SEMICONDUCTOR PHYSICS

STUDY MATERIAL

UNIT - 3 : LIGHT-SEMICONDUCTOR INTERACTION

BY:

DR. ARVIND SHARMA & DR. SANGEETA

ASSOCIATE PROFESSOR ASSISTANT PROFESSOR

DEPARTMENT OF APPLIED SCIENCES

CHANDIGARH ENGINEERING COLLEGE, LANDRAN

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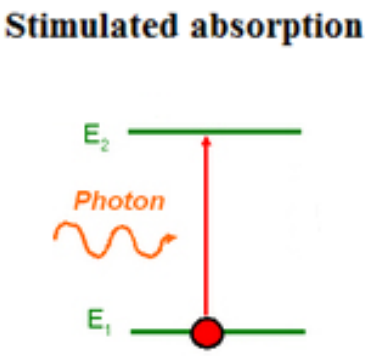
UNIT III – Light-Semiconductor Interaction

3.1 Absorption and Emission

The electron transition between two energy levels E_1 and E_2 is a simplified version of the electron transition between two energy bands (conduction band and valance band). There are three processes:

a) Stimulated Absorption:

Atoms will absorb one photon each and as a result, the electrons will undergo a transition from E1 to E2. The energy level diagram before and after the process is shown below:



The rate of stimulated absorption is defined as the number of atoms undergoing the process of stimulated absorption per unit time and is denoted by R_{sta}. Clearly, R_{sta} should be directly proportional to:

(i) The energy density u(v) of incident photons, defined as total photon energy per unit volume per unit frequency.

(ii) The number of atoms (or electrons) in energy state E_1 denoted by N_1. So,

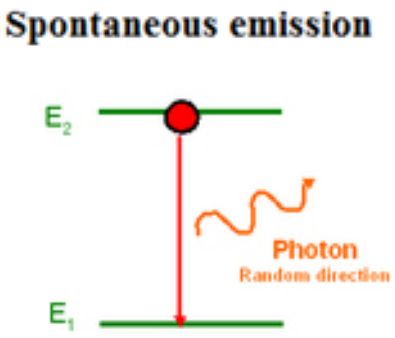
$$\text{i.e. } R_{sta} \propto N_1 u(v)$$

$$\text{or, } R_{sta} = B_{12} N_1 u(v) \qquad \textbf{(3.1)}$$

Where, B12 is Einstein coefficient for stimulated absorption, defined as probability for an electron (in state E_1) per unit time to undergo the process of stimulated absorption.

b) <u>Spontaneous Emission:</u>

In spontaneous emission, an electron in the higher energy state (i.e. E_2) stays in the state for a time equal to the life time of the state (i.e. approx. 10^{-8} s) and then falls back to the lower state (i.e. E_1) by itself spontaneously without the help of any external stimulus. This leads to a reduction in the electron energy from E_2 to E_1. The energy difference is emitted in the form of light i.e. photon and the energy of emitted photon is, $E = E_2 - E_1 = h\nu = hc/\lambda$, where ν and λ are frequency and wavelength of emitted photon. The process is shown in figure below:



Clearly the rate of spontaneous emission R_{spa} will depend only on the number of initial toms (or electrons) in the energy state E_2, denoted by N_2. So,

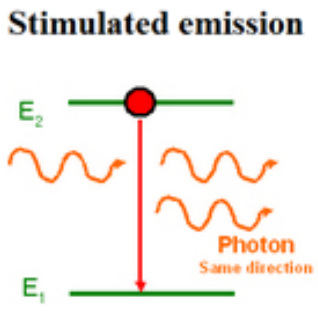
$$\text{i.e. } R_{spa} \propto N_2$$

$$\text{or, } R_{spa} = A_{21} N_2 \qquad \textbf{(3.2)}$$

Where, A_{21} is Einstein coefficient for spontaneous emission.

c) <u>Stimulated Emission:</u>

Unlike, spontaneous emission, the process of stimulated emission requires an external stimulus (in the form of an incident photon) to take place. The energy level diagram before and after the process is shown below:



In this process, an incident photon of energy, $E = h\nu = E_2 - E_1$, triggers a forcible transition of the electron in the higher state E_2 to the lower state E_1, leading to emission of another photon of the same energy (frequency), direction and phase as that of the triggering photon. Later, the energy loss of electron during its de-excitation is also not absorbed by the atom so that there are two photons at the output as compared to only one photon at the input. Therefore, in this process, a light amplification of light takes place. The emitted light is called stimulated emission and has entirely different characteristics as compared to light emitted in the process of spontaneous emission.

Clearly, the rate of stimulated emission will depends on

(i) Energy density u(v) of incident photons

(ii) Number of initial atoms (or electrons) in state (E_2) denoted by N_2

$$\text{i.e. } R_{ste} \propto N_2\, u(v)$$

$$\text{or, } R_{ste} = B_{21}\, N_2\, u(v) \qquad \textbf{(3.3)}$$

Where, B_{21} is Einstein coefficient for spontaneous emission.

3.2 Differentiation between Spontaneous and Stimulated Emission:

	Spontaneous Emission		Stimulated Emission
1	It does not require any external stimulus and occurs spontaneously.	1	It requires an external stimulus in the form of an incident photon of energy $E = h\nu = E_2 - E_1$.
2	Emission is in random direction.	2	Emission is unidirectional in the same direction of triggering photon.
3	It is not coherent.	3	It is monochromatic and highly coherent.
4	Its intensity is low.	4	Its intensity is very high.
5	This type of emission takes place in LEDs.	5	This type of emission takes place in semiconductor LASERs.

3.3 Units of Einstein Coefficients:

Units $[u(\nu)] = \frac{\text{Energy}}{\text{Volume} \times \text{frequency}} = \frac{\text{Energy} \times \text{time}}{\text{Volume}} = \frac{\text{J}.\,\text{s}}{\text{m}^3}$

Units $[R_{sta}, R_{spe}, R_{ste}] = \frac{\text{Number}}{\text{time}} = s^{-1}$

Now, $R_{sta} = B_{12} N_1 u(\nu)$

Or, $B_{12} = \frac{R_{sta}}{N_1 u(\nu)}$

Therefore, Units $[B_{12}] = \frac{s^{-1}m^3}{J\,s} = m^3 J^{-1} s^{-2}$

Similarly, Units $[B_{21}] = \frac{R_{ste}}{N_2 u(\nu)} = \frac{s^{-1}m^3}{J\,s} = m^3 J^{-1} s^{-2}$

And, Units $[A_{12}] = \frac{R_{spe}}{N_2} = s^{-1}$

3.4 Thermal Equilibrium and Population:

Thermal equilibrium means that the material has a uniform temperature throughout which is equal to the ambient temperature, so that no exchange of heat energy takes place between the material (of atoms) and its surroundings. At thermal equilibrium, the number of atoms (or electrons) in a given energy state of population of atoms (or electrons) in a given energy state E_i is given by Boltzmann distribution as,

$$N_i \propto \exp[-E_i/kT]$$

Here, E_i is the Energy of the i^{th} energy state, N_i is the number of atoms or electrons in the E_i energy state, T is the absolute temperature in Kelvin and K is the Boltzmann constant.

