Free Study Material
from
All Lab Experiments

Solid-State Physics Notes
for NET/GATE Physical Sciences
Opto-Electronics Devices

Opto Electronic Devices

(i) LED

(ii) LASER

(iii) Solar cell

(iv) photodetector

first (2) devices convert electrical energy in optical energy.
& last 2 " " optical " " electrical ".

Interaction of light (photons) with Semiconductor is described by two effects:-

1. photo voltaic effect
2. ~~ph~~ Electro luminescence

Photo voltaic Effect :- When optical energy is converted into electrical energy, this is photovoltaic effect. Devices working on this effect are → Solar cell, photodiode & photodetector.

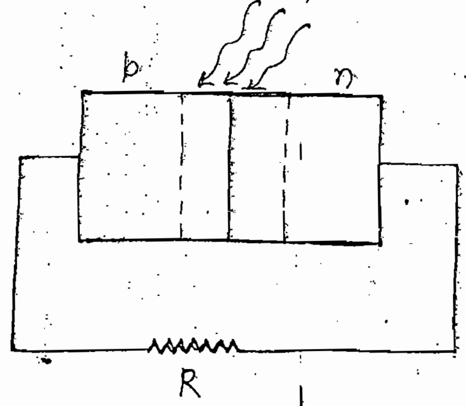
Electro luminescence :- when electrical energy is converted into optical energy, this is called Electro luminescence. Devices working on it are → LED & LASERs.

Photo diode :- It can work in 2 forms → photodetector as well as solar cell.

Basically photodiode is a p-n junc^n diode designed to respond under photon absorption

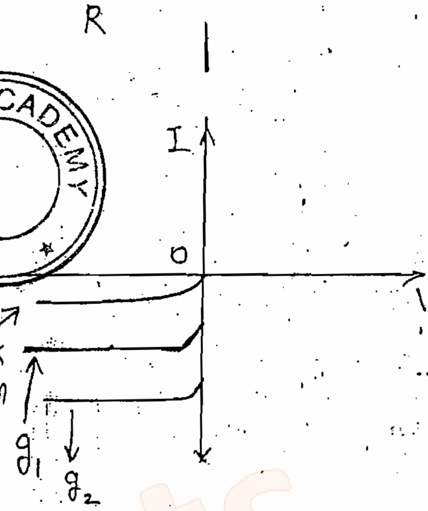
There will be absorption only if $h\nu > E_g$

If a resistance R is connected in p-n junc^n then current will pass through this R becoz p-n junc^n works as a solar cell. If current flow then it will supply the power to diode.



By incidenting light the reverse current will increase.

$g \rightarrow$ no. of e^--hole pair (EHP) generated per unit volume per second.
It is called Optical generation Rate.



Under dark cond^n $\rightarrow g = 0$

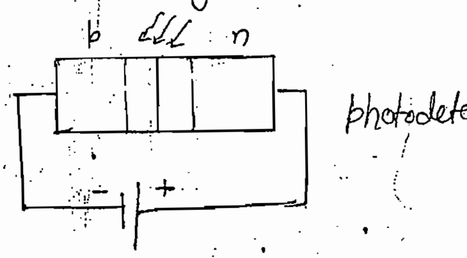
If $g \uparrow$ from g_1 to g_2 & s.t.

$g_2 > g_1$ then Reverse current $\uparrow$

This current is almost independent on applied voltage but depending upon optical generation rate.

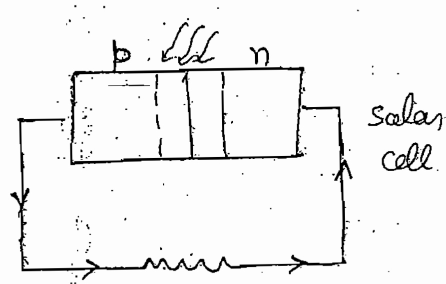
$\rightarrow$ If ~~in place of R~~ there is connected a load resistance R ~~with no o~~ and opptically illuminated p-n junc^n with no applied bais is Solar cell.

$\rightarrow$ Opptically illuminated with reverse bias at the junc^n then it become photo detector.

