

Syllabus Topic : Optical Transitions In Bulk Semiconductor

3.1 Optical Transitions In Bulk Semiconductor

- In semiconductor physics, the band gap of a semiconductor is of two types, a direct band gap or an indirect band gap.
- The minimal energy state in the conduction band and the maximal energy state in the valence band are each characterized by a certain crystal momentum (k -vector) in the Brillouin zone.
- If the k -vectors are the same, it is called 'direct band gap'. If they are different, it is called an 'indirect band gap.' The band gap is called direct, if the crystal momentum of electrons and holes is the same in both the conduction band and the valence band an electron can directly emit a photon.
- In an indirect band gap, a photon cannot be emitted because the electron must pass through an intermediate state and transfer momentum to the crystal lattice. Examples of direct band gap material includes some III and V material like InAs, GaAs. Indirect band gap materials include Si, Ge (shown in Fig. 3.1.1)
- In the solid state physics of semiconductors carrier generation and recombination are processes by which mobile charge carriers (electrons and holes) are created and eliminated. Carrier generation and recombination process are fundamental to the operation of many semiconductor up to electronic devices like photodiode LED's, LASER diodes.
- The electron hole pair is the fundamental unit of generation and recombination, corresponding to an electron transitioning, between the valence band and conduction band where generation of electrons is a transition from the valence band to the conduction band and recombination leads to a reverse transition.

Implications for radiative recombination

- Interactions among electrons, holes, photons, phonons and other particles are required to satisfy conservation of energy and crystal momentum i.e. conservation of total k vector.
- A photon with an energy near a semiconductor band gap has zero momentum.
- One important process is called radiative recombination, where an electron in the conduction band annihilates hole in the valence band releasing the excess energy as a photon.
- This is possible in a direct band gap semiconductor, if the electron has a k vector near the conduction band minima (the hole will share the same k -vector) but not possible in an indirect band gap semiconductor, because photons cannot carry crystal momentum.
- Hence the conservation of crystal momentum would be violated. For radiative recombination to occur in an indirect band gap material, the process must also involve the absorption or emission of a phonon, where the phonon momentum equals the difference between the electron and hole momentum. It can also, instead involve a crystallographic defect, which performs the same role. This is why light emitting diodes and laser diodes are almost always made of direct band gap semiconductor.

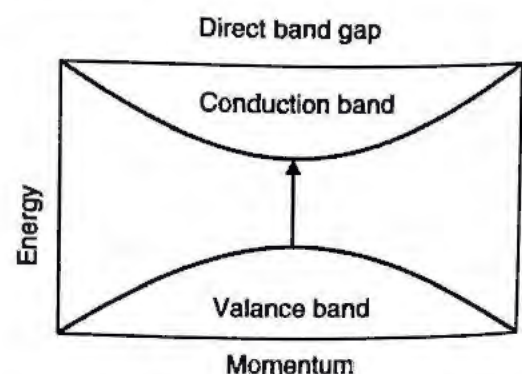
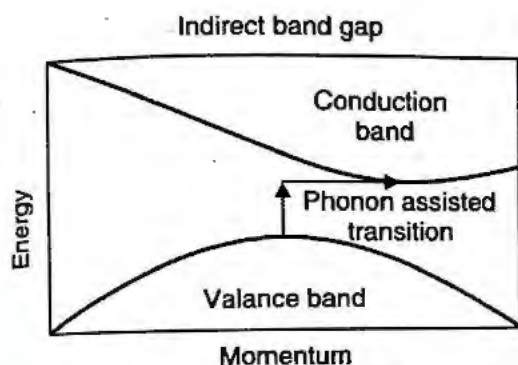


Fig. 3.1.1(a) : Contd....

Energy vs. crystal momentum for a semiconductor with a direct band gap, showing that an electron can shift from the highest-energy state in the valence band to the lowest-energy state in the conduction band without a change in crystal momentum. Depicted is a transition in which a photon excites an electron from the valence band to the conduction band

Fig. 3.1.1(a)



Energy vs crystal momentum for a semiconductor with an indirect band gap, showing that an electron cannot shift from the highest-energy state in the valence band to the lowest-energy state in the conduction band without a change in momentum. Here, almost all of the energy comes from a photon (vertical arrow), while almost all of the momentum comes from a phonon (horizontal arrow).

(b)

Fig. 3.1.1

3.2 Interaction of Radiation with Matter (Types of Absorption and Emission)

- In order to understand the working principle of a laser, let us study the quantum processes that take place in a material medium when it is exposed to radiation.
- A material medium is composed of identical atoms or molecules each of which is characterised by a set of discrete energy states.

- An atom can move from one energy state to another when it receives or releases an amount of energy equal to the energy difference between these two states.
- We know that the energy will get absorbed when atom gets excited from the lower energy level to the higher energy level. This energy absorption is equal to the difference of energies between the two levels.
- Similarly the energy will get emitted when atom jumps or moves from the higher energy level to the lower energy level, here emission of energy again is equal to the difference of the energies between two levels in the form of photon.
- Let photons strike a group of atoms and let us consider the two energy levels and which are occupied by the group of atoms.
- In normal or equilibrium state lower energy level densely populated by the number of atoms compared to the other higher energy levels like E_2 E_3 ... etc.
- When photon strikes with the energy more or less than $E_2 - E_1$ then there is no interaction with the group of atoms.
- But when photon strikes with the energy equal to the difference of the two energy levels i.e. $E_2 - E_1 = h\nu$, then atom from the level absorbs this energy and gets excited to the higher energy level E_2 . Refer Fig. 3.2.1(a). This condition in which atom remains in the excited level is E_2 nonequilibrium condition.
- The time for which an atom can remain in the ground state is unlimited, but on the other hand an atom can remain in the excited state for limited time only.
- Hence the limited time for which an atom is in excited state is known as - **Life-time** of the state.
- After the life-time of this state, the atom in the excited state gets de-excited itself and transition takes place from the excited level E_2 to the lower level spontaneously, and emits a photon of the energy $= (E_2 - E_1)$.

- The spontaneous emission depends upon the type of the atom and the type of the transition while it is independent of outside circumstances. Refer Fig. 3.2.1(b).
- Now second possibility of the transition is that as shown in Fig. 3.2.1(c). When atom is in the excited state E_2 before getting de-excited itself and need not wait for the transition to fall on its own accord spontaneously from the level E_2 to E_1 level.
- If a photon of energy $h\nu = (E_2 - E_1)$ is incident on the atom which is in the excited level E_2 then this atom gets triggered and makes the transition from the level E_2 to the lower state E_1 .
- During this transition the atom emits the photon along with the incident photon. It is coherent with the incident radiation, has the same phase and the frequency as the incident radiation.

