Interaction of Photons with Charge Carriers

→ For the optical properties of Semiconductors, the photons should interact with the charge carriers.

→ In the process of interaction, ~~they~~ there may be either the absorption of photons or ~~the~~ emission of photons

→ This is important in the case of photonic devices using Semiconductors.

Photon Interactions in Bulk Semiconductors.

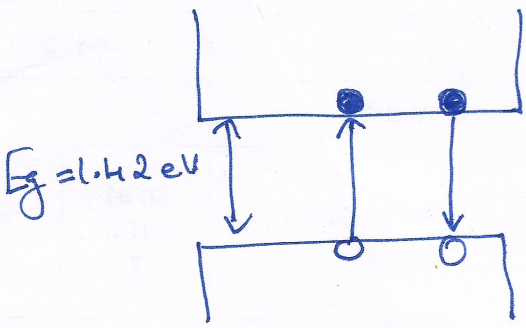
(a) Band to Band (Inter band) Transitions:→

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

→ This results in a electron-hole pair.

→ The electron-hole recombination can result in the emission of a photon.

→ Band to band transitions may be assisted by one or more phonons.



Band-to-band transitions in GaAs, can result in absorption or emission of photons of wavelength $\lambda_0 < \lambda = \frac{hc_0}{E_0} = 0.87\,\mu m$

(b) 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.

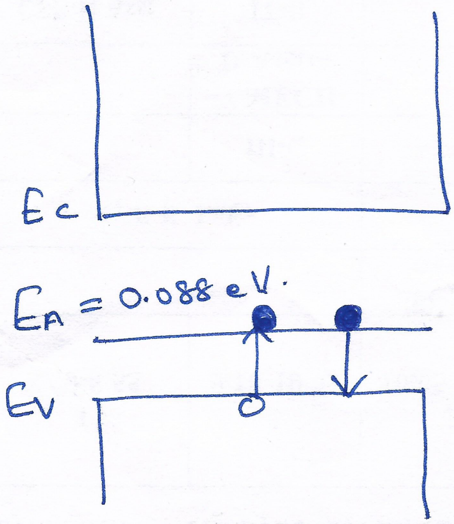
→ In a p-type material, a low-energy photon can lift an electron from the valence band to acceptor level, where it becomes trapped by a acceptor atom.

→ 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 may be the electron decays from its acceptor level to recombine with hole.

→ The energy may be released radiatively (in the form of an emitted photon) or non-radiatively (in the form of phonons).



The absorption of a photon of wavelength $\lambda_A = hc_o/E_A = 14\,\mu m$ results in a valence band to acceptor level transition in Hg-doped Ge (Ge:Hg).

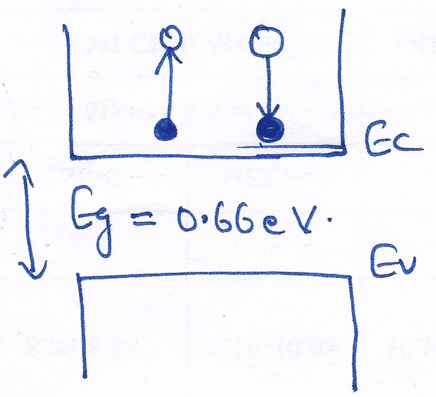
(c) Free-Carrier (Intraband Transitions).

→ 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 conduction band, can absorb a photon and move to a higher energy level within the conduction band.

→ This is followed by thermalization, a process whereby the electron relaxes down to the bottom of conduction band while releasing its energy in the form of phonons.

→ The strength of free-carrier absorption is proportional to the carrier density.



Free-carrier transitions within the conduction band of Ge.

Optical Absorption and Emission Process.

→ Consider, the direct band-to-band photon absorption and emission in bulk semiconductors.

→ This direct band-to-band absorption and emission can take place only at frequencies for which photon energy is $h\nu > E_g$.

→ The minimum frequency ν, neccessary for this to happen is $\nu_g = E_g/h$

→ The corresponding maximum wavelength, $\lambda_g = c_0/\nu_g = \frac{hc_0}{E_g}$

→ The λ_g in eV, $\lambda_g \sim \frac{1.24}{E_g}$

is known as bandgap wavelength or cutoff wavelength.

Absorption

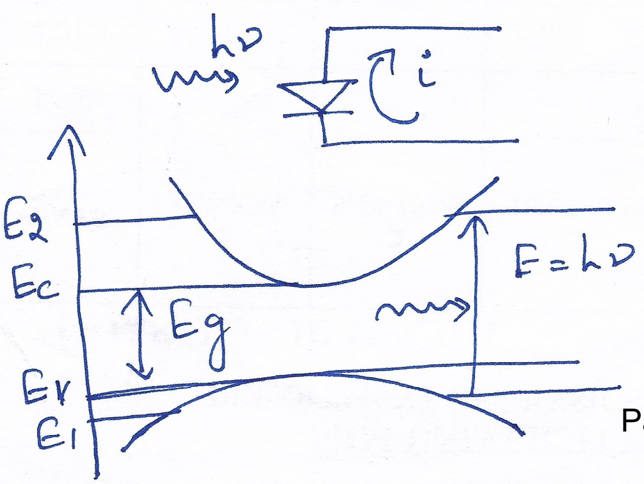
→ Electron excitation from the valence to the conduction band may be ~~introduced by~~ induced by the absorption of a photon of appropriate energy ($h\nu > E_g$ or $\lambda < \lambda_g$)

→ An electron-hole pair is generated.

→ This adds to the concentration of mobile charge carriers and increases the conductivity of the material.

→ The material behaves as a photoconductor with a conductivity proportional to photon flux.

→ This effect is used to detect light.



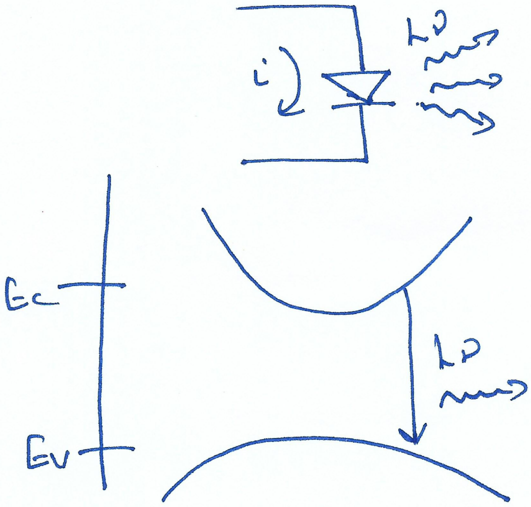
The absorption of a photon results in the generation of an electron-hole pair.

Emission

→ Electron deexcitation from the conduction band to the valence band (electron-hole recombination) may result in the spotaneous emission of a photon of energy $h\nu > E_g$.