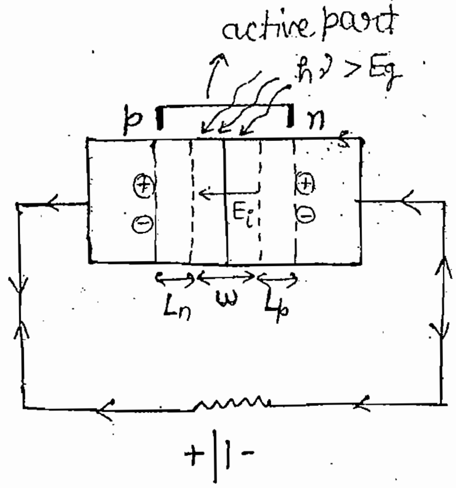


If we want to extract the power from the device then, have to work in solar cell mode.

photodetector convert $\rightarrow$
$\rightarrow$ Time varying optical signal into electrical signal. It is used in optical fiber.



Solar Cell :-



how the current will be produced -

When a light of Energy $h\nu > E_g$ incident on the P-n junction, it creates EHPs. These optically generated EHPs swept through the junction & result in a reverse current. If g_{op} is optical generation rate (EHP generated per unit volume per unit time EHP/cm³ sec) the no. of e⁻ generated per sec on p-side within the diffusion length L_n are $AL_n g_{op}$

where A → Cross sectional area of the junc^n.

Similarly, no. of holes generated per sec. in diffusion length L_p on n-side are - $AL_p g_{op}$ and EHP's generated in the depletion region are AWg_{op}.

Hence current due to optically generated charge carriers -

$$I_{op} = eAg_{op}(L_n + L_p + W) \quad \text{——— (1)}$$

If I_{th} is the thermally generated current and V is the applied voltage at the junc^n then

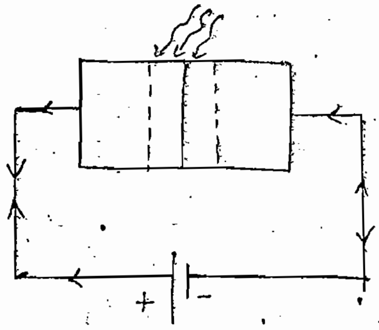
$$I_D = I_{th}\left[\exp\left(\frac{eV}{KT}\right) - 1\right] \quad \text{——— (2)}$$

I_D → dark current

If we applied a positive bias to the junc^n without any optical illumination then current due to applied voltage is equal to I_D.

Net Current; $I = I_0 \mp I_{op}$ ——— (A)

$$I = I_{th}\left(e^{eV_{oc}/k_BT} - 1\right) - eA g_{op}(L_n + L_p + W) = 0$$



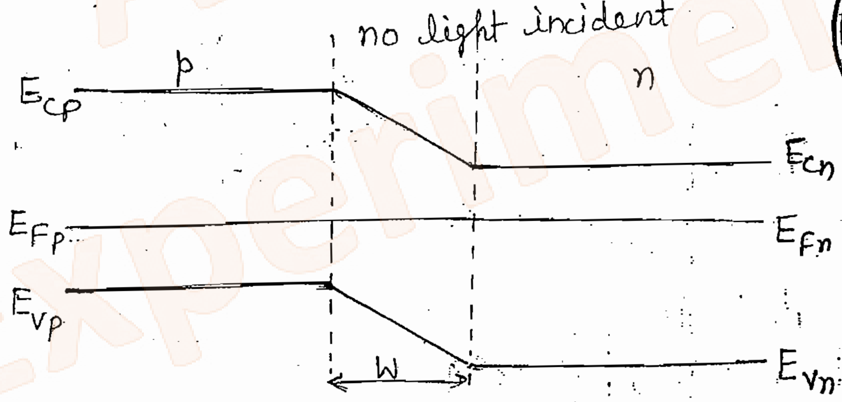
$$\Rightarrow I_{th}\left(e^{eV_{oc}/k_BT} - 1\right) = eA g_{op}(L_n + L_p + W) = I_{op}$$