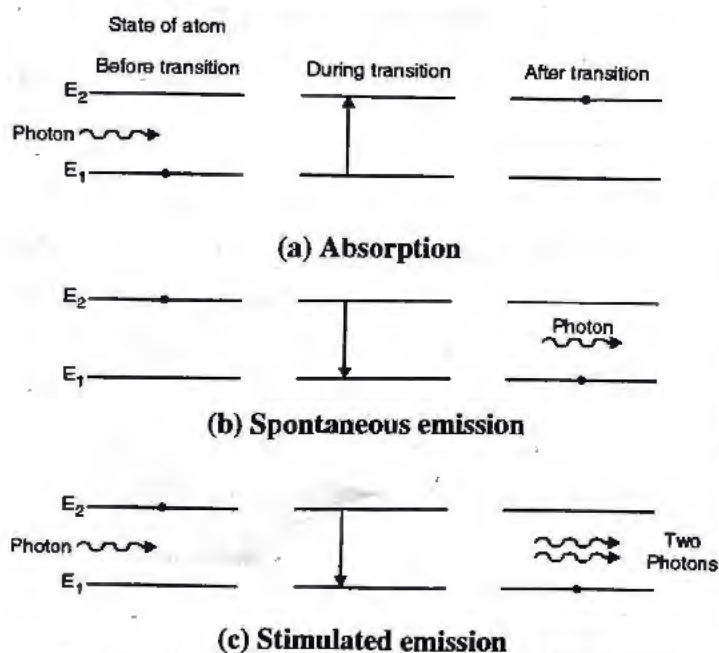


Fig. 3.2.1 : Types of transitions between two energy levels

Syllabus Topic : Absorption

3.2.1 Absorption

- A photon incident on the atomic system and excites the atom from the lower energy level E_1 to the higher energy level E_2 .

- In this case, the atom in the lower state after absorbing the incident energy gets stimulated towards the higher level E_2 . This process is known as absorption.

Syllabus Topic : Spontaneous Emission

3.2.2 Spontaneous Emission

- After the life-time of the state, the atom in the excited state, gets de-excited itself and transition is allowed, falls on own accord spontaneously from level E_2 to level E_1 and emits a photon of energy $h\nu = E_2 - E_1$. This is called spontaneous emission.
- Radiation emitted in spontaneous jumps is in random directions and not coherent. The radiation is a random mixture of quanta having different wavelengths, different phase hence has a broad spectrum

Syllabus Topic : Stimulated Emission

3.2.3 Stimulated Emission

- When the atom is in excited level E_2 then the external photon incident with the same energy stimulates this atom to the lower energy level. During this transition atom emits a photon with the same energy as the energy of incident photon. This type of emission is called as stimulated emission.
- Stimulated emission is coherent with the stimulating incident radiation. It has same direction, same phase, same frequency as the incident radiation.
- The process of stimulated emission has the following interesting characteristics :
 1. The emitted photon is identical in all respects to the incident photon. Its frequency ν is the same as that of incident photon and it is in the same phase with the incident photon. Both the photons travel in the same direction and are in the same state of polarization.

2. The process can be controlled from outside.
 3. An important feature of stimulated emission is that the number of photons goes on multiplying rapidly. Under the influence of one incident photon, a second photon is emitted. These two identical photons induce two more stimulated emissions thus giving four photons in all. These four in turn generate four more photons and so on. Thus the number of photons builds up in an avalanche.
- The combined stimulated emissions from a sample of large number of atoms leads to amplification of light.
 - The resultant effect is that the constructive interference of many waves travelling in the same direction with same frequency, same phase produces an intense coherent light beam.

Syllabus Topic : Absorption

3.1 ABSORPTION OF RADIATION :

- Absorption of radiation is the process by which electrons in the ground state absorb energy from photons to jump into the higher energy level.
- Let us consider two energy levels (E_1 and E_2) of electrons. E_1 is the ground state or lower energy state of electrons and E_2 is the excited state or higher energy state of electrons.
- The electrons in the ground state are called lower energy electrons or ground state electrons whereas the electrons in the excited state are called higher energy electrons or excited electrons.
- In general, the electrons in the lower energy state can't jump into the higher energy state. They need sufficient energy in order to jump into the higher energy state.

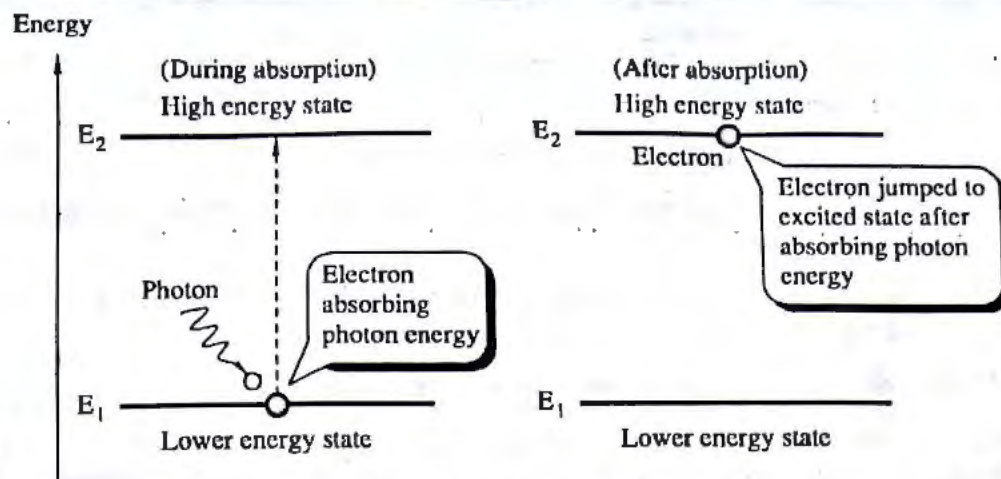
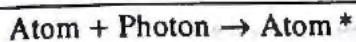


FIG. 3.1 : ABSORPTION OF RADIATION OR LIGHT

The process is represented as



The frequency of the absorbed photon is

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

Syllabus Topic : Spontaneous Emission

3.2 SPONTANEOUS EMISSION :

- Spontaneous means by "own" or "natural".
- Spontaneous emission is the process by which electrons in the excited state return to the ground state by emitting photons.
- The electrons in the excited state can stay only for a short period (10^{-8} second).

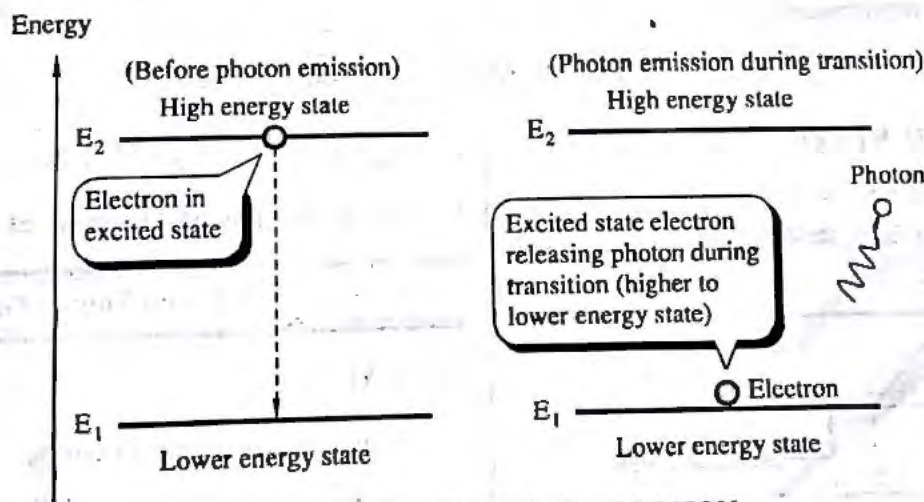
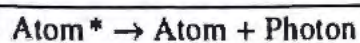


FIG. 3.2 : SPONTANEOUS EMISSION

- Thus, after the short lifetime of the excited electrons, they return to the lower energy state or ground state by releasing energy in the form of photons, this process is known as spontaneous emission.