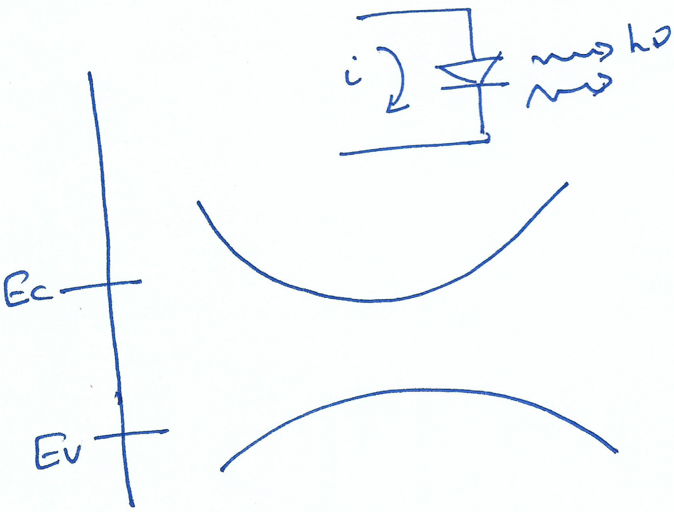
→ Or in the stimulated emission of a photon, provided that a photon of energy $h\nu \geq E_g$ is initially present.

→ Spontaneous emission is the underlying phenomenon on which the light-emitting diode is based



The recombination of an electron hole pair results in spotaneous emission of a photon. LED operate on this basis.

→ Stimulated emission is responsible for the operation of semiconductor optical amplifiers and laser diodes.



Electron-hole pair recombination can be induced by a photon. This results in the stimulated emission of the identical photon.

Recombination Process.

→ The operation of all optoelectronic devices is based on Creation ~~of~~ or annihilation of electron-hole pairs.

→ Pair formation essentially involves raising an electron in energy from the valence band to conduction band, leaving a hole behind in valence band.

→ Simplest way to achieve this phenomenon is to ~~irradiate~~ irradiate the Semiconductor.

→ Photons with Sufficient energy are absorbed, and these impart their energy to the valence band electrons and raise them to the Conduction band. This process is called absorption.

→ Recombination: the reverse process of electron hole pairs annihilation, where energy is released is called recombination

→ Recombination may be radiative or non-radiative.

→ Non-radiative transition: is the process where the excess energy due to recombination is usually imparted to ~~photons~~ phonons and dissipated as heat.

→ Radiative Transition: is the process where the excess energy due to recombination is dissipated as photons, with energy usually equal to bandgap

→ ~~Lumiscence~~ Luminescence: The luminescent process is in which the electron-hole pairs are created and recombined radiatively.

→ Photoluminescence: ~~inst~~ involves the radiative recombination of electron-hole pairs created by injection of photons.

→ Cathodoluminscence: is the process of radiative recombination of electron-hole pairs created by electron bombardment.

→ Electroluminscence: is the process of radiative recombination following injection with pn junction or Similar device.

(2)

→ When a Semiconductor in equilibrium, without any incident photons or injection of electrons, the carrier densities canbe calculated from an equilibrium fermilevel by using Fermi-Dirac statististics. (electrons).

→ When excess carriers are created by one of the techniques, non-equilibrium conditions are generated and the concept of fermi-level is no longer valid.

→ The non-equilibrium distribution functions:

for electrons, $$f_n(E) = \frac{1}{1+\exp\left(\frac{E-E_{fn}}{k_B T}\right)}$$

for holes, $$1-f_p(E) = \frac{1}{1+\exp\left(\frac{\mathcal{E}-\mathcal{E}_{fn}}{K_B T}\right)}$$

where, $\mathcal{E}_{fn}$ → Quasi fermi level for electrons.

$\mathcal{E}_{fp}$ → Quasi fermi level for holes.

→ Then, $$f_n(\mathcal{E}) \cong \exp\left(\frac{\mathcal{E}_{fn}-\mathcal{E}}{K_B T}\right)$$

$$f_p(\mathcal{E}) \cong \exp\left(\frac{\mathcal{E}-\mathcal{E}_{fp}}{K_B T}\right)$$

→ The Non-equilibrium Carrier Concentrations are:

$$n = N_c \exp\left(\frac{\mathcal{E}_{fn}-\mathcal{E}_c}{K_B T}\right)$$

$$p = N_v \exp\left(\frac{\mathcal{E}_v-\mathcal{E}_{fp}}{K_B T}\right)$$

③

→ ~~The~~ non-equilibrium electron and hole concentrations are:

$$n = \Delta n + n_0 .$$
$$p = \Delta n + n_i^2 / n_0$$

→ The excess carriers created in a semiconductor must eventually recombine. Under ~~eq~~ equilibrium,

$$G = R.$$

→ Generation and recombination processes involve transition of carriers across the energy bandgap

→ They are different for direct and indirect bandgap SC.

→ The probability of radiative recombination is very high in direct bandgap semiconductors, due to energy and momentum considerations.

→ On the injection of electron-hole pairs, depending on injection level, a steady state excess density $\Delta n = \Delta p$ is established in the crystal.

→ This equality is also neccessary for the maintanence of over charge neutrality.

→ When the excitation source is removed, the density of excess charge carriers returns to ~~equi~~ equilibrium states. values of p_0 & n_0.

→ There are bulk recombination processes and surface recombination process.

→ In general, the excess charge carriers decay by radiative and non-radiative recombination, in which the excess energy is dissipated by photons and phonons

→ The total lifetime τ.

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

τ_r → radiative lifetimes

τ_{nr} → non-radiative lifetimes.

→ The total recombination rate

$$R_{total} = R_r + R_{nr} = R_{sp}.$$

R_r → radiative recombination.

R_{nr} → non-radiative recombination.

R_{sp} → Spotaneous recombination.

→ The internal quantum efficiency.

$$\eta_r = \frac{R}{R_r + R_{nr}} = \frac{1}{1 + T_r/T_{nr}}$$

T_r/T_{nr} → as ~~tar~~ Small as possible

T_{nr} → as large as possible.

Einstein's Coefficient - Basic Principle of Absorption and Emission

(1)

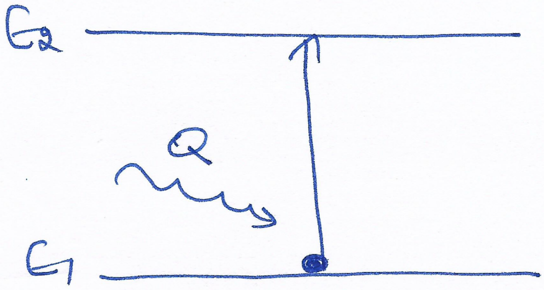
Absorption:

→ Consider a system containing two energy levels namely, the ground state and the excited state.

→ Usually the number of atoms in the ground state is more than the number of atoms at the excited state.

→ For an atom/particle to move from the ground state to the excited state, it should absorb energy at least equal to difference between two energy levels.

→ The energy required should be greater or equal to $E_2 - E_1$.



→ Then, the ~~nu~~ number of atoms undergoing transitions/absorption per unit volume per unit time is expressed as,

$$N_{ab} = B_{12} N_1 Q$$

where, B_{12} → Proportionality Constant.

Q → The energy density of incident radiation

N_1 → Number of atoms at E_1

Emissions:

→ An atom/particle after absorbing energy goes to the excited state and does not stay there indefinitely or forever.