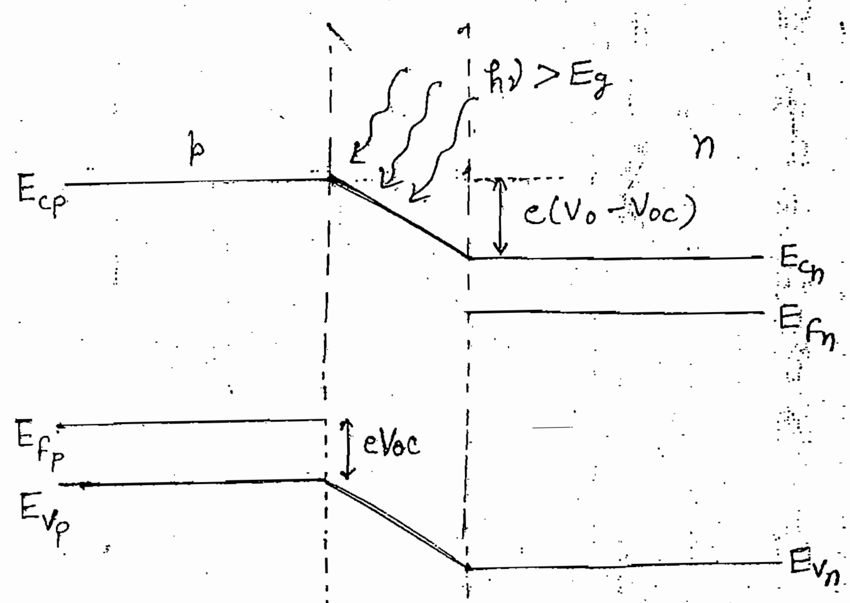
$$e^{eV_{oc}/k_BT} = \frac{I_{op}}{I_{th}} + 1$$

$$\boxed{V_{oc} = \frac{k_BT}{e}\ln\left(\frac{I_{op}}{I_{th}} + 1\right)} \quad \text{——— (3)}$$

V_{oc} → open circuit ~~cu~~ voltage

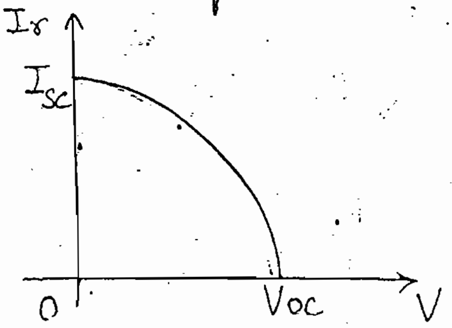
If we use the high intensity beam then it have greate g_{op}. Current will flow from n → p and this is reverse current.

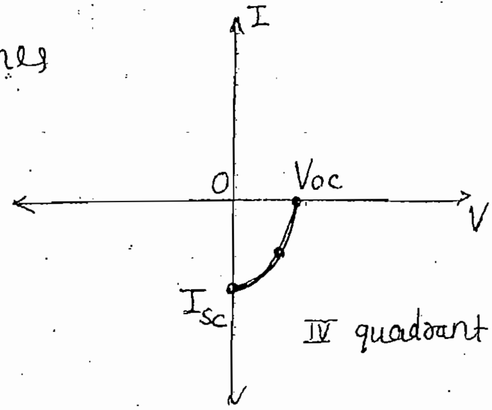




I-V characteristics :-

I_{sc} → short circuited current. (sometimes it plotted like this),





When $V=0$ then from (A) ⟹ $I_{sc} = -I_{op}$

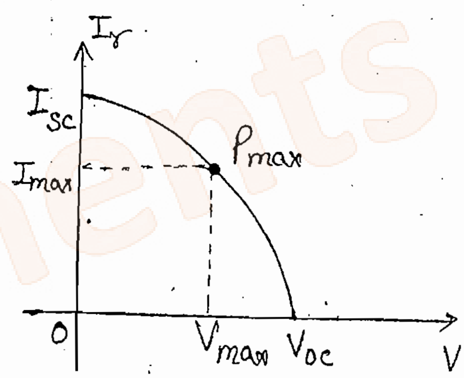
Maximum Power P_{max} drawn from solar cell -

$$P = IV$$

If we are performing an experiment of solar cell then we note down current w.r.t. to applied voltage.

I_{max} → Max. desired current

V_{max} → Max. desired voltage



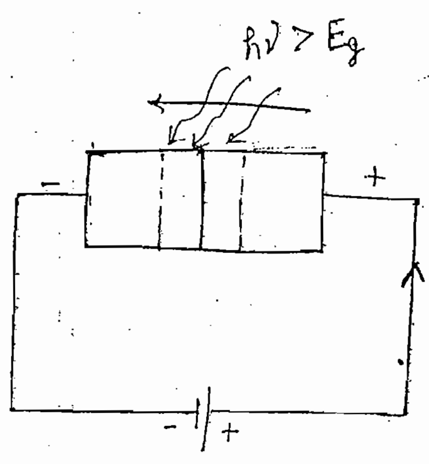
Fill Factor :-

$$\eta = \frac{I_{max} \cdot V_{max}}{I_{sc} \cdot V_{oc}}$$

η → measure of efficiency of the solar cell.