Therefore, $\frac{N_2}{N_1} = \frac{e^{-E_2/kT}}{e^{-E_1/kT}} = e^{-(E_2 - E_2)/kT} = e^{-h\nu/kT} = e^{-hc/\lambda kT}$ **(3.4)**

3.5 Relation between Einstein Coefficients:

At thermal equilibrium, the rate of absorption equal rate of emission, i.e.

$$R_{absorption} = R_{emission}$$

$$R_{sta} = R_{spe} + R_{ste}$$

$$\mathrm{B_{12}\,N_1 u(v)} = A_{21}N_2 + B_{21}N_2u(\nu)$$

Dividing both sides by '$B_{21}N_2$', we get,

$$\frac{\mathrm{B_{12}\,N_1 u(v)}}{B_{21}N_2} = \frac{A_{21}N_2}{B_{21}N_2} + \frac{B_{21}N_2u(\nu)}{B_{21}N_2}$$

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

$$\mathrm{u(v)}\left[\frac{\mathrm{B_{12}}}{B_{21}}\frac{\mathrm{N_1}}{N_2} - 1\right] = \frac{A_{21}}{B_{21}}$$

Since, $\frac{N_1}{N_2} = e^{h\nu/kT}$, therefore using equation (3.4), we get,

$$\mathrm{u(v)}\left[\frac{\mathrm{B_{12}}}{B_{21}}e^{\frac{h\nu}{kT}} - 1\right] = \frac{A_{21}}{B_{21}}$$

$$\mathrm{u(v)} = \frac{\frac{A_{21}}{B_{21}}}{\left[\frac{\mathrm{B_{12}}}{B_{21}}e^{\frac{h\nu}{kT}} - 1\right]} \qquad \textbf{(3.5)}$$

The above equation is to be compared with the energy density of black body radiation given by,

$$u(v) = \frac{\frac{8\pi h\nu^3}{c^3}}{\left[e^{\frac{h\nu}{kT}}-1\right]} \qquad \textbf{(3.6)}$$

On comparing equation (3.5) and (3.6), we get,

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \qquad \text{and} \qquad \frac{B_{12}}{B_{21}} = 1$$

It implies that the probability for stimulated absorption between two states E_1 and E_2 equals to the probability for stimulated emission between them, i.e., $B_{12} = B_{21}$. Likewise, the probability for spontaneous emission between them if $\frac{E_2-E_1}{h} = \nu$, is very large and vice versa.

3.6 Population Inversion:

LASER stands for Light Amplification by Stimulated Emission of Radiation. At thermal equilibrium and in the absence of any incident radiation, most of the atoms (or electrons) in the material are present in the lower energy state i.e. E_1 and $N_1 >> N_2$. We also observe that

$$\frac{R_{ste}}{R_{spe}} = \frac{B_{21}}{A_{21}}u(v)$$

Therefore, to enhance the stimulated emission over spontaneous emission, one must have a large value of $u(v)$ or incident photon energy density. Also, we observe that,

$$\frac{R_{ste}}{R_{sta}} = \frac{B_{21}N_2}{A_{21}N_1} = \frac{N_2}{N_1} \qquad \textbf{(3.7)}$$

Hence, if the stimulated emission is to dominate over the stimulated absorption, $N_2 > N_1$ is required. Which mean a higher electron density in the upper energy level is required than the lower energy level. This condition is called *population inversion*, since under thermal equilibrium, the reverse is true. Therefore, population inversion is the necessary condition for LASER action. All practical LASERs use large values of $u(v)$ to achieve population inversion so that the rate of stimulated emission becomes dominant over both stimulated

absorption as well as spontaneous emission. To achieve a high level of $u(v)$ an optical resonant cavity is used to increase the photons inside a LASER.

3.7 Absorption/Emission in Semiconductor:

Electron excitation from the valence to the conduction band may be induced by the absorption of a photon of appropriate energy *($hv > E_g$).* An electron-hole pair is generated [Fig. 1 (a)]. This adds to the concentration of mobile charge carriers and increases the conductivity of the material. The material behaves as a photoconductor with conductivity proportional to the photon flux. This effect is used to detect light.

Electron de-excitation from the conduction to the valence band (electron-hole recombination) may result in the spontaneous emission of a photon of energy $hv > E_g$ [Fig. 1 (b)], or in the stimulated emission of a photon, provided that photon of energy $hv > E_g$ is present [Fig. 1 (c)]. Spontaneous emission is the underlying phenomenon on which the light-emitting diode is based. Stimulated emission is responsible for the operation of semiconductor amplifiers and laser.

Figure 1(a) represents the absorption of a photon results in the generation of an electron-hole pair. This process is used in the photo-detection of light. Figure 1(b) represents the recombination of an electron-hole pair results in the spontaneous emission of a photon. Light-emitting diodes (LEDs) operate on this basis. Figure 1(c) represents electron-hole recombination can be stimulated by a photon. The result is the induced emission of an identical photon. This is the underlying process responsible for the operation of semiconductor injection lasers.

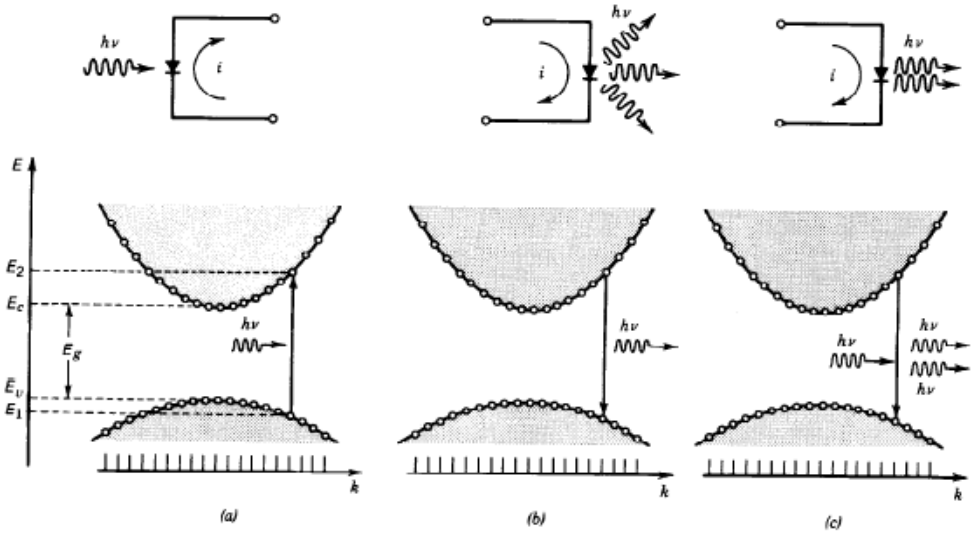


Figure 1: *(a)* The absorption of a photon, *(b)* The recombination of an electron-hole pair and (c) Electron-hole recombination can be stimulated by a photon.

3.8 Photon Transition in Bulk Semiconductors:

Several mechanisms can lead to the absorption and emission of photons in a semiconductor. The most important of these are:

(a)Band-to-Band (Inter band) Transitions:

An absorbed photon can result in an electron in the valence band making an upward transition to the conduction band, thereby creating an electron-hole pair [Fig. 2(a)]. Electron-hole recombination can result in the emission of a photon. Band-to-band transitions may be assisted by one or more phonons. A phonon is a quantum of the lattice vibrations that results from the thermal vibrations of the atoms in the material. Direct band-to-band absorption and emission can take place only at frequencies for which the photon energy hv > E_g . The minimum frequency v necessary for this to occur is $v_g = E_g / h$, so that the corresponding maximum wavelength is $\lambda_g = c/v_g = hc/E_g$. If the band gap energy is given in eV (rather

than joules), the band gap wavelength $\lambda_g = hc/eE_g$ in μ.m is given by

$$\lambda_g = \frac{1.24}{E_g}$$

The quantity λ_g is called the bandgap wavelength (or the cutoff wavelength).

(a) Impurity-to-Band Transitions:

An absorbed photon can result in a transition between a donor (or acceptor) level and a band in a doped semiconductor. In a p-type material, for example, a low-energy photon can lift an electron from the valence band to the acceptor level, where it becomes trapped by an acceptor atom [Fig. 2(b)]. A hole is created in the valence band and the acceptor atom is ionized. Or a hole may be trapped by an ionized acceptor atom; the result is that the electron decays from its acceptor level to recombine with the hole. The energy may be released radiatively (in the form of an emitted photon) or non-radiatively (in the form of phonons). The transition may also be assisted by traps in defect states, as illustrated in Fig.3.