Spotaneous Emission

→ The Spotaneous emission does not require any external energy.

→ The atom goes back to its ground state after its lifetime in the excited State.

→ Then, the number of atoms making Spontaneous emission per unit volume per unit time can be expressed as.

$$N_{sp} = A_{21} N_2$$

where, A_{21} → the proportionality Constant

N_2 → number of atoms in E_2.

Stimulated Emission:

→ The atoms in the excited State is given an external energy and is forced to go the ground State.

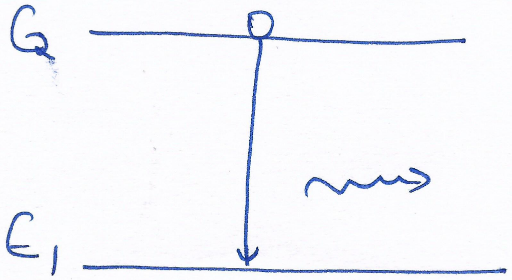
→ The atom in the excited State is not allowed to stay for its lifetime.

→ Then, the number of transitions per unit volume per unit time is given by.

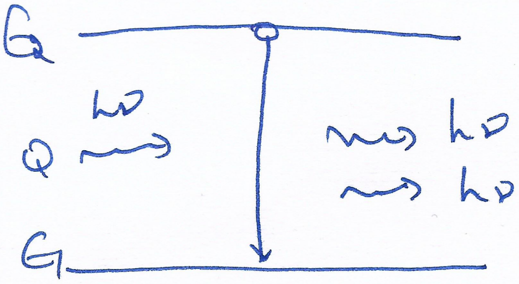
$$N_{st} = B_{21} N_2 Q$$

where, B_{21} → the proportionality Constant

N_2 → number of atoms at E_2.



Spotaneous Emission



Stimulated Emission

→ At thermal equilibrium,

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

$$Q = \frac{A_{21}}{\frac{N_1}{N_2} B_{12} - B_{21}}$$

→ From Boltzmann's distribution law, at a given temperature T, the ratio of the population of two levels is given by,

$$\frac{N_1}{N_2} = e^{(E_2 - E_1)/KT} = e^{h\nu/KT}$$

→ Also, According to Planck's black body radiation theory,

$$Q = \frac{8\pi hc}{\lambda^5} \frac{1}{e^{h\nu/KT} - 1} \longrightarrow (1)$$

→ Then, $Q = \dfrac{A_{21}}{B_{12} e^{h\nu/KT} - B_{21}} = \dfrac{A_{21}}{B_{21} (e^{h\nu/KT} - 1)}$ → (2)

for $B_{21} = B_{12}$

→ Comparing (1) & (2)

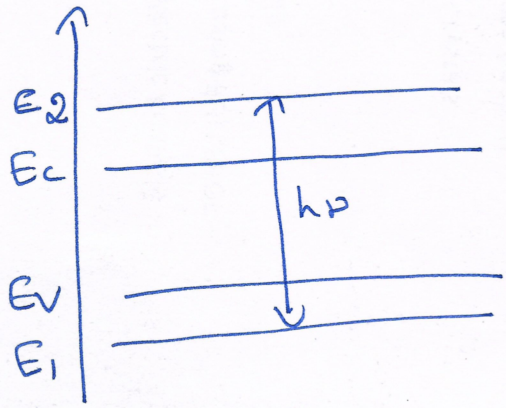
$$\frac{A_{21}}{B_{21}} = \frac{8\pi hc}{\lambda^5}$$

Here, A & B are called as Einstein's Coefficients. which gives the value of ratio of Spontaneous to Stimulated emission.

Optical Joint Density of States.

There are Conditions under which the transitions leading to absorption and emission of radiation takes place.

Conservation of Energy:



→ The absorption or emission of a photon of energy $h\nu$ requires that the energies of the two states involved in the interaction be Separated by $h\nu$.

→ The Conservation of energy is followed ~~whe~~ for a photon emission to occur by electron-hole recombination, when an electron occupying an energy level E_2 interacts with a hole occupying an Energy level E_1.

$$E_2 - E_1 = h\nu$$

Conservation of Momentum:

→ Momentum must also be Conserved in the process of photon emission/absorption,

$$p_2 - p_1 = h\nu/c = h/\lambda$$

$$k_2 - k_1 = 2\pi/\lambda$$

→ The photon/momentum magnitude h/λ is very Small in Comparison with range of momentum values that electrons and holes can assume.

→ Hence, the momenta of the electron and hole participating in the interaction must therefore be approximately equal.

→ This Condition, $k_2 \simeq k_1$, is Called the k- Selection rule.

→ Transitions obeying this rule are represented in E-k diagram by vertical lines, indicating that the change in k is negligible on the Scale of the diagram.

Energies and Momenta of the Election and Hole with which a photon interacts.

→ Conservation of energy and momentum require that a photon of frequency ν interact with electrons and holes of Specific energies and momenta determined by Semiconductor E-k relation.

→ for a direct bandgap Semiconductor,

$$E_c - E_v = E_g .$$

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

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

$$\frac{1}{m_r} = \frac{1}{m_v} + \frac{1}{m_c}$$

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

$$E_1 = E_v - \frac{m_r}{m_v} (h\nu - E_g) = E_2 - h\nu$$

→ If $m_c = m_v$.

$$E_2 = E_c + \frac{1}{2} (h\nu - E_g).$$

Optical Joint Density of States

→ The density of States $\rho(\nu)$ with which a photon of energy $h\nu$ interacts under Conditions of energy and momentum Conservation in a direct-bandgap Semiconductor.

→ This quantity incorporates the density of States in both the Conduction and valence bands is called the optical joint density of States.

Density of States of Conduction band, $\rho_c(E_2)$

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

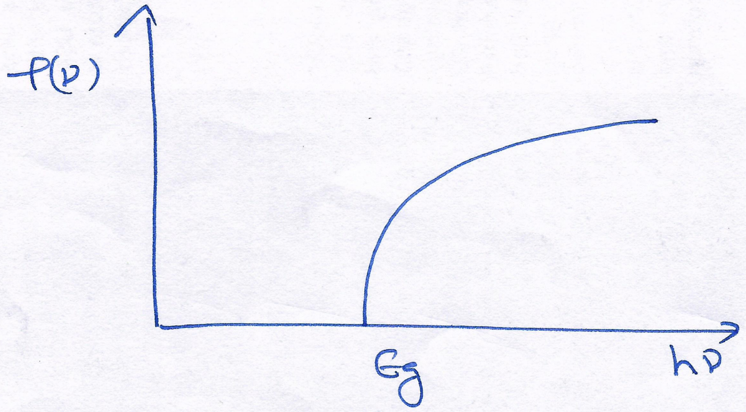
$$\rho(\nu) = \frac{dE_2}{d\nu}\,\rho_c(E_2).$$

$$\rho(\nu) = \frac{h m_r}{m_c}\,\rho_c(E_2)$$

→ The numbers of states per unit volume per unit frequency

$$\rho(\nu) = \frac{(2m_r)^{3/2}}{\pi\hbar^2}\sqrt{h\nu - E_g}\,, \quad h\nu \geq E_g$$

[Optical Joint Density of States]



The DOS with which a photon of energy $h\nu$ interacts increases with $h\nu - E_g$ in accordance with a square-root law

Density of States for Photons.