η can not approach 1 ($\eta < 1$) always

Photodetector :-

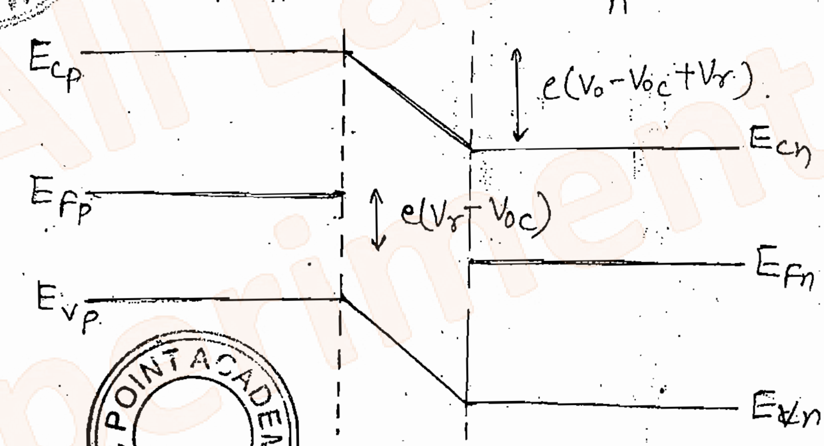


When the photodiode operates in the III quadrant of I-V characteristic meanings, reverse biased P-N jun^n with optical illumination then the reverse current is almost independent of applied voltage but proportional to the optical generation rate.

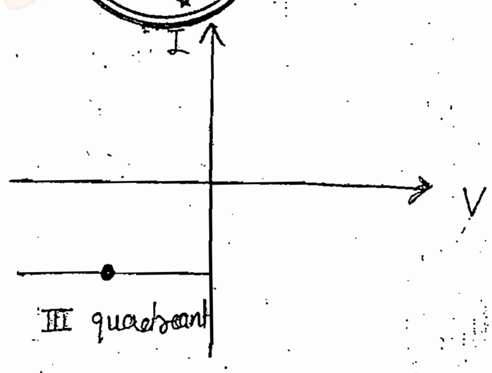
Such a device is very useful in converting time varying optical signal into electrical signal.

Photogenerated minority carriers electrons on p-side, holes on n-side cross the jucⁿ & gives rise to a reverse current. If there is a reverse bias at the jucⁿ, charge carriers sweep the jucⁿ more fast as compare to no bias at the jucⁿ hence device has high speed response. So it can work at high freq.

Energy band diagram :-



I-V Characterstics



Imp

Parameter of Photodetector :-

(1) Photosensitivity and responsivity :- rep^n by S or R.
It is defined as optically generated current in amp devided by power incident in watts.

$$S \text{ or } R = \frac{I_{op}(A)}{P_{in}(W)} \quad amp/W$$

Valid for Solar cell also.

(2) Quantum Efficiency :-

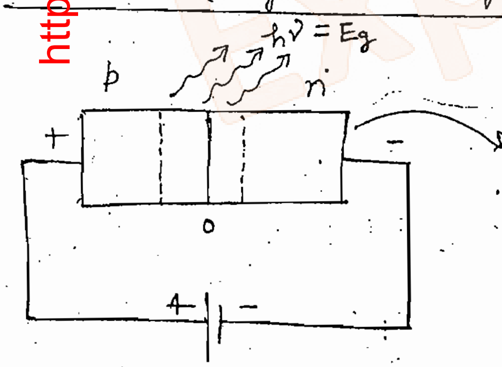
$$Q.E. = \frac{R \times 1240}{\lambda (nm)} \leq 1$$

R ⟶ Responsivity (Amp/W)

$\eta = 1$ means each photon is absorbed is contributed to the current.

Devices Working on Electroluminiscence :-

(1) LED (Light Emitting diode) :- LED is forward bais p-n jun^n diode.



If we apply F.B. then EHP recombine near the jun^n hence recombination energy emitted ~~foom~~ in the foom of photon of energy $h\nu = E_g$.