The process is represented as



3.3 STIMULATED EMISSION :

- Stimulated means under the influence of some external force.
- Stimulated emission is the process by which incident photon interacts with the excited electron and forces it to return to the ground state.
- In stimulated emission, the light energy is supplied directly to the excited electron instead of supplying light energy to the ground state electrons.
- The stimulated emission is not a natural process it is an artificial process.
- When incident photon interacts with the excited electron, it forces the excited electron to return to the ground state. This excited electron release energy in the form of light while falling to the ground state.

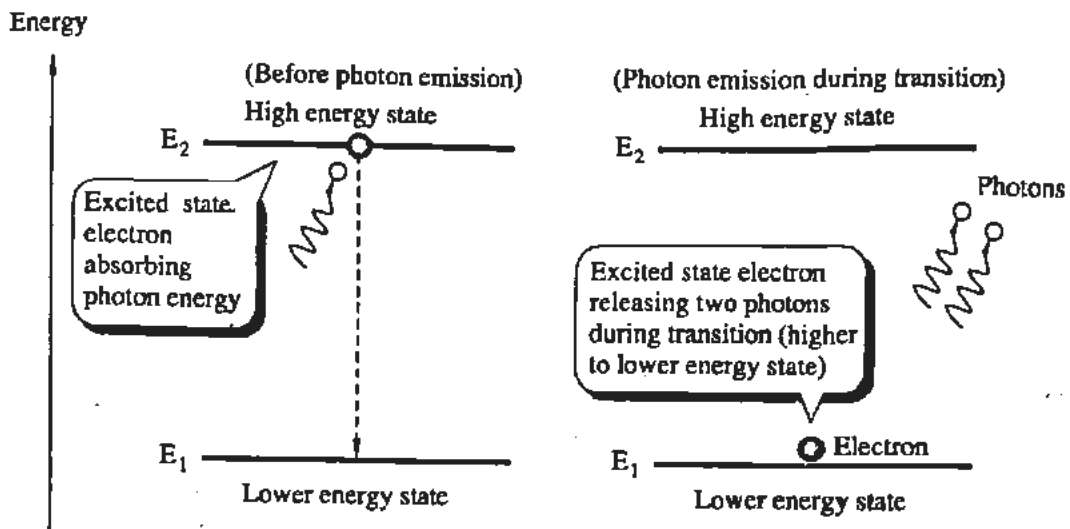


FIG. 3.3 : STIMULATED EMISSION

- The stimulated emission process is very fast compared to the spontaneous emission process.
- The process is represented as



3.4 META STABLE STATE :

- It is the state where the atoms get excited and remains in the excited state for longer time than the normal state.

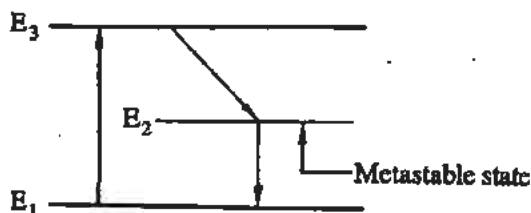


FIG. 3.4 : META STABLE STATE

- This state plays an important role in lasing action.
- In metastable state, atoms stay of the order of 10^{-3} to 10^{-2} second. In excited state other than metastable atom stay of order of 10^{-8} second.

- Let, E_1, E_2, E_3 be the energy levels of the system.
- E_2 is the metastable state of the system.

Syllabus Topic : Gain

3.5 GAIN :

- When atoms come down to ground state from metastable state, they emit photons in random directions.
- When emitted photons incident normally on mirror (optical resonator), they bounce back and forth. So they induce stimulated emission and laser action grows.

- The Laser intensity (I) grows exponentially and intensity on one bounce will be

$$I = I_0 e^{2\beta d} \quad \dots (1)$$

where, d = path length in active medium.

β = gain coefficient

I_0 = initial intensity.

- In optical resonator losses are present when light bounces back and forth.
- Light absorption by medium and by mirrors here all losses except reflectance losses may be grouped into a single loss constant α , then intensity loss per unit length when length of medium is d .
- Suppose the reflections of the front and back mirrors be R_1 and R_2 .

$$I = I_0 e^{2\beta d} e^{-2\alpha d} R_1 R_2 \quad \dots (2)$$

$$\therefore \frac{I}{I_0} = e^{2\beta d} e^{-2\alpha d} R_1 R_2 \quad \dots (3)$$

- The gain $\frac{I}{I_0} = G$

- So, $G = e^{2\beta d} e^{-2\alpha d} R_1 R_2$

for laser action $G \geq 1$

$$e^{2\beta d} e^{-2\alpha d} R_1 R_2 \geq 1$$

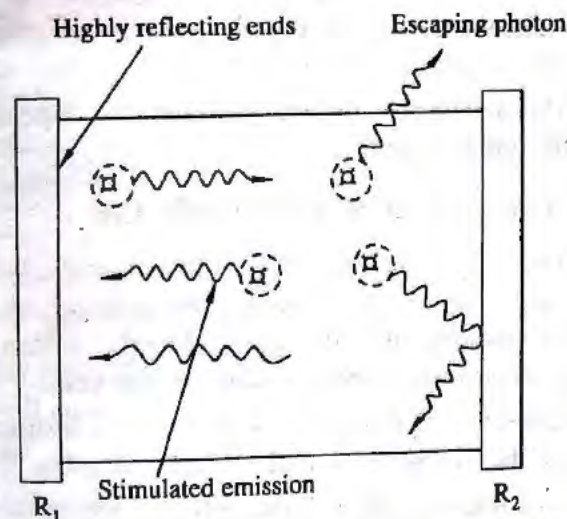


FIG. 3.5 : A LASER CAVITY WITH HIGHLY REFLECTING ENDS SHOWING THE STIMULATED EMISSION OF LIGHT AND THE ESCAPE OF SOME PRIMARY PHOTONS THROUGH THE SIDE WALLS Δv .

3.7 Optical Joint Density of States / Density of States for Photons

- Before discussing about the concept of optical joint density of states, we must know about radiative and non radiative transition.
- As the name indicates, radiative transition involves emission or absorption of a photon.
- A non-radiative transition does not involve emission or absorption of a photon.
- Let us look at the Fig. 3.7.1. Where we can see clearly that when an electron which sits in the conduction band, it makes a downward transition, into the valence band, then the difference in energy is given in the form of $h\nu$.

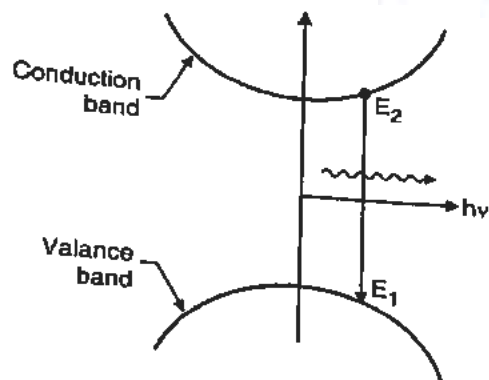


Fig. 3.7.1

E_1 = Some energy level in the valence band

E_2 = Some energy level in the conduction band]

3.7.1 Radiative Transition

- Radiative transition involves emission or absorption of a photon or it could be the incident photon leading to the transition of an electron from the valence band to the conduction band.
- In the case of non-radiative transition the energy difference is given in the form of phonon.
- The energy difference is usually the dominant process in the case of indirect band gap semiconductor. So if the given figure shows an indirect band gap semiconductor, whatever be the process of excitation, whether it is optical process of excitation or current injection it essentially leads to injection of carriers into this band which then comes down by the thermalization and accumulate at the bottom of the band.
- Similarly whatever hole generated or wherever generated it will start moving to the top because the top of the band corresponds to low energy for holes or electrons move down to the lower level and holes accumulate at point.
- Now if an electron wants to make recombination with holes then, it has to make an oblique transition and this is not permitted by the K selection rule.