→ To define the density of states for the photon field, the periodic boundary condition is used that the wave function should be periodic in x, y, z directions with a period L.

→ Therefore,

$$k_x = l\frac{2\pi}{L}, \quad k_y = m\frac{2\pi}{L}, \quad k_z = n\frac{2\pi}{L}$$

→ The volume of a state in k-space is therefore $(2\pi/L)^3$

→ The volume of a state in k-space is therefore $(2\pi/L)^3$

→ Using the dispersion relation for the photon.

$$\omega_k = \frac{kc}{n_r}.$$

when c/n_r is the speed of light in the medium with a refractive index n_r,

→ By changing the sum over $\vec{k}$ to an integral,

$$\frac{d^3k}{(2\pi/L)^3} = \frac{k^2\, dk\, d\Omega}{(2\pi/L)^3}$$

where, $(2\pi/L)^3 \rightarrow$ differential volume in k-space.
$d\Omega \rightarrow$ differential solid angle

→ Then,
$$N(E_{21}) = \frac{2}{V}\sum_k \delta(E_2 - E_1 - E_k)$$
$$= 2\int \frac{k^2 dk\, d\Omega}{(2\pi)^3}\,\delta\,[E_2 - E_1 - E_k]$$

where V is the volume of space

$E_k = \hbar\omega_k = \frac{\hbar k c}{n_r}$ is the photon energy

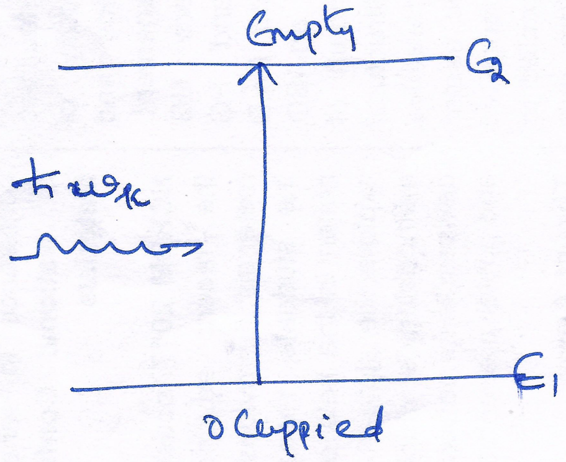
Here, the integration over solid angle is 4π.

$\rightarrow$ Then, $N[E_{21}] = \dfrac{8\pi n_r^3 E_{21}^2}{h^3 c^3} = \dfrac{n_r^3 E_{21}^2}{\pi^2 \hbar^3 c^3}$

which is the number of states with photon energy E_{21} per unit volume per energy interval, $cm^{-3}(eV)^{-1}$

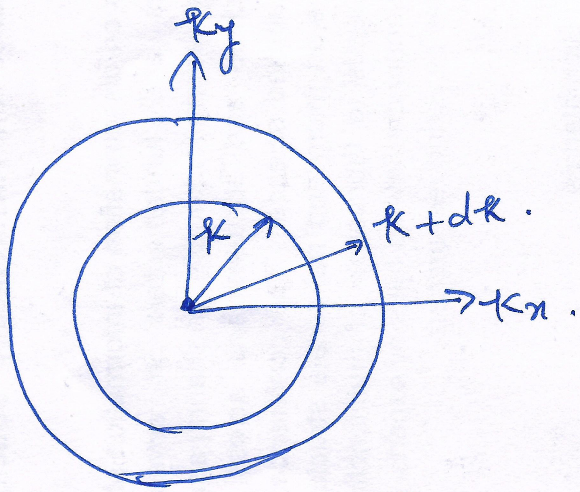
& $E_{21} = E_2 - E_1$ is the energy spacing between the two levels.

(a)



A photon incident on a discrete two-level system where level 1 is occupied and level 2 is empty.

(b)



The k-space diagram for the density of photon states.

$k_x = l\dfrac{2\pi}{L}$, $k_y = m\dfrac{2\pi}{L}$, $k_z = n\dfrac{2\pi}{L}$.

Optical Transitions Using Fermi's Golden Rule

→ Consider a Semiconductor illuminated by light.

→ The interaction between the photons and the electrons in the Semiconductor can be described by the Hamiltonian

$$\vec{H} = \frac{1}{2m_0}(\vec{p} - e\vec{A})^2 + \vec{V}(r)$$

where, m_0 is the free electron mass.

$e = -|e|$ for electrons.

$\vec{A}$ is the vector potential accounting for the presence of electromagnetic field.

$V(r)$ ~~is~~ the periodic potential.

→ The electron-photon interaction Hamiltonian can be derived by ~~exap~~ expanding the Hamiltonian,

$$\vec{H} = \frac{p^2}{2m_0} + \vec{V}(r) - \frac{e}{2m_0}(\vec{p}\cdot\vec{A} + A\cdot\vec{p}) + \frac{e^2 A^2}{2m_0}$$

$$\simeq H_0 + H'$$

where, $H_0 \rightarrow$ Unperturbed Hamiltonian.

$H' \rightarrow$ Perturbation due to light Hamiltonian

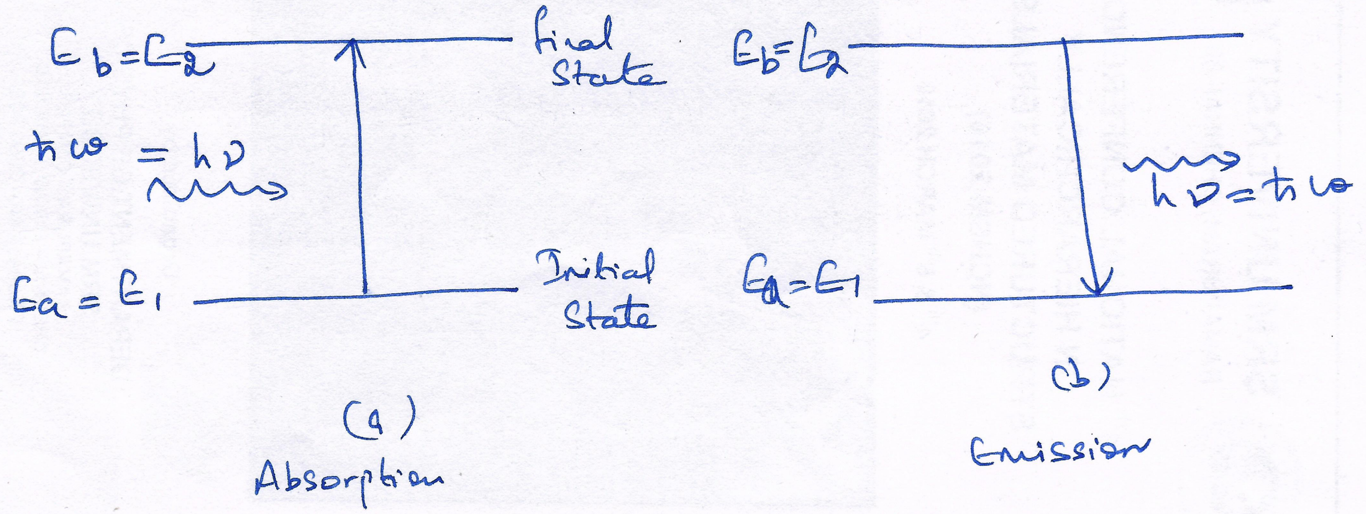
$$H_0 = \frac{p^2}{2m_0} + \vec{V}(r)$$

$$H' \simeq -\frac{e}{m_0}\vec{A}\cdot\vec{p}$$

Also, the Coloumb gauge $\nabla\cdot\vec{A} = 0$

since, $\vec{p} = (\hbar/i)\,\nabla$

→ Transition rate due to Electron - Photon interaction.



