum of solar energy is not absorbed.
- ✓ Reflection loss of light.
- ✓ Less intensity of light.

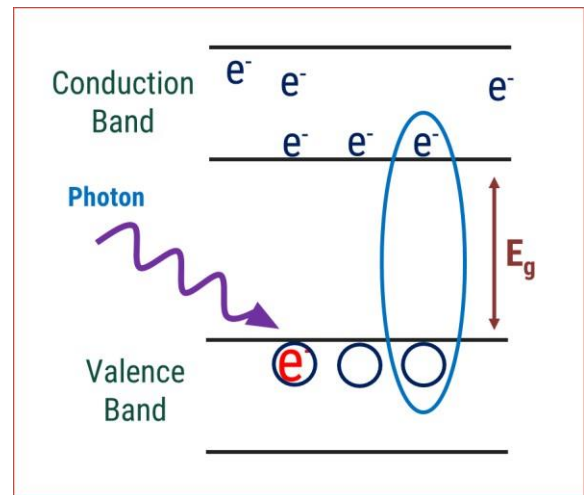
Remedies:

1. Proper selection of materials, increases the efficiency of solar cell.
2. Solar cell can be made thicker for more absorption of light.
3. Top contact coverage of the solar cell surface can be minimized.
4. Anti-reflection coating can be used on the top surface to increase absorption.
5. The optical path length can be increased by a combination of surface texturing and light trapping.

3.7 Exciton:

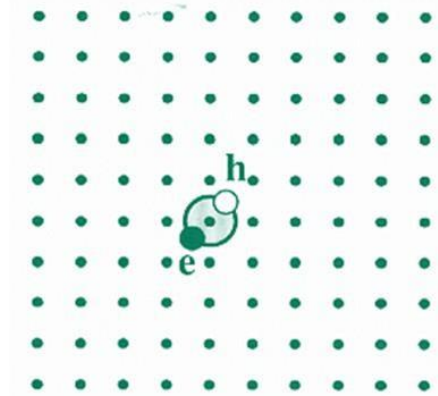
- ✓ The concept of excitons was first proposed by Yakov Frenkel in 1931.
- ✓ The absorption of a photon by an inter band transition in a semiconductor creates an electron in conduction band and a hole in valence band.
- ✓ These oppositely charged particles attract each other through Coulomb interaction and there may be a probability of formation of a neutral electron hole pair called exciton.
- ✓ "An exciton is a bound state of an electron and hole which are attracted to each other by an electrostatic force."

- ✓ When the photon is absorbed by a semiconductor, an electron-hole pair is created.
- ✓ The electron in the conduction band is now attracted to the localized hole by repulsive Coulomb forces from the large number of electrons surrounding the hole and excited electrons.
- ✓ This attraction provides a stabilizing energy balance.



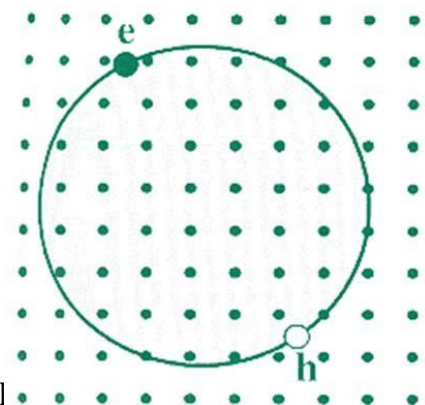
3.7.1 Frenkel exciton:

- ✓ “When there is a strong electron hole attraction, like in ionic crystals, the electrons and holes are tightly bound to each other, this type of exciton is called Frenkel exciton.”
- ✓ They are also called tight bound excitons. They are found in insulators and molecular crystal.
- ✓ They are bound to specific atoms or molecules and they move by hopping from one atom to another. Their binding energy is of a range 0.1 eV to 1 eV. They are stable at room temperature.



3.7.2 Wannier – Mott excitons :

- ✓ “When the electron hole separation is much larger to the lattice constant, then the exciton is called Wannier-Mott exciton.”
- ✓ In this, the electron hole pair is weakly bound. They are also called free excitons. They mainly exist in semiconductor. They have a large radius.
- ✓ They are delocalized states that can move freely throughout the crystal. They have a binding energy of around 0.01 eV. They are stable



3.8 Drude model:

- ✓ Electrons in a metal behave like particles in an ideal gas. (I.e. No coulombian interaction and collision between particles). This is called independent electron approximation.
- ✓ The effect of electron-electron and electron-ion interaction is ignored.
- ✓ Mean free time between collisions is τ . It is independent of electrons position and velocity.
- ✓ Electrons achieve thermal equilibrium by collisions with ions and their mean kinetic energy can be given by: $\frac{1}{2} m v^2 = 3 K T$.
- ✓ Mean free time between collisions is τ .
- ✓ It is independent of electrons position and velocity.
- ✓ After the collisions, they move in random directions with a speed that depends on the temperature of the region where collision occurred i.e., hotter the region higher is the speed of emerging electrons.