- K selection rule requires that the transition needs to be vertical i.e. ΔK should be nearly equal to zero. But this is not permissible by K selection rule. However as we have seen phonons can have large momentum. Because momentum is given by $\hbar K$ which is equal to \hbar multiplied to $\frac{2\pi}{\lambda}$ here. So this is λ of phonon. λ of phonons are of the same order, as that of electrons. Therefore this difference in ΔK is made up by phonons. There is also another class of transition which are called phonon assisted radiative transition.
- In this case an oblique transition can also lead to the emission of photon but it will assisted by a phonon (one or more). This is called phonon assisted radiative transition and the energy difference can be given out and momentum difference can be made out by the number of phonons participating and there is also a possibility of one photon + phonon leading to this transition which is called phonon assisted radiative transition.
- The energy difference is primarily made up of photon but the momentum difference is primarily made up of phonons and that is called phonon assisted radiative transition.
- So keeping this in mind let us discuss the topic of optical joint density of states.
- Now let us understand the need of defining optical joint density of states.
- A detailed discussion on density of states tell us the number of states available per unit volume and if we recall that our objective now is to realize the sources and detectors.
- We are interested in emission and absorption means we want to see the number of transitions, or number of emissions because the number of emissions will tell us the number of photons emitted and therefore we can estimate the power emitted.

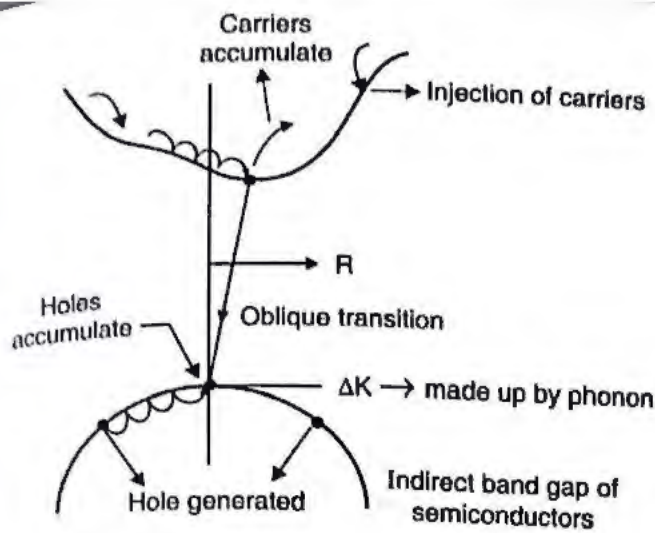


Fig. 3.7.2 : Phonon-assisted radiative transition

- Number of emissions per unit volume is given by the number of density of states multiplied by the probability of occupations.
- Previously we have seen that the carrier density of electrons in the conduction band was given by density of states $\rho_c(E)$ multiplied by probability of occupations.

∴ number of emissions/per unit volume

$$= \text{density of states} \times \text{probability of occupations.}$$

Carrier density of electrons $n(E)$ in the conduction band
 $= \text{density of states } \rho_c(E) \times \text{probability of occupations } \rho_c(E) f(E)$

We can recall :

$$n(E) = \rho_c(E) f(E)$$

and

$$n(\text{carrier concentration}) = \int n(E) dE = \int \rho_c(E) f(E) dE$$

$$\text{Similarly } p = \int p(E) dE = \int \rho_v(E) [1 - f(E)] dE$$

the probability of occupations of holes

- Keeping this at the background (Fig.3.7.3), let us consider radiation which is incident of energy $h\nu$ and consider an energy level E_1 in the valence band and an energy level E_2 in the conduction band.

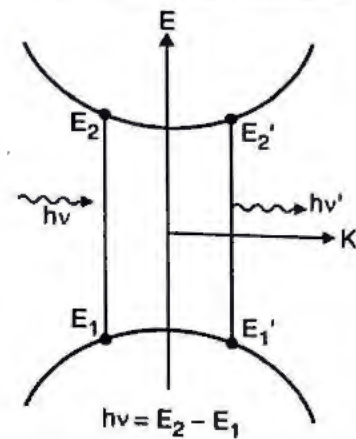


Fig. 3.7.3 : E - k diagram

- For a given photon of energy $h\nu$ of frequency ν , if E_2 is fixed (even automatically) by the condition that $h\nu = E_2 - E_1$ an emission or absorption involves e.g. absorption involves an electron state at E_1 in the valence band and a vacant state E_2 in the conduction band.
- Similarly for emission if we see, then it involves an electron sitting in the conduction band at some other value.
- Let us say E_2' in conduction band and a vacant state at E_1' in the valence band.
- This could lead to the emission of photon of energy $h\nu'$.
- So emission and absorption process simultaneously involves a state in the valence band and a state in the conduction band and therefore any process involves states in the valence band and state, in the conduction band.
- Normally in this case we had density of states in the conduction band $[\rho_c(E)]$ and density of states in the valence band $[\rho_v(E)]$.
- Because whole concentration does not depend on the density of states in conduction band, it depends on the density of states in the valence band.

- But in photon interaction we have one state in valence band and one state in conduction band and therefore we define an optical joint density of state which simultaneously takes care of the number of states for a given energy $h\nu$.
- Here it is to be understood that if an incident energy $h\nu$ (photon of energy $h\nu$) is incident and if E_2 is fixed, E_1 is also fixed because the difference has to be the same (considering allowed transition and not considering oblique transition) those transitions which followed "K-selection rule.
- So when E_2 is fixed, E_1 is also fixed.
- Then it is possible that we define a joint density of states.
- It will be only clear if we proceed with a derivation.
- We can then observe that joint density of states does not depend on the actual value of E_2 and E_1 , but will always depend on $E_2 - E_1$.
- So the need for defining an optical joint density of states is because the transition involved states in the valence band and conduction band and there can be several combinations of E_2 and E_1 which will be equal to $h\nu$.
- In the Fig. 3.7.3, we see it is E Vs k where k is a vector.
- Depending on the direction of propagation of the electron beam the E - k diagram continuously changes which means for a given energy $h\nu$ there are several pairs of $E_2 - E_1$ and therefore there is a density of state. i.e. a number of states, number of pairs of states available for a photon of energy $h\nu$ to interact and this is given by density of states. This will be clear as we proceed further.

So,

$$E_2 = E_c + \frac{\hbar^2 k^2}{2m_c}$$

This is a parabolic approximation which is valid near the bottom of the band.

$$\text{and } E_1 = E_v - \frac{\hbar^2 k^2}{2m_v}$$

$$h\nu = E_2 - E_1 = E_g + \frac{\hbar^2 k^2}{2} \underbrace{\left(\frac{1}{m_c} + \frac{1}{m_v} \right)}_{\frac{1}{m_r}}$$

Where, m_r = reduced mass

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

From this expression we have :

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

Substituting the value of k in the expression

$$E_2 = E_c + \frac{\hbar^2 k^2}{2m_c} \text{ we have}$$

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

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

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

We see here that for every value of E_2 there is a value ν . In the above expression we find that there is no E_1 .