Here we use direct band gap S/c such that most of the light must emitted in the foom of photon. Energy of photon depands on the band gap of the S/c.

$$E_g = h\nu$$

$$E_g = \frac{hc}{\lambda} \Rightarrow E_g = \frac{1240}{\lambda (nm)} eV$$

- LED emits incoherent light

Parameter :-

(1) Quantum Efficiency of LED :- It is defined as -

$$Q.E. = \frac{\text{optical power out}}{\text{Electrical power in}} \leq 1$$

e.g. If $\eta = 80\%$ means 80% part of electrical power convert into optical power.

Power is Energy per sec.

$$E\ (\text{energy/sec}) = n h\nu$$

$n \rightarrow$ no. of photons/sec.

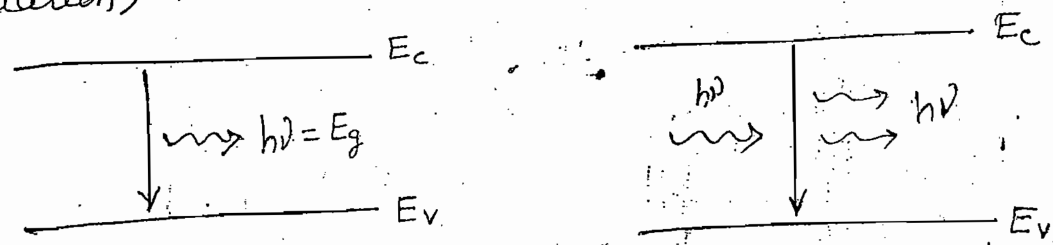
by this formula we can calculate the no. of photon/sec if we know power of Energy/sec

For GaAs $\rightarrow$ $E_g = 1.43\ eV = h\nu$

(2) Slop efficiency :- It is defined as optical power out divided by input current.

$$\text{Slop efficiency} = \frac{\text{optical power out}}{\text{Input current}} \left(\frac{W}{A}\right)$$

- LASER (Light amplification by stimulated emission of radiation) :-



Spontaneous Emission   Stimulated emission

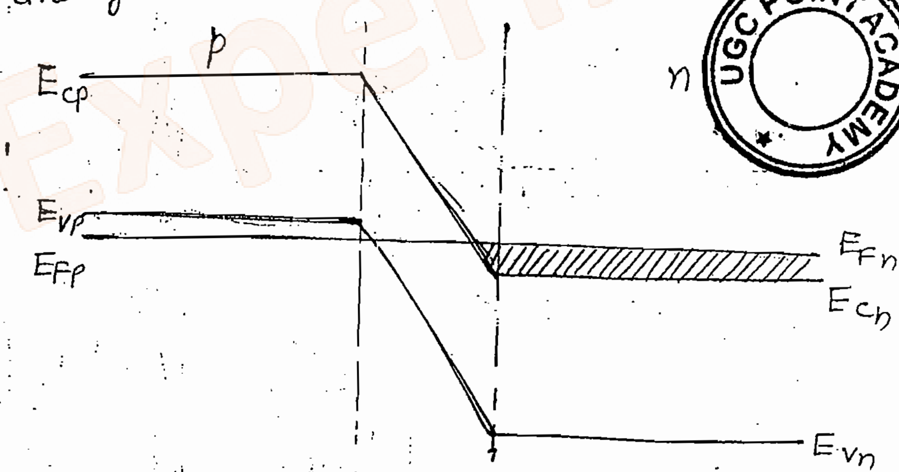
here we only concerned about semiconducting lasers.

Population Inversion :- Particle in the excited state is more than the ground state. Generally it does'nt happen becoz atoms follows M-B statistics & acc. to this $N \propto e^{-E/KT}$

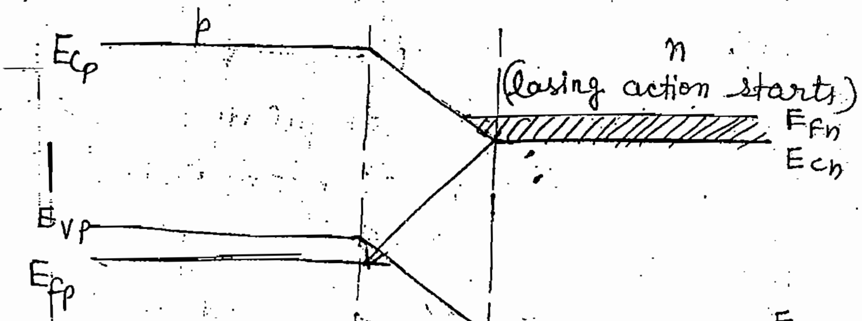
So here we need to pump, which is called optical pumping.