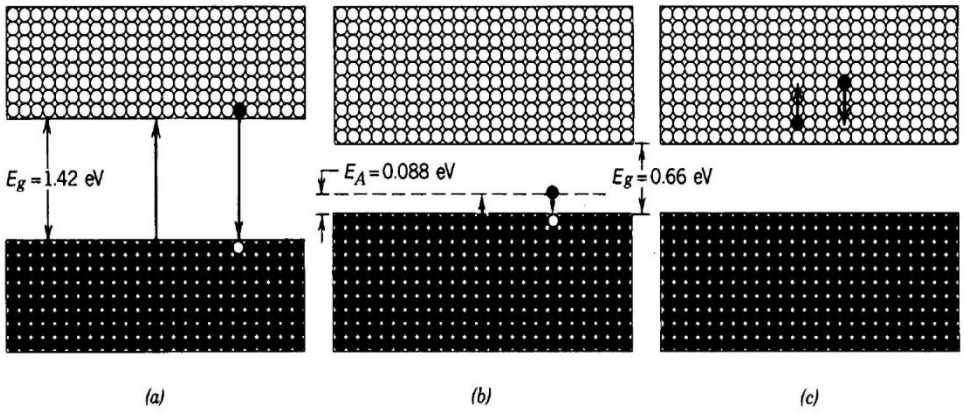


Figure 2: Examples of absorption and emission of photons in a semiconductor. (a) Band-to-band transitions in GaAs can result in the absorption or emission of photons of wavelength (b) The absorption of a photon results in a valence-band to acceptor-level transition (c) A free-carrier transition within the conduction band.

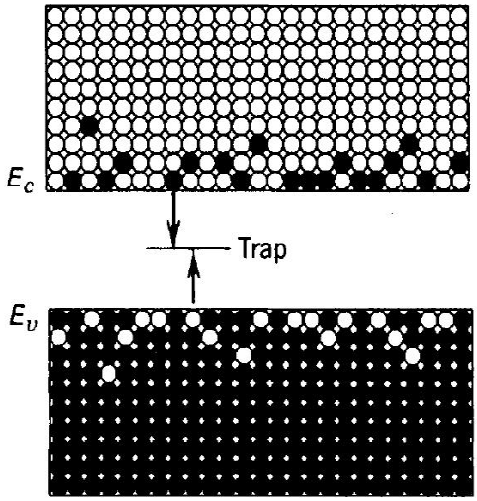


Figure 3: Electron-hole recombination via a trap

(b) Free-Carrier (Intra band) Transitions:

An absorbed photon can impart its energy to an electron in a given band, causing it to move higher within that band. An electron in the conduction band, for example, can absorb a photon and move to a higher energy level within the conduction band [Fig. l (c)]. This is followed by thermalization, a process whereby the electron relaxes down to the bottom of the conduction band while releasing its energy in the form of lattice vibrations.

(c) Phonon Transitions:

Long-wavelength photons can release their energy by directly exciting lattice vibrations, i.e., by creating phonons.

(d) Excitonic Transitions:

The absorption of a photon can result in the formation of an electron and a hole at some distance from each other but which are nevertheless bound together by their mutual Coulomb interaction. An electron in the vicinity of a hole need not annihilate itself by recombination. It can occupy any one of the higher energy levels available to it in the acceptor atom and bind itself with the hole and behaves much like a hydrogen atom. The energy of formation of the exciton is less than the bandgap energy. So, its

energy levels lie in the band gap. This means that the excitons can be produced by incident photons having energy less than the band gap energy.

The excitons are neutral and so they do not give rise to electrical conductivity. Therefore, low energy photons absorbed by the excitons do not give rise to photoconductivity.

3.9 Condition for Absorption and Emission:

(a) Conservation of Energy:

The absorption or emission of a photon of energy hv requires that the energies of the two states involved in the interaction (E_1 and E_2 in the valence band and conduction band, respectively) be separated by hv. Thus, for photon emission to occur by electron-hole recombination, for example, an electron occupying an energy level E_2 must interact with a hole occupying an energy level E_1, such that energy is conserved, i.e.,

$$E_2 - E_1 = hv$$

(b) Conservation of Momentum:

Momentum must also be conserved in the process of photon emission/absorption, so that $p_2 \approx p_1 = \text{hv/c} = h/\lambda$, or $k_2 - k_1 = 2\pi/\lambda$. The photon-momentum magnitude h/λ is, however, very small in comparison with the range of values that electrons and holes can assume. The semicon-ductor E-k diagram extends to values of k of the order $2\pi/a$, where the lattice constant a is much smaller than the wavelength A, so that $2\pi/\lambda \ll 2\pi/a$. The momenta of the electron and the hole involved in interaction with the photon are therefore roughly equal. This condition $k_2 \approx k_1$ is called the k-selection rule.

3.10 Energies and Momenta of Charge Carriers:

The conservation of energy and momentum require that a photon of frequency *v* interact with electrons and holes of specific energies and momentum determined by the semiconductor *E-k* relation. Since the energy bands are parabolic near the band edges,

$$E_1 = E_V - \frac{\hbar^2 k^2}{2m_h^*} \tag{3.8}$$

$$E_2 = E_C + \frac{\hbar^2 k^2}{2m_e^*} \tag{3.9}$$

Where, $k_2 - k_1 = k$ and m_h^* = effective mass of hole in the valance band and m_e^* = effective mass of electron in the conduction band. Therefore,

$$E_2 - E_1 = \left[E_C + \frac{\hbar^2 k^2}{2m_e^*}\right] + \left[E_V - \frac{\hbar^2 k^2}{2m_h^*}\right] = \left(E_C - E_V\right) + \frac{\hbar^2 k^2}{2m_r}$$

Where,

$$\frac{1}{m_r} = \frac{1}{m_e^*} + \frac{1}{m_h^*}$$

So,

$$E_2 - E_1 = E_g + \frac{\hbar^2 k^2}{2m_r} = h\nu$$

Or,

$$k = \frac{\left(2m_r\right)^{1/2}}{\hbar}\sqrt{h\nu - E_g} \tag{3.10}$$

Or,

$$p = \hbar k = \left(2m_r\right)^{1/2}\sqrt{h\nu - E_g}$$

Putting (3.10) in (3.9) and (3.8), we get

$$E_2 = E_C + \frac{m_r}{m_e^*}\left(h\nu - E_g\right)$$

And

$$E_1 = E_V - \frac{m_r}{m_h^*}\left(h\nu - E_g\right) = E_2 - h\nu$$

If $m_e^* = m_h^* = m$ and $\frac{1}{m_r} = \frac{2}{m}$ or $m_r = \frac{m}{2}$ so that

$$E_2 - E_1 = \left[E_C + \frac{1}{2}\left(h\nu - E_g\right)\right] - \left[E_V - \frac{1}{2}\left(h\nu - E_g\right)\right] = E_g + h\nu - E_g = h\nu$$

3.11 Density of States

We already know that the density of energy states in the conduction band is given by

$$D(E_2) = 4\pi\left(\frac{2m_e^*}{h^2}\right)^{3/2}(E_2 - E_C)^{1/2} \qquad \textbf{(3.11)}$$

and

$$E_2 = E_C + \frac{m_r}{m_e^*}\left(h\nu - E_g\right)$$

i.e.

$$E_2 - E_C = \frac{m_r}{m_e^*}\left(h\nu - E_g\right) \qquad \textbf{(3.12)}$$

Substituting (3.12) in (3.11), we get

$$D(E_2) = 4\pi\left(\frac{2m_e^*}{h^2}\right)^{3/2}\left(\frac{m_r}{m_e^*}\right)^{1/2}\sqrt{h\nu - E_g} \qquad \textbf{(3.13)}$$