E_c , m_r , m_c , E_g are all constants. Only E_2 and ν are variables E_2 gets automatically fixed once we say $h\nu$, and therefore there is a 1 - 1 correspondence.

Exactly, like this we can also write for E_1 and see that there is a 1 - 1 correspondence between E_1 and ν .

This means that :

$$\rho_c(E_2) dE_2 = \rho(\nu) d\nu$$

where $\rho(v) dv$ is the number of state per unit volume available for photons of energy between $h\nu$ and $h(\nu + d\nu)$ to interact (emit or absorb).

- We are therefore interested to get ρ_v . Because once we get the density of states available for interaction (emission or absorption) multiplied with the probability of emission or absorption will give the total number of emissions or total number of absorptions per unit volume.
- That is our interest to find out the number of photons emitted per unit volume of the material and then of course if multiplied with rate constant will give us rate of emissions.
- Finally we are interested in the rates of emissions and absorptions. So advantage of optical joint density of states is that it simultaneously takes care of the number of states in the valence band and the conduction band.
- It does not know which is E_1 and which is E_2 . But it denotes if $h\nu$ is the energy gap, it can find out the possibilities of the number of packs and position corresponding to which the energy difference between valence band and the conduction band.
- It denotes the number of states available for photons of energy $h\nu$ to interact with. That is given by optical joint density of states.

$\rho(v) dv$ is the number of state per unit volume for a photon of energy between $h\nu$ and $h\nu + d\nu$ to interact with

To simplify :

$$\rho(v) = \rho_c(E_2) \frac{dE_2}{d\nu}$$

From the previous derivation ,

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

We get,

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

- This is important because next we will multiply with the probability of emission and probability of absorption and we will gain an expression for gain coefficient which will contain all these terms. So we need the given derivation for $\rho(v)$.
- Optical joint density of states tells us the number of states available for photons to interact with.
- It simultaneously takes care of states in valence band and conduction band.
- In all optical processors it is the joint density of states which are important.
- In electronic processors it deals with valence band and conduction band separately .

$$\rho(v) = \rho_c(E_2) = \frac{dE_2}{d\nu}$$

$$\begin{aligned} \text{Now } \rho_c(E_2) &= \frac{1}{2\pi^2} \left(\frac{2m_c}{h^2}\right)^{3/2} (E_2 - E_c)^{1/2} h \frac{m_r}{m_c} \times \frac{dE_2}{d\nu} \\ &= \frac{1}{\pi h^2} (2m_c)^{3/2} \frac{m_r}{m_c} \left(\frac{m_r}{m_c}\right)^{1/2} (h\nu - E_g)^{1/2} \\ \therefore \rho(v) &= \frac{1}{\pi h^2} (2m_r)^{3/2} (h\nu - E_g)^{1/2} \end{aligned}$$

is the final expression.

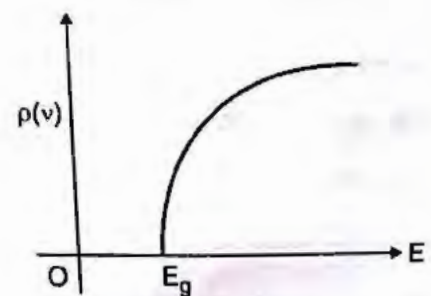


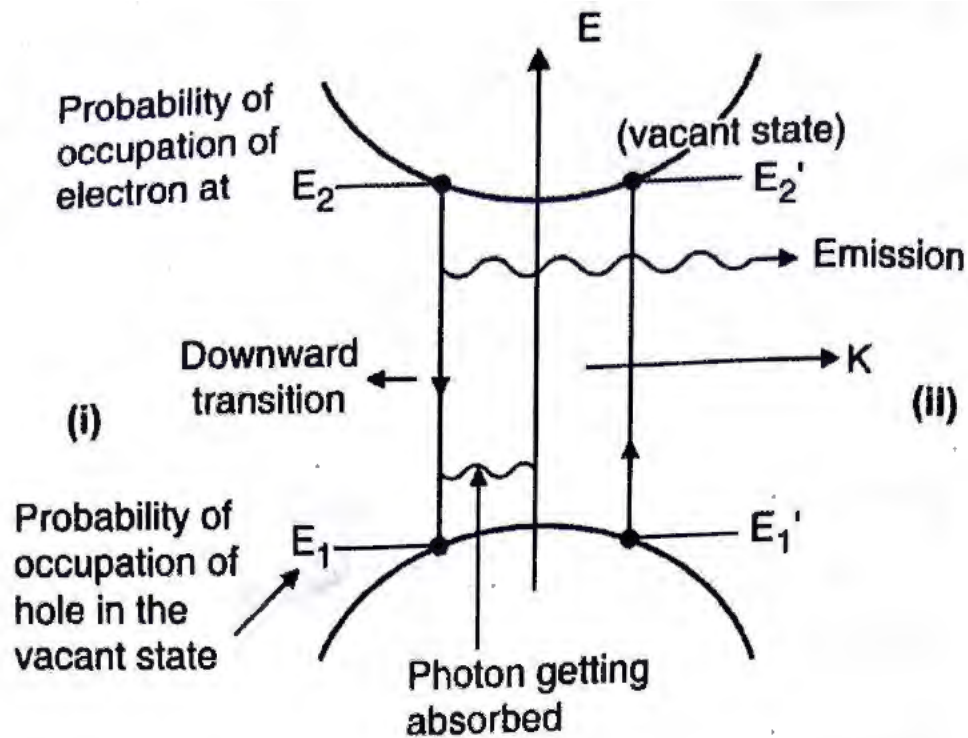
Fig. 3.7.4

- Now we will plot a graph (Fig. 3.7.4) of $\rho(v)$ versus E . In this graph when $h\nu > E_g$, it will provide interband transition. Next we will about intra band transition. Before we saw the mathematical expression of $\rho(v)$. This is important because next we will multiply with

the probability of emission and probability of absorption and we will gain an expression for gain co-efficient which will contain all these terms. So we need the above derivation.

- Optical joint density of states tells us the number of states available for photons to interact with.
- It simultaneously takes care of states in the valence band and conduction band.
- In all optical processors, it is the joint density of states which are important.
- In electronic processors, it deals with valence band and conduction band separately.
- Photon emission and absorption involves a state in the valence band and a state in the conduction band simultaneously.
- Therefore we need to take optical joint velocity of state simultaneously.
- Let us go to probability of emission and absorption.
- All the while E-k diagram was discussed. Everything can be seen by the E-k diagram. The normal band, energy band doesn't tell you anything.
- Let us consider direct band gap semiconductors and we are looking at vertical transition, other effects are not taken at this moment.
- For emission we need electron in E_2 which makes a downward transition and makes a hole in E_1 .
- Now what is the probability of emission? Probability of emission requires that the state E_2 is occupied by electron and state E_1 is a vacant state in the valence band which is the hole. Therefore probability of emission is a product of probability of occupation of electron and probability of occupation of hole.

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**Fig. 3.7.5 (i) direct band semiconductor
(ii) Vertical transition**

$$h\nu = E_2 - E_1$$

$$P_e = f(E_2) [1 - f(E_1)]$$

$$P_a = f(E_1') [1 - f(E_2')]$$

Where $f(E_1)$, $f(E_2)$ are fermi functions.