→ Using Time-dependent perturbation theory, the transition rate for the absorption of a photon can be derived, assuming an electron is initially at State E_1, is given by Fermi's Golden rule.

→ $$W_{abs} = \frac{2\pi}{\hbar} \left| \langle b | H'(r) | a \rangle \right|^2 \delta(E_b - E_a - \hbar\omega)$$

Where, $E_b > E_a$ is assumed.

→ The total upward transition rate per unit volume ($s^{-1}cm^{-3}$) in the Crystal taking into account the probability that State E_a is occupied and State b is empty is.

$$R_{a \to b} = \frac{2}{V} \sum_{k_a} \sum_{k_b} \frac{2\pi}{\hbar} |H'_{ab}|^2 \delta(E_b - E_a - \hbar\omega) f_a (1 - f_b)$$

$\sum$ denotes the Sum over initial and final States

f_a → Fermi-Dirac distribution that E_a is occupied

$(1 - f_b)$ → Fermi-Dirac distribution that E_b is empty

→ The prefactor 2 takes into account the Sum over Spins.

3

→ The Matrix element H'_{ba} is given by.

$$H'_{ba} = \langle b | H'(r) | a \rangle = \int \psi_b^*(r)\, H'(r)\, \psi_a(r)\, d^3r$$

→ Similarly, the transition rate for the emission of a photon if an electron is initially at state E_b is.

$$W_{ems} = \frac{2\pi}{\hbar} \left| \langle a | H'^{+}(r) | b \rangle \right|^2 \delta(E_a - E_b + \hbar\omega)$$

→ The downward transition rate per unit volume ($s^{-1} cm^{-3}$) is

$$R_{b\to a} = \frac{2}{V} \sum_{k_a} \sum_{k_b} \frac{2\pi}{\hbar} \left| H'^{+}_{ab} \right|^2 \delta(E_a - E_b + \hbar\omega)\, f_b (1 - f_a)$$

→ Using even property of δ (delta function)

$$\delta(-x) = \delta(x)$$

$$|H'_{ba}| = |H'^{+}_{ab}|$$

→ The net upward transition rate per unit volume can be given as

$$R = R_{a\to b} - R_{b\to a}$$

$$= \frac{2}{V} \sum_{k_a} \sum_{k_b} \frac{2\pi}{\hbar} |H'_{ba}|^2 \delta(E_b - E_a - \hbar\omega)\, (f_a - f_b)$$

→ Optical Absorption Coefficient.

The absorption coefficient α (1/cm) in the crystal is the fraction of photons absorbed per unit distance

$$\alpha = \frac{\text{Number of photons absorbed per second per unit volume}}{\text{Number of injected photons per second per unit area.}}$$

→ The injected number of photons per second per unit area is the optical intensity $P\,(W/cm^2)$ divided by the energy of a photon here.

→ Therefore,

$$\alpha(\hbar\omega) = \frac{R}{P/\hbar\omega} = \frac{\hbar\omega}{\left(\frac{n_r c \varepsilon_0 \omega^2 A_0^2}{2}\right)} R$$

where, $R \rightarrow$ net upward transition rate per unit volume

$\omega \rightarrow 2\pi/\lambda$, wave number/angular velocity.

$c \rightarrow$ Velocity of light

$n_r \rightarrow$ refractive index of the medium.

$A \rightarrow$ Vector potential for electromagnetic field.

$\varepsilon_0 \rightarrow$ permittivity of free space

Optical Amplification and feedback.

Laser Amplification

→ Light amplification is achieved by stimulated emission from an atomic or molecular system with a transition whose population is inverted.

→ Population inversion: The upper energy level is more ~~at~~ populated than the lower.

→ The laser amplifier is a distributed-gain device characterized by its gain coefficient (gain per unit length) $\gamma(\nu)$, which governs the rate ~~of~~ at which the photon-flux density, ϕ increases

→ When the photon-flux density ϕ is small, the gain coefficient

$$\gamma_0(\nu) = N_0 \sigma(\nu) = N_0 \frac{\lambda^2}{8\pi t_{sp}} g(\nu)$$

Where,

N_0 = equilibrium population density difference, N_0 increases with increasing pumping rate

$\sigma(\nu) = \dfrac{\lambda^2}{8\pi t_{sp}} g(\nu)$ = transition cross section

t_{sp} = Spontaneous lifetime

$g(\nu)$ = transition lineshape.

$\lambda = \dfrac{\lambda_0}{n}$ = wavelength in the medium with refractive index n

Losses inside amplification system.

→ The intensity of a light beam in a amplifier system, gradually diminishes owing to various losses such as absorption, radiation through the side surface, etc.

→ The intensity diminishes by an exponential law

$$I(z) = I_0 \exp(-\alpha z)$$

where, α is the loss factor.

→ The energy in the beam diminishes exponentially according to the equation,

$$W(t) = W_0 \exp(-t/\tau_c)$$

where, the energy falls to its W/e value in time τ_c

→ The distance covered by the light flux in time τ_c is

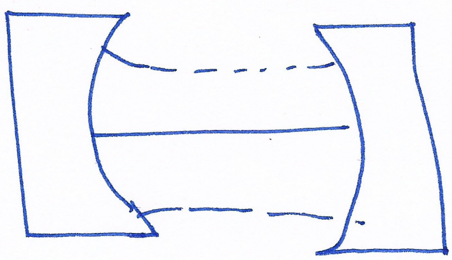
$$z = c\tau_c$$

$$I(z) = I_0/e$$

where, $\alpha z = \alpha c \tau_c = 1 \Rightarrow \alpha = 1/c\tau_c$

→ If the losses are of different types, the association of α_i lossfactor with each of loss is possible and further, if they are independent of each other, then

$$\alpha = \sum \alpha_i$$



(a) A ~~Conco~~ Confocal Resonator

Photovoltaic Effect

→ Sunlight can be converted to electricity due to the photovoltaic effect discovered by Edmund Becquerel, a French scientist in 1839.

→ Sunlight is composed of photons, or packets of energy. These photons contain various amount of energy corresponding to the different wavelengths of light.