3.12 Optical Joint Density of States:

We now determine the density of states $D(\nu)$ with which a photon of energy $h\nu$ interacts under conditions of energy and momentum conservation in a direct-gap semiconductor. This quantity incorporates the density of states in both the conduction and valence bands and is called the optical joint density of states. The one-to-one correspondence between E_2 and ν, permits us to relate density of states of photons $D(\nu)$ to

the density of states $D(E_2)$[or $D(E_1)$] in the conduction band [or valance band] by use of the incremental relation,

$$D(E_2)\,dE_2 = D(v)\,dv = -D(E_1)\,dE_1$$

Because as many photons are emitted as the number of electrons (or holes) leave (or enter) the conduction band (or valance band) leading to an electron-hole recombination. So,

$$D(v) = \frac{dE_2}{dv} D(E_2)$$

Using equations (3.12) and (3.13), we get

$$D(v) = \left(\frac{m_r h}{m_e^*}\right) 4\pi \left(\frac{2m_e^*}{h^2}\right)^{3/2} \left(\frac{m_r}{m_e^*}\right) \sqrt{hv - E_g}$$

$$D(v) = \frac{4\pi}{h^2} (2m_r)^{3/2} \sqrt{hv - E_g}$$

Or

$$D(v) = \frac{(2m_r)^{3/2}}{\pi\hbar^2} \sqrt{hv - E_g} \qquad \left(\because \hbar = \frac{h}{2\pi}\right)$$

For $h\nu > E_g$, plot between D(v)and energy is illustrated in Figure 4 below:

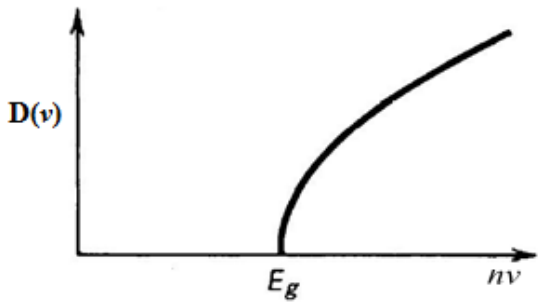


Figure 4: The density of states with which a photon of energy *hv* interacts increases with $hv - E_g$ in accordance with a square-root law.

3.13 Photon Emission Is Unlikely in an Indirect Band Gap Semiconductor:

Radiative electron-hole recombination is unlikely in an indirect-gap semiconductor. This is because transitions from near the bottom of the conduction band to near the top of the valence band (where electrons and holes, respectively, are most likely to reside) requires an exchange of momentum that cannot be accommodated by the emitted photon. Momentum may be conserved, however, by the participation of phonons in the interaction. Phonons can carry relatively large momenta but typically have small energies so their transitions appear horizontal on the E-k diagram (see Fig. 5). The net result is that momentum is conserved, but the k-selection rule is violated. Because phonon-assisted emission involves the participation of three bodies (electron, photon, and phonon), the probability of their occurrence is quite low. Thus Si, which is an indirect-gap semiconductor, has a substantially lower radiative recombination rate than does GaAs, which is a direct-gap semiconductor. Si is therefore not an efficient light emitter, whereas GaAs is.

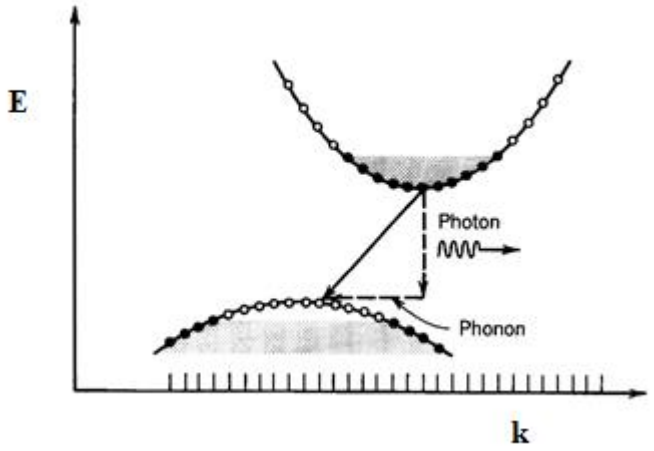


Figure 5: Photon emission in an indirect-gap semiconductor.

The recombination of an electron near the bottom of the conduction band with a hole near the top of the valence band requires the exchange of energy and momentum. The energy may be carried off by a photon, but one or more phonons are required to conserve momentum. This type of multi-particle interaction is unlikely.

3.14 Photon Absorption is Not Unlikely in an Indirect Band Gap Semiconductor:

Although photon absorption also requires energy and momentum conservation in an indirect-gap semiconductor, this is readily achieved by means of a two-step process (Fig. 6). The electron is first excited to a high energy level within the conduction band by a vertical transition. It then quickly relaxes to the bottom of the conduction band by a process called **thermalization** in which its momentum is transferred to phonons. The generated hole behaves similarly. Since the process occurs sequentially, it does not require the simultaneous presence of three bodies and is thus not unlikely. Si is therefore an efficient photon detector, as is GaAs.

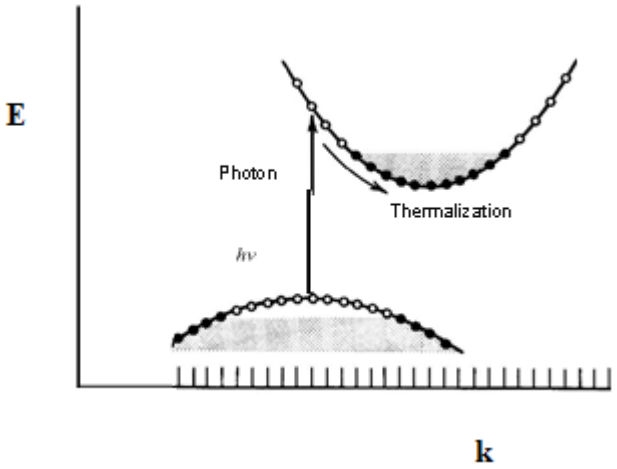


Figure 6: Photon absorption in an indirect-gap semiconductor.

The photon generates an excited electron and a hole by a vertical transition; the carriers then undergo fast transitions to the bottom of the conduction band and top of the valence band, respectively, releasing their energy in the form of phonons. Since the process is sequential it is not unlikely.

3.15 Optical Absorption:

Assume that a semiconductor is illuminated from a light source with hv>E_g and a photon of intensity I_0 (energy per unit area per unit time). As the photons travel through the semiconductor, a fraction of the photons absorbed is proportional to the intensity of photons, i.e.

$$-dI = \alpha I dx$$

where α is proportionality constant and is known as absorption coefficient.