- If an electron, is sitting at E_1' and vacant state at E_2' then a photon can get absorbed.
- So the probability of occurrence of this process and probability of absorption is the probability of occupation.
- Let us see graphically Fig. 3.7.5 because the net probability will depend on which is greater.
- If probability of emission is greater than absorption then we will have net emission and vice versa.

Syllabus Topic : Transition Rates (Fermi Golden Rule)

3.7 FERMI'S GOLDEN RULE :

- In quantum physics, Fermi's golden rule is used to calculate the transition rate.
- A transition rate depends upon the strength of the coupling between the initial and final state of a system and upon the number of ways the transition can happen (i.e., the density of the final states).
- In many physical situations the transition probability is given by

$$\lambda_{if} = \frac{2\pi}{h} |M_{if}|^2 \rho_f \quad \dots (1)$$

where, λ_{if} = Transition probability

$|M_{if}|$ = Matrix element for the interaction

ρ_f = Density of final state

- The above equation is known as Fermi's golden rule.
- The transition probability λ is also called the decay probability and is related to the mean lifetime τ of the state by $\lambda = \frac{1}{\tau}$.
- The general form of Fermi's golden rule can apply to atomic transitions, nuclear decay, scattering ... a large variety of physical transitions.
- A transition will proceed more rapidly if the coupling between the initial and final states is stronger. This coupling term is traditionally called the "matrix element" for the transition: this term comes from an alternative formulation of quantum mechanics in terms of matrices rather than the differential equations of the Schrodinger approach.
- The matrix element can be placed in the form of an integral where the interaction which causes the transition is expressed as a potential V which operates on the initial state wave function.
- The transition probability is proportional to the square of the integral of this interaction over all of the space appropriate to the problem.

$$M_{if} = \int \psi_f^* \cdot V \cdot \psi_i \cdot dv \quad \dots (2)$$

where, V = Operator for the physical interaction which couples the initial and final state of the system.

ψ_f^* = Wave function for final state

ψ_i = Wave function for initial state

- The transition probability is also proportional to the density of final states ρ_f .

Syllabus Topic : Photovoltaic Effect

3.8 PHOTOVOLTAIC EFFECT :

- The effect due to which light energy is converted to electric energy in certain semiconductor materials is known as photovoltaic effect.
- "Photo" means light and "Voltaic" means voltage.

3.8.1 Photovoltaic Cell or Solar Cell :

Definition :

- The photovoltaic cell is the semiconductor device that converts the light into electrical energy.
- The voltage induced by the PV cell depends on the intensity of light incident on it. The name Photovoltaic is because of their voltage producing capability.
- The electrons of the semiconductor material are joined together by the covalent bond. The electromagnetic radiations are made of small energy particles called photons. When the photons are incident on the semiconductor material, then the electrons become energised and start emitting.
- The energised electron is known as the Photoelectrons. And the phenomenon of emission of electrons is known as the photoelectric effect.
- The working of the Photovoltaic cell depends on the photoelectric effect.

3.8.2 Construction of Photovoltaic Cell :

- The semiconductor materials like arsenide, indium, cadmium, silicon, selenium and gallium are used for making the PV cells. Mostly silicon and selenium are used for making the cell.
- Consider the figure below shows the constructions of the silicon photovoltaic cell.
- The upper surface of the cell is made of the thin layer of the p-type material so that the light can easily enter into the material. The metal rings are placed around p-type and n-type material which acts as their positive and negative output terminals respectively.

The output voltage and current obtained from the single unit of the cell is very less.

The magnitude of the output voltage is 0.6 V, and that of the current is 0.8 V. The different combinations of cells are used for increasing the output efficiency.

The solar module is constructed by connecting the single solar cells. And the combination of the solar modules together is known as the solar panel.

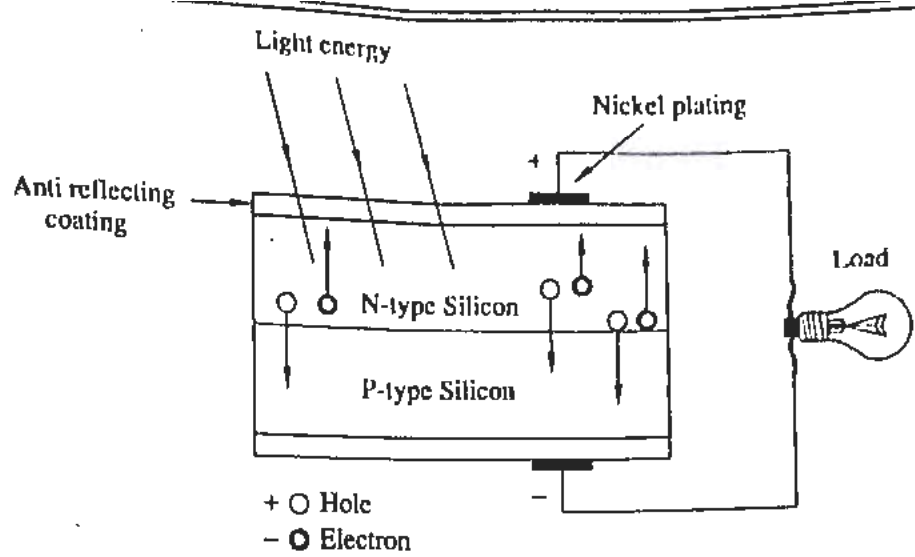


FIG. 3.7 : CONSTRUCTION OF PHOTOVOLATIC CELL

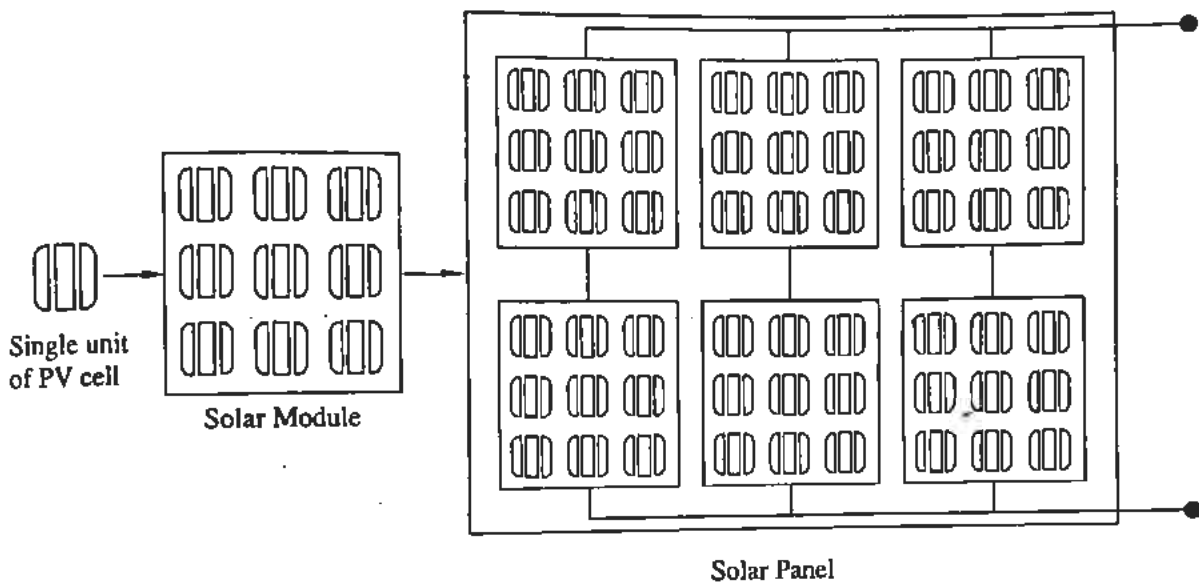


FIG. 3.8 : SOLAR CELL, SOLAR MODULE AND SOLAR PANEL

18.3 Working of PV Cell :

The light incident on the semiconductor material may be pass or reflected through it.