→ When photons strike a solar cell, a semiconductor P-N junction device, they may be reflected or absorbed, or they may pass through the cell.

→ Absorption of a photon in a solar cell results in the generation of electron-hole pair (EHP)

→ This EHP, when separated from each other across the P-N junction, results in the generation of a voltage across the junction.

→ This voltage can drive a current in an external circuit, which is called as photocurrent

→ The device is called as Photovoltaic cell or device.

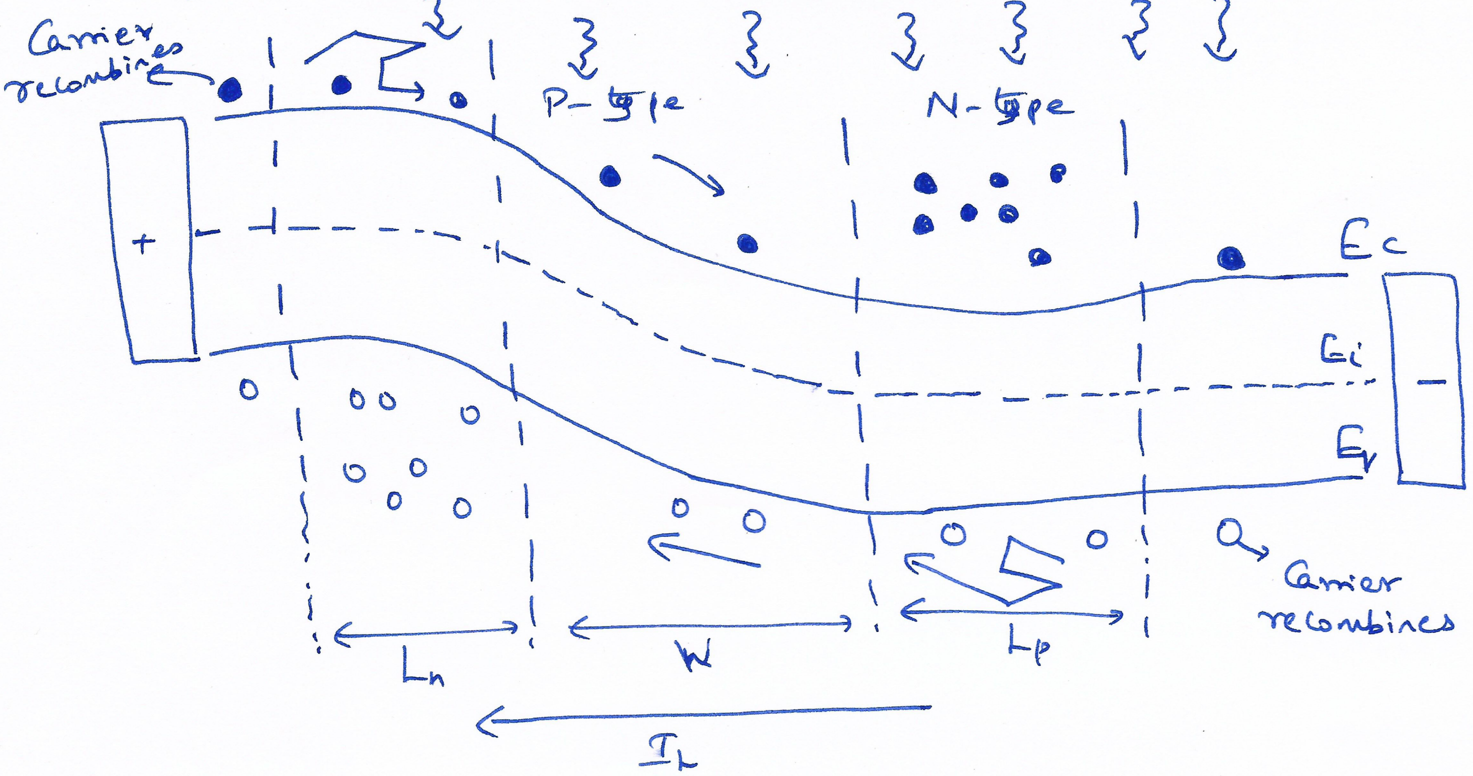
Photovoltaic Effect – p-n Junction under Illumination.

→ When there is no light falling on the diode (p-n junction) no electron-hole pair is generated for photocurrent.

→ But p-n junction is illuminated, its absorbs solar radiation and electron-hole pairs are generated.

→ It can be safely assumed that the generation rate of electron-hole pairs will be uniform in the p-n junction area, extended to the entire device area.

p-n Junction Under illumination



→ Under the uniform illumination Condition, generation of Carrier will occur in the Space-Charge region as well as quasi-neutral region.

→ The Carriers that are generated in the Space-Charge region will be immediately be Swept away due to the electric field (electrons towards N-side and holes towards p-side).

→ Due to the electric field, Chances of recombination of these electron pairs are quite less.

→ The electron-hole pairs which are generated in the quasi-neutral region will move around in a random manner.

→ In their random motion, Some of the generated minority Carriers will Come near to the Space-charge region edge, where they will experience a force due to electric field and will be pulled at the other Side.

→ Only the minority Charge Carriers will Cross the junction.

→ Minority electrons from P-side will come to N-side (leaving behind their positively charged partner, hole)

→ Minority holes will come from N-side to P-side (leaving behind their negatively charged partner, an electron).

→ There is a net increase in the positive charges at P_side and a net increase in negative charge at N-side.

→ This build up of a positive and negative charge causes a potential difference to appear across the P-N junction due to light falling on it.

→ This generation of photovoltage is called Photovoltaic effect

→ The contribution to the photovoltage is coming only from the carriers that are generated within the width $(L_n + W + L_p)$

Light Generated current

→ In a P-N junction diode, four current component are present in equilibrium condition: electron drift, electron diffusion hole current and hole diffusion.

→ In equilibrium condition, net current is zero which requires the drift and diffusion currents of carriers to be equal and opposite.

→ When pn-junction is illuminated, a net large drift current due to minority electrons and holes, which flows from N-side to p-side.

→ Since, this current flow is generated by light, it is known as light-generated current or photo current, I_L.

→ Hence, the power can be generated by the device.

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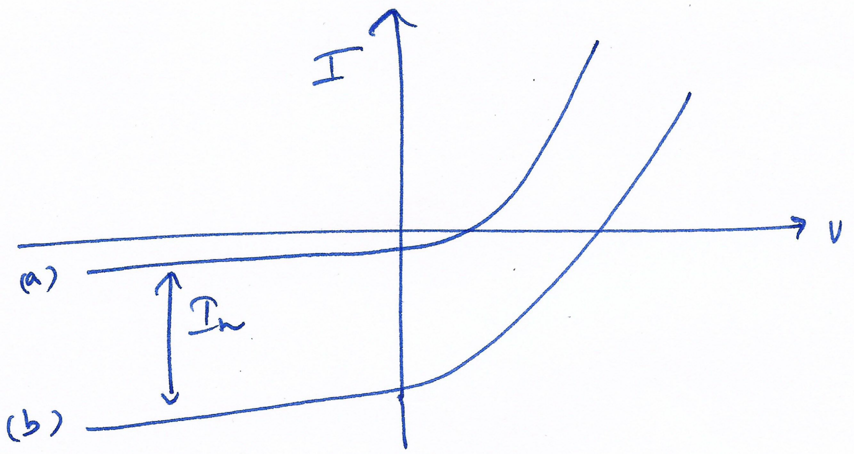


(a) Dark I-V Curve.