$$\int_{I_0}^{I} \frac{dI}{I} = -\int_{0}^{x} \alpha dx$$

or

$$\ln\left(\frac{I}{I_0}\right) = -\alpha x$$

or

$$I(x) = -I_0 e^{-\alpha x}$$

where the negative sign indicates a decreasing photon intensity with distance due to absorption. If the width of the semiconductor is W, then

$$I_W = I_0 e^{-\alpha W}$$

So, that the intensity absorbed will be

$$I_{absorbed} = I_0 - I_W = I_0(1 - e^{-\alpha W}).$$

If ϕ = photon flux= Number of photons per second, then

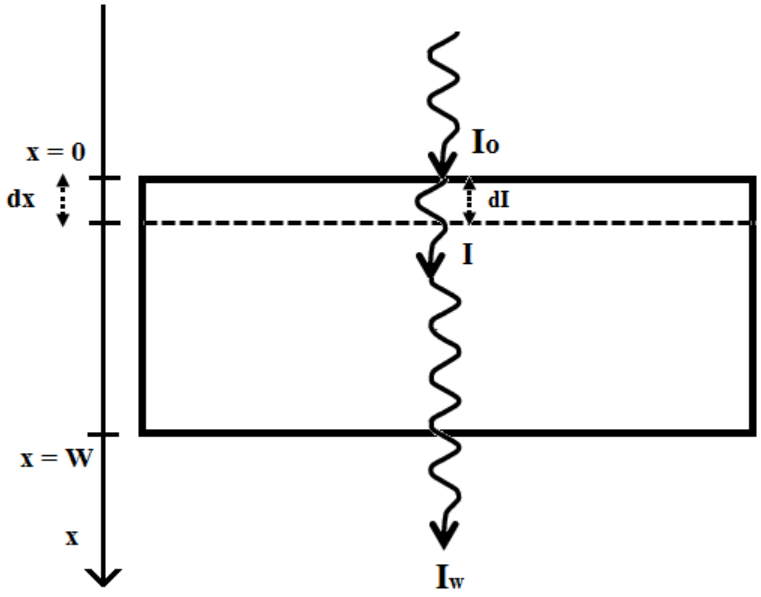
$$\frac{IWA}{h\nu} = \phi$$

and W= width of material and A= area of illumination.

$$\phi_{absorbed} = P_0(1-e^{-\alpha W}) = \text{Photon flux absorbed}$$

and Power absorbed will be

$$P_{absorbed} = h\nu\phi_0(1-e^{-\alpha W}) = P_0(1-e^{-\alpha W})$$



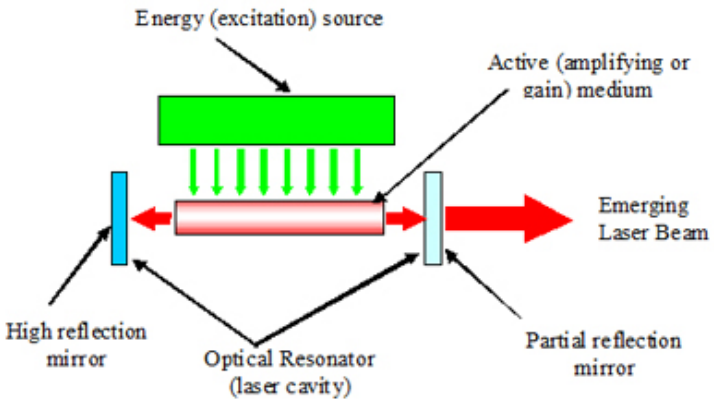
3.16 Semiconductor LASER:

(a) LASER components:

LASER device consist of three basic or essential components:

1. LASER medium (or Active medium): It is the material in which the LASER action is made to take place.
2. Energy source (or Pump): It is an essential source of energy that excites the electrons of the active medium to higher energy states and lead to the situation of population inversion.
3. Resonant cavity (or Resonator): It consists of a pair of plane or spherical mirrors having a common principle axis. The cavity between the mirrors is filled with the active

medium. Pumping by the energy source causes population inversion in the active medium. Initially, spontaneous photons are emitted in all directions. Photons travelling along the principle axis of the mirrors get trapped within the resonant cavity due to multiple to and fro reflections from the mirrors. In this process, the number of photons multiplied or amplified due to stimulated emission and LASER light is produced. One of the mirrors is totally reflecting while the other is partially reflecting and partially transmitting. The second mirror enables the LASER light in the active medium inside the cavity to escape out of the cavity.



LASER components

When the laser active medium is excited with an optical pumping, its atoms absorb the optical energy and the electrons move from "ground state" energy level to a high energy "excited state". This electron can randomly return to its low energy "ground" state level by releasing a photon of light (spontaneous emission). When an electron is still in the excited high energy state, and another photon passes nearby, it can cause the excited atom to emit a photon of the same frequency, in the same direction and in phase with the incoming photon (stimulated emission). When the external excitation is sufficient so that the majority of atoms are in the excited state, any photon emitted within the active medium will stimulate other excited atoms to emit. The laser cavity serves the purpose of bouncing back and forth only those photons that propagate along the cavity axis. This

creates a sustained avalanche-like process, which allows a laser beam to be generated through the partially reflecting mirror.

(b) Principle/Construction/Working of Semiconductor Laser:

Principle:

LASER (light amplification by stimulated emission of radiation) is a source of highly monochromatic, coherent and directional light. It operates under the principle of stimulated emission condition. The function of a laser diode is to convert electrical energy into light energy. The population inversion is the necessary condition for LASER operation.

Construction: Typical fabrication process of semiconductor LASER is as follows:

i) Firstly, highly doped n-type GaAs (Gallium Arsenide) is taken. This will serve as ohmic contact between metal and semiconductor for negative terminal of the battery.

ii) A layer of n-type AlGaAs (Aluminium Gallium Arsenide) is coated. This will serve as n-type semiconductor of p-n junction.

iii) After this, a layer of p-type GaAs (Gallium Arsenide) is coated on it. This layer will serve as active medium of LASER and in the medium LASER action will occur.

iv) A layer of p-type AlGaAs (Aluminium Gallium Arsenide) is coated on it. This will serve as p-type semiconductor of p-n junction.

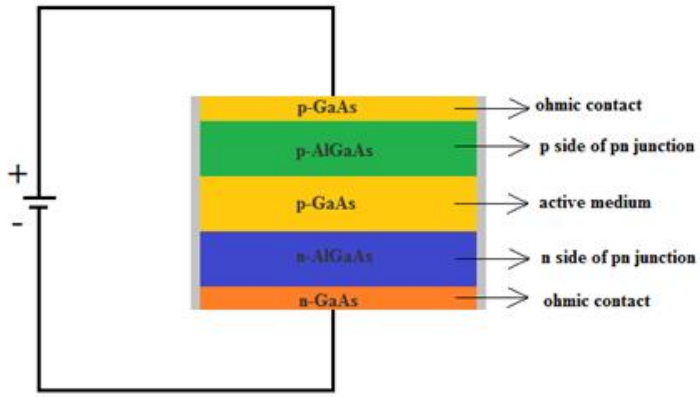


Figure 1: Double heterojunction LASER structure.

v) Finally, a layer of highly doped p-type GaAs (Gallium Arsenide) is coated on the top of all. This will serve as ohmic contact between metal and semiconductor for positive terminal of the battery.

vi) A resonant cavity is provided by polishing the opposite phases of the junction.

vii) The process of pumping occurs by passing the electric current from an ordinary source.

Working:

In semiconductor LASER fabricated as above and shown in figure 1, the semiconductor materials are AlGaAs with band gap of 2 eV and GaAs with band gap of 1.4 eV. The p-type GaAs region is a thin layer typically around 0.1-0.2 μm. This layer constitutes the active in which stimulated emission take place.