When the semiconductor material absorbs light, the electrons of the materials starts emitting.

This happens because the light consists small energise particles called photons.

When the electrons absorb the photons, they become energise and starts moving into the material.

Because of the effect of an electric field, the particles move only in the one direction and develops current. The semiconductor materials have the metallic electrodes through which the current goes out of it. Consider the figure below shows the PV cell made of silicon and the resistive load is connected across it.

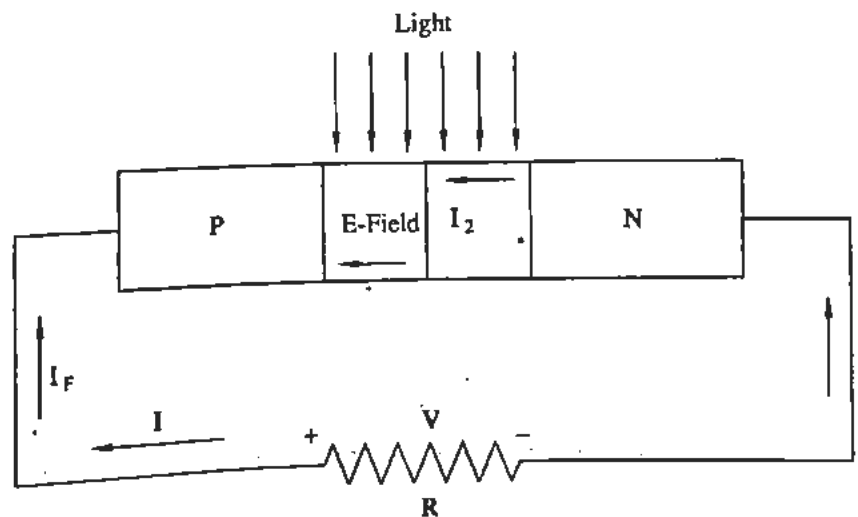


FIG. 3.9 : WORKING OF PV CELL

- The PV cell consists the P and N-type layer of semiconductor material. These layers are joined together to form the PN junction.
- The junction is the interface the p-type and n-type material. When the light fall on the junction the electrons starts moving from one region to another.

3.8.4 Advantages of Photo Voltaic Technology :

1. Its simple and solid state electronics device which converts directly solar energy into electricity.
2. They do not have any movable mechanical components.
3. The device can be operational without any maintenance for long time.
4. They can be made into modules and arrays suitable to load requirements of any system.
5. No special expertise and skills are required to operate the photo voltaic device.
6. Their reliability of working is quite high.
7. They are the power generators without any pollution of any kind. Hence they give green power.
8. Their applications are very wide ranging from small calculators and mobile devices to space, industries, homes and railways etc.

3.8.5 Disadvantages of Photo Voltaic Technology :

1. Solar cells can generate electricity only during day times. They do not give energy during night times.
2. Electrical energy storage devices like batteries are required when the sun rays are not available during night time or cloudy weather.
3. Efficiency of solar cell varies from 6% to 20% only.
4. The modules and solar panels require large area to install them to any system.

3.8.6 Applications of Solar Photo Voltaic (SPV) Technology :

1. The solar energy is most convenient forms of technology to harness for any small application to very large system like electrical power plants and space technology.

2. Where electrical power grid is not available in remote area, solar photo voltaic panels can supply electrical energy for domestic lighting, water pumps, TV, and mobile towers for communications purposes.
3. Solar Power is frequently used in consumer product applications like calculators and mobiles, which require small amounts of energy.
4. Solar cells are used recreation Vehicles (RVs).
5. Solar cells are also used boating and in battery recharging stations.
6. Large-scale desalination plants can also be PV powered. Larger off-grid systems using an array of PV modules and having more battery storage capacity.
7. Like conventional power plants, central power plants using only solar energy have been installed in the countries like Spain, Italy and U.S., Japan etc.
8. Central power plants using concentrating collectors and heliostats.
9. The unused areas required for installations of SPV modules are rooftops, sunshades, walls balcony and doors and panes used to fix solar panels in office, commercial and domestic buildings.

Syllabus Topic : Optical loss in Photovoltaic Cell

3.9 OPTICAL LOSSES :

- The working efficiency of solar cell is decreased because of following reasons :
 1. Mismatch the bandgap of the material with the solar spectrum.
 2. Reflection loss of light.
 3. Total spectrum of solar energy is not absorbed.
 4. Less intensity of light.
- There are a number of ways to reduce the optical losses :
 1. Top contact coverage of the cell surface can be minimised.
 2. Anti-reflection coatings can be used on the top surface of the cell.
 3. The solar cell can be made thicker to increase absorption.
 4. The optical path length in the solar cell may be increased by a combination of surface texturing and light trapping.

3.10 EXCITON :

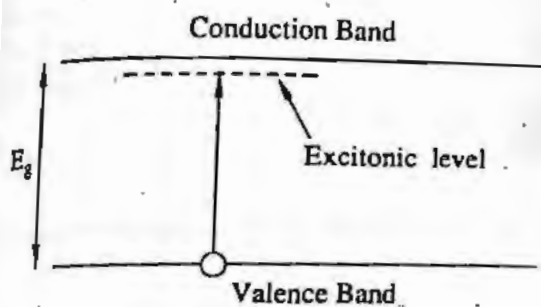
An exciton is a bound state of an electron and an electron hole which are attracted to each other by the electrostatic coulomb force.

The concept of excitons was first proposed by Yakov Frenkel in 1931, where he described the excitation of atom in a lattice insulators.

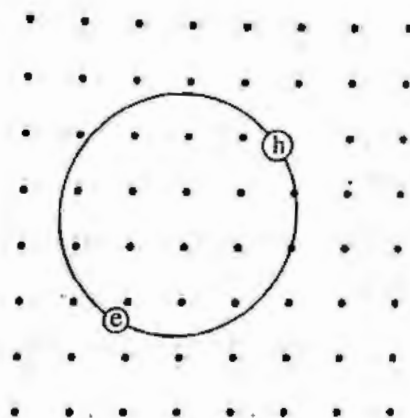
He proposed that this excited state would be able travel in a particle like fashion through the lattice without the net transfer of charge.

There are two types of exciton.

1. Frenkel exciton
2. Mott-Wannier exciton



(a) Energy level diagram for a typical semiconductor along with the excitation energy level



(b) Mott-Wannier exciton in typical lattice

FIG. 3.10



Yakov Frenkel

Yakov Frenkel (1894 – 1952)

He was a Soviet physicist and known for his works in the field of condensed matter physics. He contributed to semiconductor and insulator physics by proposing a theory, which is now commonly known as the Frenkel effect. In 1930 to 1931, Frenkel showed that neutral excitation of a crystal by light is possible, with an electron remaining bound to a hole created at a lattice site identified as a quasiparticle, the exciton.