(b) when light shines on a p-N Junction diode, IV Curve of illuminated p-n Junction

→ The overall effect of light shining is to shift the I-V Curve of the diode downwards in the current-voltage axis.

Application of Photovoltaic Effect - Solar Cell.

→ When light shines on a Solar Cell, photovoltage is generated.

→ The generated voltage across the Solar cell can drive the current in external circuit and therefore can deliver power.

→ In order to collect the energy of a photon in the form of of electrical energy, through Solar Cells, the following actions must take place:

(a) increase in the potential energy of carriers (generation of electron-hole pair).

(b) Separation of carriers.

→ I-V equation for the Solar Cell can be derived in the same manner as that for a P-N junction diode.

→ Here, the generation term G will not be zero, as it is taking place in the space charge region and recombination is zero.

→ The Total Current through the junction is given by,

$$I_{total} = qA\left(\frac{D_n}{L_n} n_p p_o + \frac{D_p}{L_p} p_{n0}\right)\left(e^{qV/kT} - 1\right) - qAG\left(L_n + L_p + W\right)$$

$$I_{total} = I_o\left(e^{qV/kT} - 1\right) - I_L.$$

where $I_L = qAG(L_n + L_p + W)$ is the light generated current.

→ This indicates that the carriers generated within the volume of cross-sectional area A and length $(L_n + L_p + W)$ contribute to I_L.

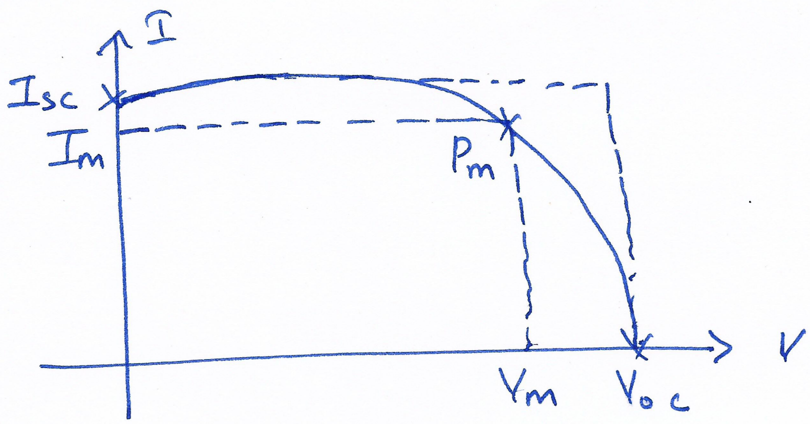
Determination of Efficiency of a Solar Cell.

→ Solar Cells are characterized and compared with each others with four parameters:

(1) Short Circuit Current, I_{sc}: (mA/cm^2)

→ This is the maximum current ~~that~~ flows in a solar cell when its terminals at p-side and N-side are shorted with each other, i.e, $V = 0$

→ $I_{sc} = -I_L$, where Shortcircuit current is nothing but the light-generated current.



Typical plot of a solar cell I-V curve and its parameters.

(2) Open Circuit Voltage V_{oc}: (mV or V)

→ It is the maximum voltage generated across the terminals of a solar cell when they are kept open, i.e, $I = 0$.

$$V_{oc} = \frac{kT}{q} \ln\left(\frac{I_L}{I_o} + 1\right)$$

(3) Fill factor FF: (%)

→ It is the ratio of the maximum power $P_m = V_m \times I_m$ that can be extracted from a solar cell to the ideal power $P_o = V_{oc} \times I_{sc}$.

$$FF = \frac{P_m}{P_o} = \frac{V_m I_m}{V_{oc} I_{sc}}$$

→ ff represents the squareness of the solar I-V curve.

(4) Efficiency η: (mW/cm^2 or W/m^2)

→ The ratio of the power output to power input.

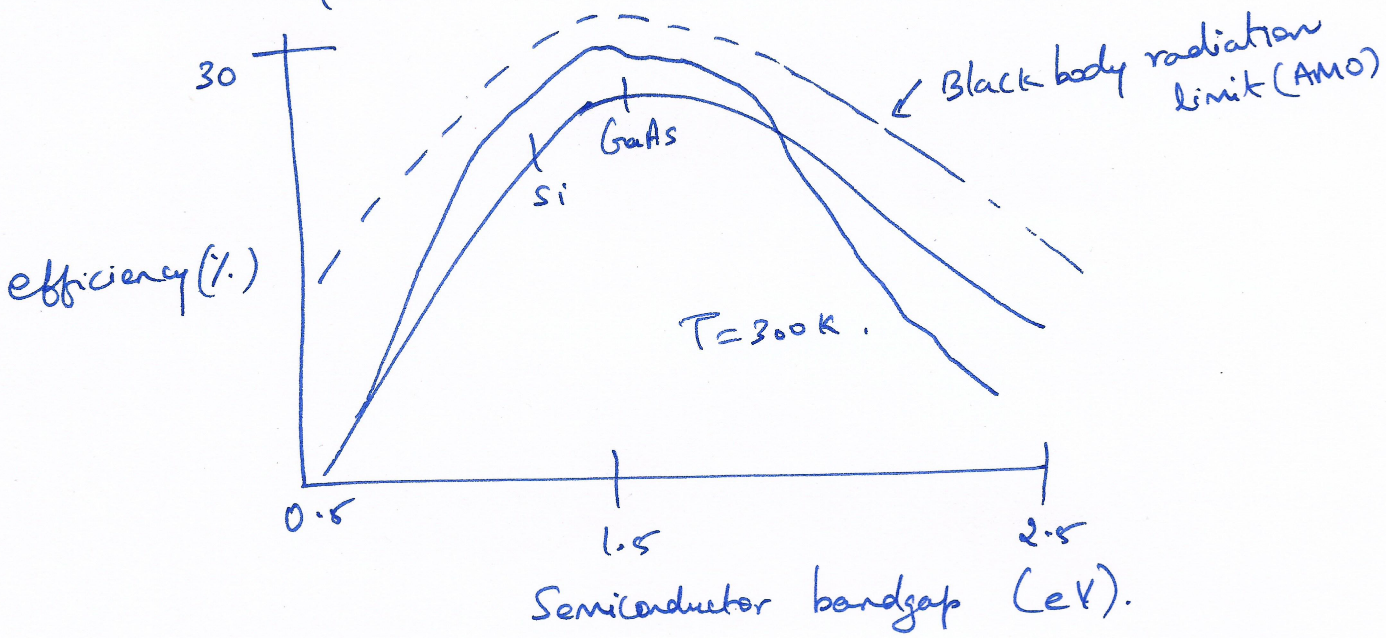
→ The power output is the maximum power point P_m of a solar cell.