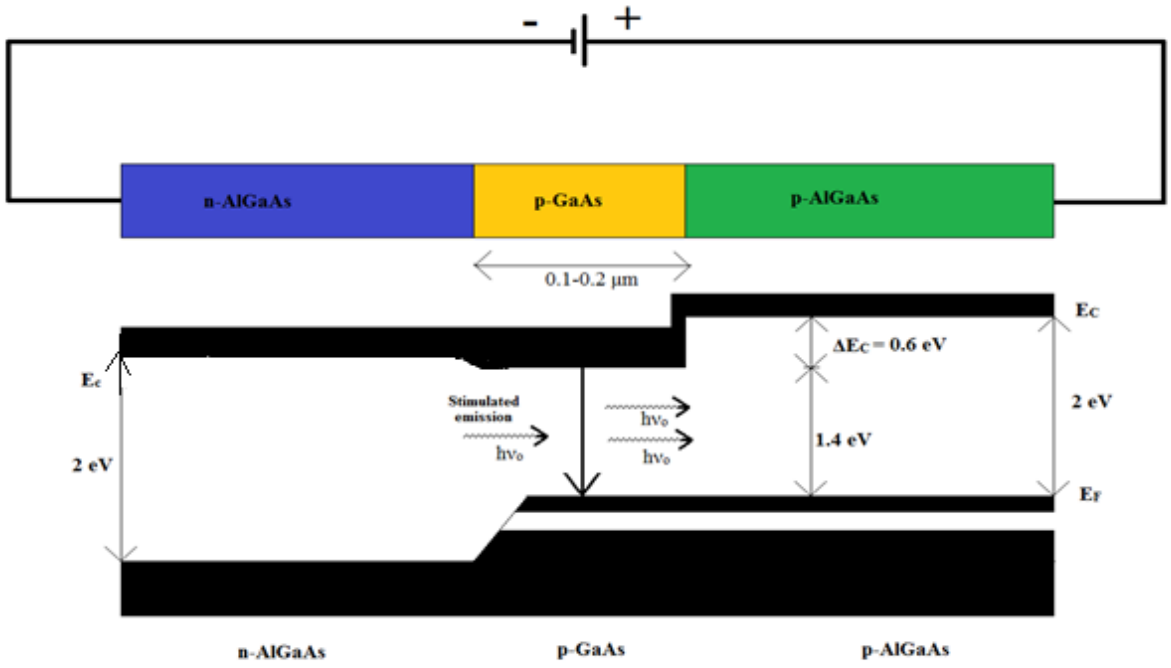


Figure 2: Energy level diagram of semiconductor LASER

Both p-type GaAs and p-type AlGaAs are heavily p-type doped and are regenerated with the Fermi level E_{FP} in the valance band. When the sufficiently large forward bias is

applied, E_C of n-AlGaAs moves very close to the E_C of p-GaAs which leads to large injection of electrons in the conduction band of n-AlGaAs into p-GaAs as shown in figure 2. In fact, with sufficiently large forward bias, there is an enormous amount of electron injection from n-AlGaAs into conduction band of the p-GaAs. These injected electrons however, are confined to conduction band of the p-GaAs, since; there is a barrier ΔE_C between p-GaAs and p-AlGaAs due to change in band gap.

The p-GaAs layer is degenerately doped. Thus, the top of valance band is full of holes and it has all the electronic states empty above the Fermi level E_{FP} in this layer. The large forward bias injects a very large concentration of electrons from n-AlGaAs into the conduction band of p-GaAs.

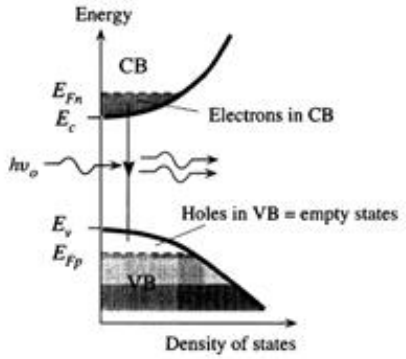


Figure 3: Density of states versus Energy.

Consequently, as shown in figure 3, there is a large concentration of electrons in conduction band and totally empty space at the top of valance band. This means that, there is a population inversion. An incoming photon with energy $h\nu_o$ (just above the E_g) can stimulate an conduction electron in the p-GaAs layer to fall from conduction band to valance band and emit a photon by stimulated emission as depicted in figure 3. Such a transition is a photon stimulated electron hole recombination or a lasing recombination. Thus, an avalanche of stimulated emission in the active layer provides an optical amplification of photons with energy $h\nu_o$ in this layer. The amplification depends on the

extent of population inversion and hence on the diode forward current. By modifying the composition of the active layer, it is possible to control the wavelength of lasing emission from 652 to 900 nm.

Advantages:

i) Efficiency of GaAs LASER can be as high as 40%.

ii) The output frequency is highly stable.

iii) They are compact in size.

iv) Price is less.

v) The spectral frequency of the LASER can be controlled by changing the doping level of forward bias potential.

Applications of Laser Diode:

i) Laser Diode Modules are ideal for applications such as life science, industrial, or scientific instrumentation. Laser Diode Modules are available in a wide variety of wavelengths, output powers, or beam shapes.

ii) Low power Lasers are used in an increasing number of familiar applications including CD and DVD players and recorders, bar code readers, security systems, optical communications and surgical instruments

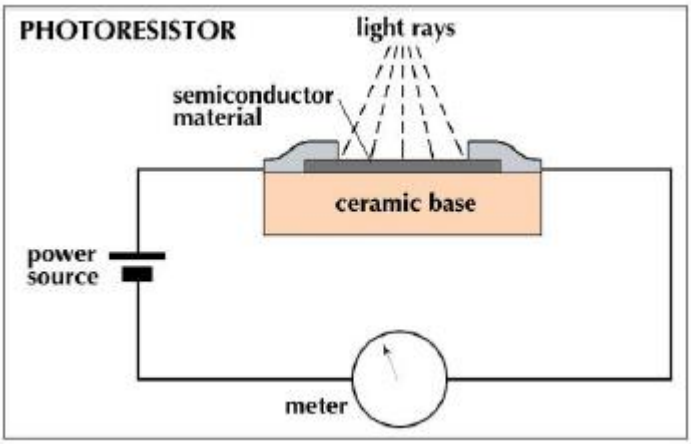
iii) Industrial applications: Engraving, cutting, scribing, drilling, welding, etc. Medical applications remove unwanted tissues, diagnostics of cancer cells using fluorescence, dental medication. In general, the results using lasers are better than the results using a surgical knife.

iv) Telecom: In the telecom field 1.3 μm and 1.55 μm band laser diodes used as the main light source for silica fibre lasers have a less transmission loss in the band. The laser diode with the different band is used for pumping source for optical amplification or for the short-distance optical link.

v) Semiconductor LASER is also used in high speed laser printer.

3.17 Photoconductivity

Photoconductivity is an optical and electrical phenomenon in which a material becomes more electrically conductive due to the absorption of electromagnetic radiation such as visible light, ultraviolet light, infrared light, or gamma radiations. It is the effect of increasing electrical conductivity Φ in a solid due to light absorption. When the so-called internal photo effect takes place, the energy absorbed enables the transition of activator electrons into the conduction band and the charge exchange of traps with holes being created in the valence band. In the process, the number of charge carriers in the crystal lattice increases and as a result, the conductivity is enhanced. When light is absorbed by a material such as a semiconductor, the number of free electrons and electron holes changes and raises its electrical conductivity. To cause excitation, the light that strikes the semiconductor must have enough energy to raise electrons across the band gap. When a photoconductive material is connected as part of a circuit, it functions as a resistor whose resistance depends on the light intensity. In this context the material is called a photo resistor. Fig.1 depicts the current flow in a photo resistor when exposed to light rays.



Semiconductor resistors that depend on the irradiance (photoconductive cells) are based on this principle. They have opened up a wide field of applications and are, among other

things, employed in twilight switches and light meters. The semiconductor materials most commonly used are cadmium compounds, particularly CdS. The photocurrent is studied as a function of the voltage applied to the photo resistor at a constant irradiance (current-voltage characteristics) and as a function of the irradiance at a constant voltage (current-irradiance characteristics).

- **Photovoltaic Effect:**

The photovoltaic effect is the generation of a voltage (or electric current) due to optical excitation when a semiconductor is illuminated at the electrodes or at internal barriers or PN-junction. Two possibilities exists when a semiconductor body containing a PN-junction is exposed to optical illumination:

1) When one ohmic contact is on the p-region and the second is on the n-region of the body.
2) When both contacts are on same type of material.

The first one is called transverse photovoltaic effect and second is called lateral photovoltaic effect. The transverse effect is used in solar energy converters, photodiodes, radiation detection, tracking detection etc. The lateral photovoltaic effect is used commonly for radiation tracking transducers.