Semiconducting lasers is also a F.B. p-n junc^n made from degenerate S/c. Degenerate S/c are those S/c which are so heavily dopped that fermi level on p-side lies in the valance band and on n-side lies in the conduction band. As we increase doping (donar) then fermi level will move in upward dir^n & for acceptor impurity fermi level will move in downward dir^n. Law of mass action is not valid for degenerate S/c.

Optical pumping in LASER is corresponds to apply a F.B. to the junc^n.



When we apply F.B. → the lasing ~~acting~~ action will start after a thereshold value.



In SC lasers we can vary the W.L. by changing the doping concentration.

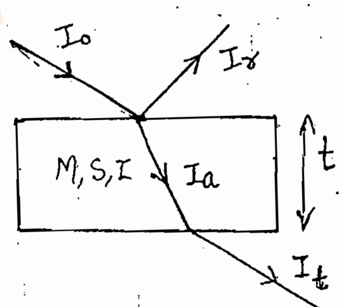
e.g. $Al_{1-x}Ga_xAs$ → It have different band gap for different x. (In semiconductor)

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

Advantages of SC Lasers :-

(i) It is small and compact
(ii) It has high efficiency.
(iii) Less power consumption.
(iv) Laser light W.L. can be easily modulated by changing the bandgap of the semiconductor.

If we have a crystal & we incident light on it, this crystal can be made up of metal, semiconductor or insulator. Then some part of light reflect through the crystal & some part will be transmitted.



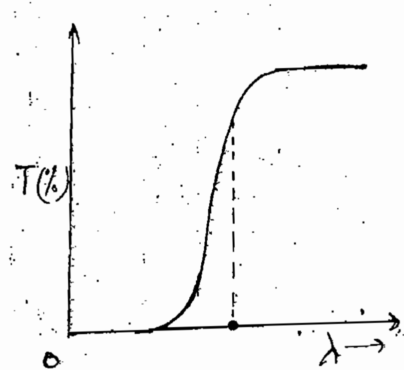
$$I_o = I_t + I_r$$
$$I_t = I_o - I_r$$

If no reflection by the surface → $I_o = I_a + I_t$

$$I_t = I_o e^{-\alpha t}$$

and $\boxed{A + T = 1}$

where A → absorbance
T → Transmittance



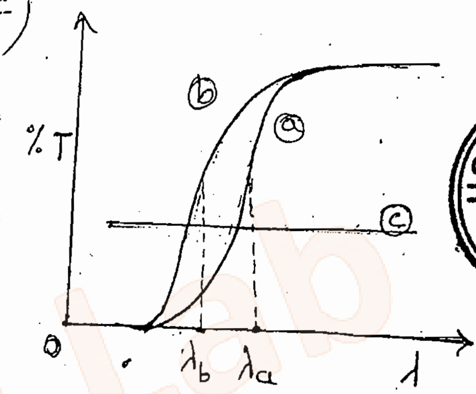
(i) If $h\nu < E_g$ then $A = 0$
$T \simeq 100\%$

& corresponding W.L. will be more.

(ii) If $h\nu = E_g$ then transmittance decreases.
We can calculate the approx. band gap by ~~expo~~ extrapolation of this curve. $\left(E_g = \frac{hc}{\lambda}\right)$

b → insulator
a → semiconductor
c → metal

$\lambda_a > \lambda_b$



Graph of absorptance Vs λ is just opposite to the
" " Transmittance Vs λ.

• UV- Visible spectroscopy by this we can calculate the band gap of any semiconductor which have high band gap (lies in UV-region).