Application of Drude model:

1. Electrical conductivity and Drude model:

- ✓ To apply the Drude model the density of gas formed by free electrons must be known. This parameter is called the 'conduction electron density'. i.e. no. of electrons per unit volume. The conduction electron density can be computed by assuming that each atom contributes 'z' electrons for conduction, where 'z' is the no. of outer shell electrons for metal atoms.
- ✓ The average drift velocity of an electron in metal can be computed by following equation.

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

- ✓ The current density can be computed as

$$\therefore J = neV_d$$

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

✓ From, electrical conductivity $J = \sigma E$

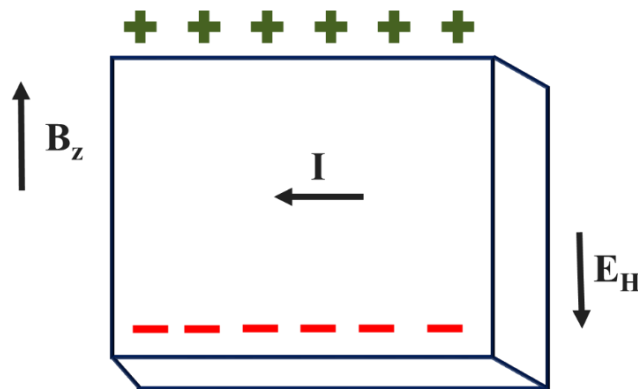
$$\therefore \sigma E = \frac{ne^2 E \tau m}{ne^2 \tau m}$$

$$\therefore \sigma =$$

✓ This is the expression for DC conductivity in Drude Model.

2. Hall effect and Drude model:

- ✓ The Drude model also explains the Hall effect. It is a phenomenon in which an electric field “ E_H ” arises perpendicular to both the current density ‘ J_x ’ (The point in the direction of electron movement) and magnetic field ‘ E_H ’.
- ✓ The Hall effect occurs when a current flows through a conductor which is already under the influence of a magnetic field. As a result of the magnetic field, the positive charges accumulate on one side of the conductor.



- ✓ For electrons to pass through the given region, the field ‘ E_H ’ must cancel the Lorentz force that acts in opposite direction.

$$F_L = qE + qV \times B$$

- ✓ The magnitude of Hall field can be calculated as below: $E_H = R_H J_x B_z$

where, R_H is the Hall coefficient

$$R_H = - \frac{1}{n e}$$

- ✓ J_x is the current density
- ✓ B_z is the magnetic field
- ✓ As the Hall coefficient, approaches unity, The Hall field “EH” more likely cancels the Lorentz force.

3. Wiedemann – Franz law and Drude model:

- ✓ The Wiedemann – Franz law states that for any metal at a given temperature, the ratio of thermal conductivity to electrical conductivity is a constant ‘L’ (L is called the Lorentz number).

$$\therefore \frac{K}{\sigma} = L T$$

- ✓ K = Thermal conductivity
- ✓ σ = electrical conductivity
- ✓ L = Lorentz number
- ✓ T = absolute temperature
- ✓ The ideal gas related equations derived from the Drude model can be used to generate an equivalent formula for “LT”.
- ✓ Now,

$$\therefore \frac{K}{\sigma} = \frac{\frac{1}{2} n V K \lambda_B}{\frac{n e^2 \lambda V}{3 K_B T}}$$

$$\therefore \frac{K}{\sigma} = \frac{3}{2} \left(\frac{K_B}{e} \right)^2 T$$

$$\therefore \frac{K}{\sigma} = L T$$

-
- ✓ Despite some minor inconsistency, the theoretical calculation often gives accurate results.

Drawbacks of Drude model:

1. Drude model does not consider the collision between electron-electron. It also does not consider the interaction between electrons and ions.
2. De-Broglie wavelength of electrons with some thermal energy are in nanometer scale. So, electrons cannot be treated as classical particle under the conditions of Drude Model.
3. The Drude model explains the conductivity of metals at low temperatures as the assumption of constant mean free path based on atomic spacing is incorrect.
4. The Drude model can't explain the conductivity of alloys. Even small impurities can drastically decrease the conductivity of metals in a way that can't be predicted.
5. From the view of classical mechanics, the electrons should contribute greatly to the heat capacity of metals. But this result does not agree with the experimental data.