3.18 Fermi Golden Rule

In quantum mechanics, Fermi Golden Rule is a formula that describes the transition rate from one energy state into another energy state. In general, the transition rate (or the transition probability per unit time) depends on

(i) The strength of the coupling between the initial state and the final state and on

(ii) The number of ways the transition can happen i.e. the density of final states.

The transition probability per unit time has the form

$$\lambda_{if} = \frac{2\pi}{\hbar}\left|M_{if}\right|^2 \rho_f$$

where λ_{if} represents transition probability per unit time (i.e. transition rate),

M_{if} represents the coupling term between initial and final states

ρ_f represents the density of final states

The transition rate will be high i.e. the transition will occur 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 and is given by

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

Here, ψ_i is the wave function of initial state, ψ_f is the wave function of final state and V is the operator for physical interaction which couples the initial and final states.

The final transition rate between the energy states in terms of absorption and emission including perturbation is given by:

$$\lambda_{if} = \frac{2\pi}{\hbar}\left|H_{if}^{'}\right|^2 \partial\left(E_f - E_i - \hbar\omega\right) + \frac{2\pi}{\hbar}\left|H_{if}^{'*}\right|^2 \partial\left(E_f - E_i + \hbar\omega\right)$$

where the first term corresponds to the absorption of a photon by the electron (as $E_f = E_i + \hbar\omega$) whereas the second term corresponds to the emission of a photon (as $E_f = E_i - \hbar\omega$) and the harmonic disturbance (perturbation) by photon interaction is given by

$$H^{'}(\vec{r},t) = H^{'}(\vec{r})e^{-iwt} + H^{*'}(\vec{r})e^{+iwt} \text{ for } t \geq 0$$

3.19 Optical Gain & Loss in a two level system:

Consider a two level system. Consider a coherent beam of monochromatic radiation of

unity cross-section area passing through the lasing medium. Inside the medium, absorption of the radiation takes place by an electron transition from a lower energy E_1 to an upper energy level E_2. The intensity of the light beam passing through the medium changes as,

$$I = I_o e^{-\alpha x} \qquad \text{or} \qquad \frac{dI}{dx} = -\alpha I \qquad \textbf{(3.14)}$$

Here, I_o is the incident intensity at x = 0 and α is the absorption coefficient of the medium. If N_1 and N_2 are the electron population in the energy levels E_1 and E_2 respectively, then the net rate of loss of photon density N_p cane be written as,

$$-h\nu \frac{dN_p}{dt} = N_1 B_{12} u(\nu) - N_2 B_{21} u(\nu)$$

Since, $B_{12} = B_{21}$, therefore,

$$-h\nu \frac{dN_p}{dt} = (N_1 - N_2) B_{21} u(\nu) \qquad \textbf{(3.15)}$$

Note that the spontaneous emission process is neglected because the incident radiation has no effect on it. Now, by definition,

$$u(\nu) = N_p h\nu$$

Here, N_p is the number of photons per unit volume having frequency ν. Therefore,

$$I = u(\nu)\frac{c}{n_r}$$

Here, n_r is the refractive index of medium. Hence the energy crossing per unit area per unit time is,

$$I = \frac{N_p h\nu c}{n_r}$$

So,

$$N_p = \frac{I n_r}{h\nu c}$$

Therefore, change in photon density (dN_p) in the incident coherent beam as it passes through the medium between x to x+Δx, will be,

$$-dN_p = [I(x) - I(x + \Delta x)]\frac{n_r}{h\nu c} \qquad \textbf{(3.16)}$$

Now, because $\frac{dI}{dx} = \frac{I(x+\Delta x) - I(x)}{\Delta x}$ **(As per definition of differentiation)**

or $I(x+\Delta x) - I(x) = \Delta x.\frac{dI}{dx}$

So, Equation (3.16) becomes

$$-dN_p = -\frac{dI}{dx}\frac{n_r \Delta x}{h\nu c}$$

Now, the photons travel the distance Δx in the time dt = $\frac{\Delta x}{c/n_r}$, so

$$\frac{-dN_p}{dt} = -\frac{dI}{dx}\frac{1}{h\nu} \qquad \textbf{(3.17)}$$

Substituting equation (3.14) in (3.17), we get,

$$\frac{dN_p}{dt} = -\frac{\alpha I}{h\nu} = -\alpha\, u(\nu)\frac{c}{n_r}\frac{1}{h\,\nu} \qquad \textbf{(3.18)}$$

Comparing equation (3.15) and (3.18) and considering ($\nu = \nu_{12}$) , we get

$$\alpha\, u(\nu)\frac{c}{n_r}\frac{1}{h\,\nu} = (N_1 - N_2)\frac{1}{h\,\nu_{12}}B_{21}u(\nu)$$

Therefore,

$$\alpha = (N_1 - N_2)\frac{B_{21}n_r}{c}$$

As expected, the absorption coefficient (α) for the medium depends on the population difference (N_1-N_2) between the energy levels N_1 and N_2. In general, for $E_2>E_1$ and $N_1>N_2$ and so, absorption coefficient is positive which represents a medium with LOSS. If a system attains population inversion i.e. $N_2>N_1$, then absorption coefficient becomes negative and the intensity of the beam grows as it travels greater distance ***x*** inside the medium and this represents an optical GAIN. In that case, the gain is represented using the coefficient 'g' as,

$$I = I_o e^{-gx}$$

Where,

$$g = (N_2 - N_1)\frac{B_{21} n_r}{c}$$

Such gain is essential in a lasing medium.

3.20 Optical Drude Model:

The simplest possible theory of the response of a solid to an oscillating external electromagnetic field (i.e. photon) was provided by the Drude Model. The starting assumption is that the optical conducting and the dielectric constant of a material can be determined by considering the motion of free electrons. In the presence of collisions, the equation in an electric fiend is,

$$m\left[\frac{d^2x}{dt^2}\right] + \frac{m}{\tau}\left[\frac{dx}{dt}\right] = -eE \qquad \textbf{(3.19)}$$

Here, m is the mass of electron, x is the displacement and τ is the relaxation time. The second term in equation (3.18) is the collision term, which is proportional to velocity (also called the friction term). Now, if $x = x_o e^{-iwt}$, then

$$\frac{dx}{dt} = -iwx \qquad \text{and} \qquad \frac{d^2x}{dt^2} = -w^2x$$

Substituting the above equation in equation (3.18), we get,

$$-mw^2x - \frac{iwx\,m}{\tau} = -e\,E$$

$$-x\left(mw^2 + \frac{iwm}{\tau}\right) = -e\,E$$

Therefore,

$$x = \frac{e\,E}{wm\left(w + \frac{i}{\tau}\right)}$$

To obtain the optical conductivity, we suppose x = τ v, where, v is the mean velocity of electron. So, the current density will be,

$$J = \frac{ne}{\tau}\left[\frac{e\,E}{wm\left(w + \frac{i}{\tau}\right)}\right]$$

Therefore, the conductivity will be,

$$\sigma = \frac{J}{E} = \left[\frac{ne^2}{wm\tau\left(w + \frac{i}{\tau}\right)}\right]$$

In the limit, $w\,\tau \gg 1$ i.e. when the collision frequency ($1/\tau$) is small as compared with frequency 'w' of light (i.e. in absence of collisions) above equation reduces to

$$\sigma = \left[\frac{ne^2}{wm^2\tau}\right] \qquad \text{and} \qquad x = \frac{e\,E}{m\,w^2}$$

This is known as the Drude formula for optical conductivity.

3.21 Recombination and Generation Processes:

A number of mechanisms (or processes) can lead to the absorption and emission of photons in bulk semiconductor, called transitions. These transitions can be radiative or non-radiative. The operation of almost all optoelectronic devices is based on the annihilation of electron-hole pairs. The simplest way to create electron-hole pair is to irradiate the semiconductor. Photos with sufficient energy are absorbed and these impact energy to the valance band electrons and raise them to the conduction band. The reverse process is associated with the pair giving up its excess energy. In a radiative transition, the excess energy due to recombination is usually impacted to photons usually having energy equal to band gap. In a non-radiative transition, the excess energy due to recombination is usually impacted to phonons and dissipated as heat.