→ Input power is the power of solar radiation P_{rad}.

$$\eta = \frac{P_m}{P_{rad}}.$$

$$\eta = \frac{V_m I_m}{P_{rad}} = \frac{V_{oc} I_{sc}\, ff}{P_{rad}}.$$

Efficiency in terms of Bandgap.



Maximum possible solar cell efficiencies as a function of energy band gap of semiconductor materials.

→ There is an optimum band gap for which efficiency of a solar cell would be maximum.

→ The open circuit voltage of a solar cell increases with increase in bandgap.

Losses in Solar Cells determining efficiency.

① Loss of low energy photons:

→ Photons of energy value less than that of the bandgap values donot get absorbed in the material.

② Loss due to excess energy of photons:

→ when the photon energy E is higher than the bandgap energy E_g, the excess energy = $E - E_g$ is given off as a heat to the material.

③ Voltage loss:

→ The voltage corresponding to the bandgap of a material is obtained by dividing the bandgap by charge, E_g/q. This is referred to as bandgap voltage.

④ Fill factor loss:

→ The ff factor is around 0.89.

→ This type of loss arises due to the parasitic resistance (series and shunt resistance) of the cell.

⑤ Loss by reflection.

→ A part of incident photons is reflected from the cell surface

⑥ Loss due to incomplete absorption.

→ The loss of photons which have enough energy to get absorbed in the solar cell, but do not get absorbed in the cell due to limited solar cell thickness.

⑦ Loss due to metal coverage:

→ Shadows due to metal contacts, reduce illumination area

⑧ Recombination losses:

→ Not all the generated electron-hole pairs contribute to the solar cell current and voltage due to recombination losses.

Free Electron Theory of Solids

→ In Solids, electrons in the outermost orbit of atoms determine its electrical properties. Electron theory is applicable to all Solids: both metals and non-metals.

→ In addition, it explains the electrical, thermal and magnetic properties of Solids.

→ The structure and properties of solids are explained employing their electronic structure by the electron theory of solids.

Drude - Lorentz Theory.

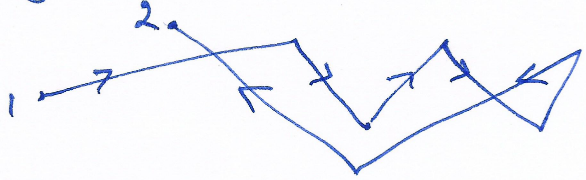
→ The first theory, namely, classical free electron theory, was developed by Drude and Lorentz in 1900.

→ According to this theory, metal Contains free electrons which are responsible for the electrical Conductivity and metals obey the laws of classical mechanics.

→ The classical free electron theory reveals that the free electrons are fully responsible for electrical Conduction.

Postulated of classical free Electron Theory.

→ The free electrons or electron gas, available in a metal move freely here and there during the absence of an electric field similar to the gas molecules moving in a vessel.

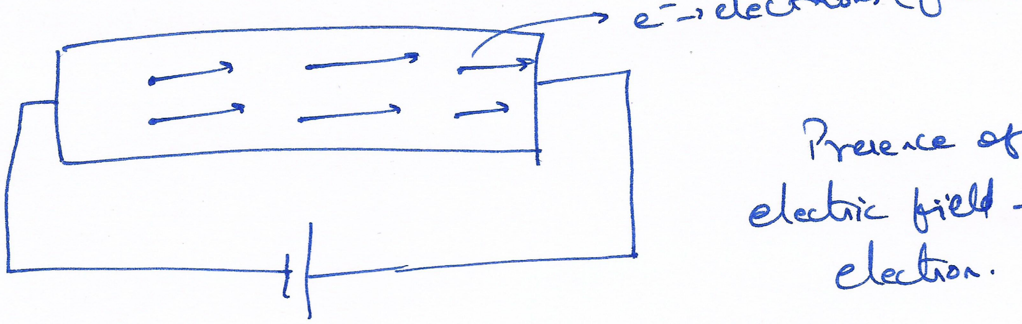


Absence of electric field, free electron.

→ These free electrons Collide with other free electrons or positive ion Cores and the walls of the Container. Collisions of this type are known as elastic Collisions.

→ The total energy of an electron is assumed to be purely Kinetic energy.

→ Suppose an electric field is applied to the material through an external source, the free electrons gain some energy and are directed to move towards a higher potential.



Presence of electric field - free electron.

→ These electrons acquire a constant velocity known as drift velocity, which obey the Maxwell-Boltzmann distribution studies.

→ Drift velocity: It is defined as the average velocity acquired by the free electrons in a particular direction during the presence of an electric field.

→ Relaxation Time: The relaxation time is defined as the time taken by a free electron to reach its equilibrium position from its disturbed position, during the presence of an applied field.

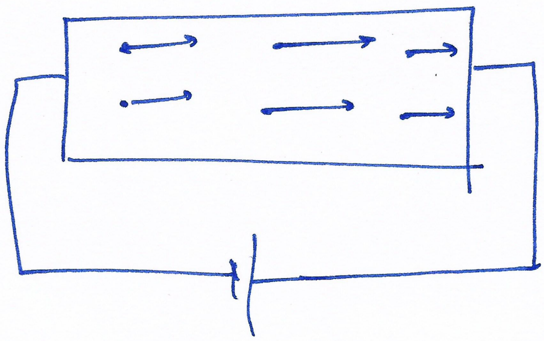
$$\tau = \frac{l}{\langle v \rangle}$$

where, l is the distance traveled by the electrons.

Expression for Electrical Conductivity.

→ Consider a conductor which is subjected to an electric field of strength E.

→ Consider that "n" is the concentration of free electrons with mass "m" and charge "e".

→ 

Metal- Conduction.

→ According to Newton's Second law of motion, the force f acquired by the electrons is equal to the force exerted by the field ~~of~~ on the electrons.

→ The equation of motion, $ma = -eE \Rightarrow a = \frac{-eE}{m}$

→ Acceleration, $a = \frac{-eE}{m}$

→ velocity, $v = -\frac{eE}{m}t + c$ (by integrating $ma = eE$)

where, c = integrating Constant

→ when there is no electric field, the average velocity of electron is zero

→ Then, $t = 0$, $\langle v \rangle = 0$ leading to $c = 0$

→ Hence velocity of an electron, $v = \frac{-eE}{m}t$

→ According to Ohm's law, the current density in a conductor,

$$J = \frac{I}{A}$$

→ The charge dq flowing through this area A in time dt is given by.

$$dq = -enAv\,dt$$

$$\frac{dq}{dt} = I = -endv$$

where I is the current flowing through the conductor with an

Cross Section A.

→ $$J = -nev = \frac{ne^2 E}{m} t$$

$$\boxed{J = \frac{ne^2 E}{m} t}$$

→ The current density is directly proportional to the applied field E.

→ When the field increases, the current density also increases and it remains infinity when the field is applied for a long time.

→ Actually, J never becomes infinity.

→ It remains constant beyond a certain field strength.

→ This is due to the presence of collision of free electrons which is not taken into account for the derivation of conductivity.