YAKOV FRENKEL

- When electron hole separation is comparable to lattice constant then exciton is known as Frenkel exciton.
- When electron hole separation is much larger compared to lattice constant, the exciton is known as Mott-Wannier exciton. (Fig. 3.10(b))
- In first case electron-hole pair is tightly bound while in second case electron-hole pair is weakly bound.
- As energy related with the energy gap E_g decides the energy required to create a free electron in conduction band and free hole in valence band then energy gap is slightly greater than the energy of such an exciton. (as shown in Fig. 3.10(a))

Syllabus Topic : Drude Model

11 DRUDE MODEL :

The Drude model of electrical conduction was proposed in 1900 by Paul Drude to explain the transport properties of electrons in materials (especially metals).

The electron theory aims to explain the structure and properties of solids through their electronic structure.

These valence electrons form an electron gas surround the ion cores and are free to move anywhere within the metals.

3.11.1 Important Point of Drude Model :

1. In an atom, electrons revolve around the nucleus and a metal is composed of such atoms.
2. The valence electrons of atoms are free to move about the whole volume of the metals like the molecules of a perfect gas in a container. The collection of valence electrons from all the atoms in a given piece of metal forms electrons gas. It is free to move throughout the volume of the metal.
3. These free electrons move in random directions and collide with either positive ions fixed to the lattice or other free electrons. All the collisions are elastic i.e., there is no loss of energy.
4. The movements of free electrons obey the laws of the classical kinetic theory of gases.
5. The electron velocities in a metal obey the classical Maxwell – Boltzmann distribution of velocities.
6. The electrons move in a completely uniform potential field due to ions fixed in the lattice.
7. When an electric field is applied to the metal, the free electrons are accelerated in the direction opposite to the direction of applied electric field.



Paul Drude

Paul Karl Ludwig Drude (1863–1906)

He was a German physicist specializing in optics. He wrote a fundamental textbook integrating optics with Maxwell's theories of electromagnetism. He derived the relationships between the optical and electrical constants and the physical structure of substances. In 1900 he developed a powerful model to explain the thermal, electrical, and optical properties of matter. He explained the transport properties of electrons in materials (especially metals).

PAUL DRUDE

3.11.2 Applications of Drude Model :

1. DC electrical conductivity of metal :

$$V = IR ; E = \rho J$$

- Number of electrons with velocity v crossing area A in time dt is $n v A dt$; each has charge $-e$; current density is then

$$j = -nev \quad \dots (1)$$

- Electrons are moving randomly; so need to take average velocity for v . In equilibrium average velocity vanishes; no net electrical current.
- Apply electric field – an electron will have a velocity $v = v_0 - \frac{e \cdot E(t)}{m}$ (t is time since last collision; v_0 is the velocity it came out with after last collision and hence random).

$$\begin{aligned} \text{So, } v &= v_0 - \frac{e \cdot E(t)}{m} \\ &= - \frac{eE\tau}{m} \quad \dots (2) \end{aligned}$$

- Now, substitute the value of (v) from equation (2) in equation (1), we get

$$j = -nev$$

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

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

$$\left[\because \frac{J}{E} = \sigma \right]$$

- This is the dc conductivity in Drude model.
- Hall Effect and Magnetoresistance :**
- Current j_x ; magnetic field B_z Lorentz force $-ev \times B$; force same on $+Ve$ and $-Ve$ charges; hence they move on the same side; Hall voltage has different sign for the two types of carriers. Can measure two quantities :

(a) magnetoresistance : $\rho(H) = \frac{E_x}{j_x}$

(b) transverse (Hall) field E_y or Hall coefficient

$$R_H = \frac{E_y}{j_x B_z}$$

3. Calculate Hall Coefficient and Magneto-resistance :

Equations of motion with \mathbf{L}_s :

$$\frac{d\mathbf{p}}{dt} + \frac{\mathbf{p}(t)}{\tau} = -e \left(\mathbf{E} + \frac{\mathbf{p} \times \mathbf{B}}{m} \right)$$

In steady state current is time-independent and hence :

$$\frac{\mathbf{p}(t)}{\tau} = -e \left(\mathbf{E} + \frac{\mathbf{p} \times \mathbf{B}}{m} \right)$$

$$\therefore \frac{p_x}{\tau} = -eE_x - \frac{ep_y B}{m}$$

$$\therefore \frac{p_y}{\tau} = -ey_x - \frac{ep_x B}{m}$$

$$\therefore \sigma_0 E_x = j_x + \omega_c \tau j_y$$

$$\therefore \sigma_0 E_y = -\omega_c \tau j_x + j_y$$

$$\therefore \mathbf{E} = \frac{1}{\sigma_0} \begin{pmatrix} 1 & \omega_c \tau \\ -\omega_c \tau & 1 \end{pmatrix} \mathbf{j}$$

For Hall samples; $j_y = 0$;

$$\text{So, } R_H = \frac{E_y}{j_x B_z} = \boxed{-\frac{1}{ne}}$$

In reality, the carrier densities are not always given correctly by the Drude formula; +Ve sign was also not understood till Quantum mechanical theories came in.

Magnetoresistance is zero according to Drude since $j_x(H) = \sigma_0 E_x = j_x(H)$; not correct in real systems.

4. AC Electrical Conductivity of Metal :

Time dependent electrical field $E(t) = E_0 e^{-i\omega t}$; equation of motion is

$$\frac{d\mathbf{p}}{dt} = -\frac{\mathbf{p}(t)}{\tau} - e\mathbf{E}$$

Solution $\mathbf{p}(t) = p_0 e^{-i\omega t}$;

$$\therefore -i\omega p_0 = -\frac{p_0}{\tau} - eE_0$$

$$\therefore j = -\frac{nep}{m} = \frac{\sigma_0}{1 - i\omega\tau} E$$

$$\therefore \frac{J}{E} = \frac{\sigma_0}{1 - i\omega\tau}$$

$$\therefore \sigma(\omega) = \frac{\sigma}{1 - i\omega\tau}$$

The AC conductivity $\sigma(\omega) = \frac{\sigma_0}{1 - i\omega\tau}$.

EXERCISE

- Define following terms with respect to Light-semiconductor devices.
 - Absorption of radiation. (Refer Section-3.1)
 - Spontaneous emission. (Refer Section-3.2)
 - Stimulated Emission. (Refer Section-3.3)
 - Meta Stable State. (Refer Section-3.4)
- Write short notes on Density of state for photons. (Refer Section-3.6)
- Explain Fermi Golden rule for transition probability. (Refer Section-3.7)
- Explain photovoltaic effect in detail. (Refer Section-3.8)
- Explain the working solar cell with neat diagram. (Refer Section-3.8.1, 3.8.2 & 3.8.3)
- Discuss the advantages and disadvantages of photovoltaic technology and its application. (Refer Section-3.8.4, 3.8.5 & 3.8.6)
- Explain optical losses in photovoltaic cell. (Refer Section-3.9)
- Define and explain exciton. (Refer Section-3.10)
- Write short notes on Drude model. (Refer Section-3.11)
- Explain Drude model and discuss how it is used for D.C. and A.C. conductivity measurement. (Refer Section-3.11.2(1) & (4))
- Explain Drude model and discuss how it is used for Hall measurement and magnetoresistance. (Refer Section-3.11.2(2) & (3))