(a) Recombination Process: A process whereby the electrons and holes (carriers) are annihilated or destroyed is known as recombination process. Following are the different types of recombination process:

(i) Band to band Recombination (or Intra band transitions):

Band to band recombination, also referred to as direct thermal recombination, is conceptually the simplest of all recombination processes. As pictured in Fig.a, it merely involves the direct annihilation of a conduction band electron and valence band hole, the electron falling from an allowed conduction band state into a vacant valence band state. This process is typically radiative, with the excess energy released during the process going into the production of a photon (light).

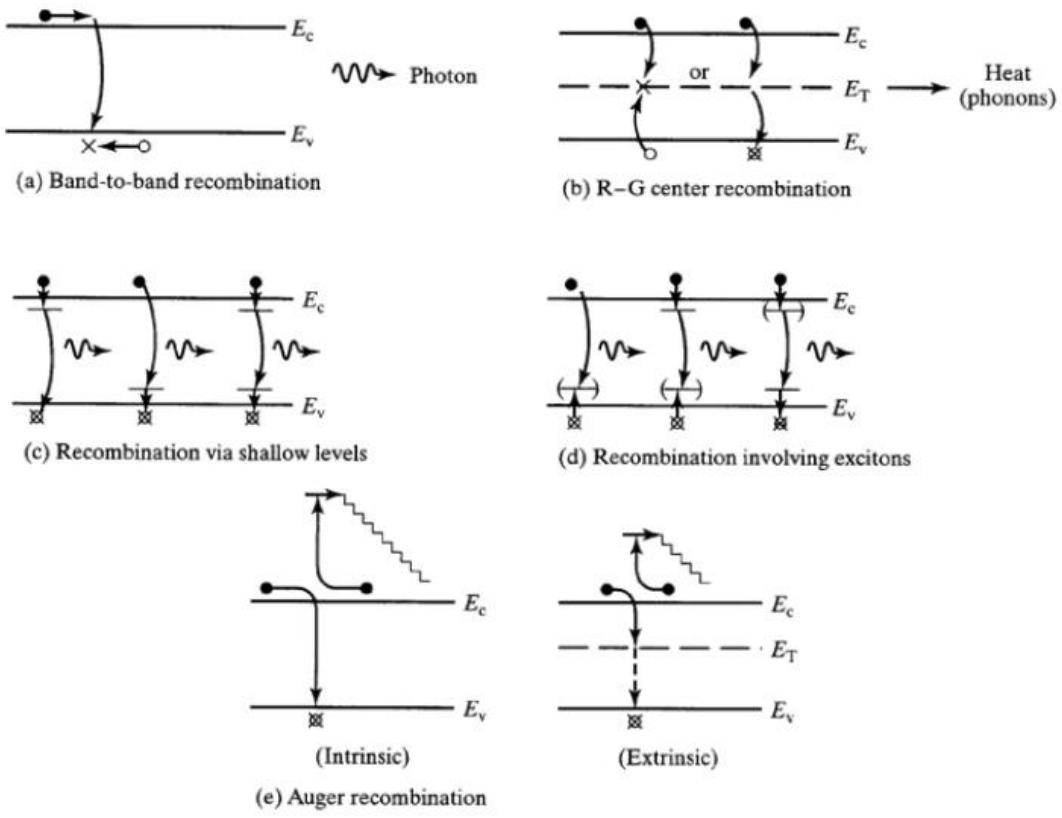
(ii) R-G Center Recombination:

As shown in Fig. (b), the R-G centers there by created act as intermediaries in the envisioned recombination process. First one type of carrier and the other type of carrier is attracted to the R-G center. The capture of an electron and a hole at the

same site leads to the annihilation of the electron-hole pair. Alternatively, the process may be described in terms of the state-to-state transitions of a single carrier: a carrier is first captured at the R-G site and then makes an annihilating transition to the opposite carrier band. R-G center recombination, also called indirect thermal recombination, is characteristically non-radiative. Thermal energy (heat) is released during the process, or equivalently, lattice vibrations (phonons) are produced.

(iii) Recombination via Shallow levels:

Like R-G centers, donor and acceptor sites can also function as intermediaries in the recombination process. If an electron is captured at the donor site, however, it has a high probability at room temperature of being re-emitted into the conduction band before completing the remaining steps of the recombination process. A similar statement can be made for the holes captured at acceptor sites. For this reason donor and acceptor sites may be likened to extremely in-efficient R-G centers, and the probability of recombination occurring via shallow levels is usually quite low at room temperature. It should be noted, nevertheless, that the large energy step in shallow-level recombination is typically radiative and that probability of observing shallow level processes increases with decreasing system temperature, explained in Fig. (c).



(iv) Recombination Involving Excitons:

Normally, electrons and holes may be viewed as individual particles that respond independently to applied forces. However, it is possible for an electron and a hole to become bound together with hydrogen atom- like arrangement which moves as a unit in response to applied forces. This coupled electron-hole pair is called an exciton. It is also possible for one of the exciton components to be trapped at a shallow level site; the resulting configuration is called a bound exciton. Since a certain amount of energy goes into the formation of an exciton, the difference between the electron and hole energies of the coupled pair can be less than the band gap energy. The formation of an exciton is therefore viewed as introducing a temporary level into the band gap slightly above the valence band edge or slightly below the valence band edge. In Fig. (d) these levels are enclosed by parentheses.

AS pictured in Fig.(d), recombination of the exciton components can give rise to sub band-gap radiation.

Recombination involving exciton is very important mechanism at low temperature and is the major light-producing mechanism in the Light Emitting Diodes containing shallow-level isoelectronic centers.

(v) Auger Recombination:

The final recombination processes to be considered are the non-radiative type processes. In an auger process (See Fig. (e)), band-to-band recombination or trapping at a band centers occurs simultaneously with the collision between two like carriers. Then energy released by the recombination or trapping sub process is transferred during the collision to the surviving carrier. Subsequently, this highly energetic carrier "thermalizes"----- loses energies in small steps through collisions with semiconductor lattice. The "staircases" in Fig. (e), represent the envisioned stepwise loss of energy. Because the number carrier-carrier collisions increases with increased carrier concentration, Auger recombination like increases with carrier concentration, becoming very important at high carrier concentrations. Auger recombination must be considered, for example, in treating degenerately doped regions of a doped structure and in the detailed operational modeling of concentrator type solar cells, junction lasers and LEDs.

(b) Generation Process: A process by whereby electrons and holes are created is called generation process. Any of the foregoing processes can be reversed to generate carriers. Note that either thermal energy or light can provide the energy required for the band-to-band transition. If thermal energy is absorbed, the process is alternatively referred to as direct thermal generation. If extremely introduced light is absorbed, the process id called photo-generation. The thermally assisted generation of carriers with R-G centers acting as intermediators is called R-G center generation. The photo emission of carriers from band gap canters is typically a rather improbable process. In the impact ionization also called the inverse of Auger recombination process, an electron-hole pair is produced as a result of the energy released when a highly energetic carrier collides with

the crystal lattice. The generation of carriers through impact ionization routinely occurs in the high electric field regions of devices and is responsible for the avalanche breakdown in pn-junctions.

All the above transitions, contribute to the overall absorption coefficient of the material. For photon energies greater than the band gap energy, the absorption is dominated by band-to-band transitions that form the basis of many photonic devices. The spectral region where the material changes from being relatively transparent ($h\nu < E_g$) i.e. little absorption to strongly absorbing ($h\nu > E_g$) is known as the absorption edge of the spectrum.