Properties of electrons & holes in a filled band of S/c :-

(i) $\vec{K_h} = -\vec{K_e}$

(ii) $E_h(K_h) = -E_e(K_e)$

(iii) $m_h^* = -m_e^*$

(iv) $\vec{v_h} = \vec{v_e}$

(v) $\hbar \frac{d\vec{K_h}}{dt} = e(\vec{E} + \vec{v_h} \times \vec{B})$ (for holes)

$\hbar \frac{d\vec{K_e}}{dt} = -e(\vec{E} + \vec{v_e} \times \vec{B})$ (for e⁻s)

- When we apply force then e^- & holes will gain momentum in opposite dir^n.

$$p = \hbar k = mv$$

$$\Rightarrow \hbar k_h = -\hbar k_e$$

$$\Rightarrow m_e v_e = (-) m_h v_h$$

this -ve sign corresponds to effective mass & veloci[ty] is +ve

Exercise - "B"

Que. 1 :- A 0.46 um thick sample of GaAs is illuminated with a monochromatic light of energy $h\nu = 2$ eV. The absorpti[on] co-effi. of GaAs is $5 \times 10^{+4}$ cm^{-1}. The incident power on th[e] sample is 10 mW. If the bandgap of the crystal is 1.43 eV. Calculate -

(i) Total power absorbed by the sample.

(ii) Total no. of EHP generated /sec from the absorption assuming perfect Quantum efficiency.

Q.2 :- The donar concentration of n-type S/C ($E_g = 2.303$ eV) is $N_d = 2 \times 10^{16}$/cm^3. Find the temp. (in terms of Boltzma[nn] constant K_B) at which the SC starts behaving like an intrins[ic] SC. The density of states in conduction & valance bands are 4×10^{19}/cm^3 & 1×10^{19}/cm^3 respectively.

Q.3 :- A hypothetical S/C has an intrinsic carrier concentration of 1×10^{10}/cm^3 at 300 K. It has conduction & valance band effective density of states N_c & N_v both equal to 10^{19}/cm^3.

(a) What is the bandgap of the S/C.

(b) If SC is doped with $N_d = 1 \times 10^{16}$/cm^3. What are the equilibrium e^- & hole conc. at 300 K.

(c) If this piece of S/c already having $N_d = 1\times10^{16}/cm^3$ is also doped with $N_a = 2\times10^{16}/cm^3$ then calculate new e^- & hole conc.

(d) Consistent with your ans. to part c what is the fermi ~~level~~ position w.r.to intrinsic level E_i

Q.4:- A Si sample is doped with 10^{16} As atoms/cm^3. Calculate the equilibrium e^- & hole concentration at 300 K. Also find the position of E_F w.r.to E_i. Given $n_i = 1.5\times10^{10}/cm^3$.

Q.5:- An intrinsic ~~S/c~~ GaAs e^- and hole mobilities are 0.85 & 0.04 met^2/Vsec respectively & corresponding effective masses are $0.068\, m_0$ & $0.5\, m_0$ where m_0 is the rest mass of the e^- if band gap of this crystal is 1.43 eV at 300 K. Determine n_i & σ.

Q.6:- Resistivity of an unknown intrinsic S/c is 4.5 Ω-m at 20°C & 2 Ω-m at 32°C. Find the energy band gap of this S/c

Q.7:- (a) Show that the minimum conductivity of SC sample occur when $n = n_i\sqrt{\frac{\mu_h}{\mu_e}}$ & $p = p\, n_i\sqrt{\frac{\mu_e}{\mu_h}}$.

(b) Write the relation b/w minimum conductivity & intrinsic conductivity for this s/c.

Q.8:- Intrinsic Germanium has a band gap of 0.7 eV & e^- mobility is two times that of hole mobality at 300 K. Calculate the position of fermi level w.r.to the V.B. edge.

Q.9 :- A Si Solar cell with I_{th} = 5mA is illuminated s.t. short circuit is 200 mA. Calculate the V_{oc} at 300 K.

Q.10 :- A Si Solar cell with 2cm X 2 cm cross sectional area i I_{th} = 32 nA has an optical generation rate of 10^{18} EHP/cm^3 (g_{op}) within $L_n = L_p$ = 2 µm & W = 1 µm. Calculate I_{sc} & V_o

Q.11 :- A Solar cell has a short-circuit current of 50 mA & open circuit voltage of 0.7 volt under full solar illumination. What is the maxi. power delivered by this cell, If fill factor is 0.8.

Q.12 :- A photoconductive cell having dimension 1×1×1 mm^3 made from cds crystal is illuminated with the light of W.L. 450 nm & Intensity of 1 mW/cm^2. ~~Light of W.L. 450 nm~~ Assuming Q.E. of unity. Calculate the no. of EHP generated/sec. Given that Energy gap of Cds, E_g = 2.6 eV.

Q.13 :- What W.L. of light is emitted by a LED. If it is made from a SC.

(a) Ge (0.7 eV)
(b) Si (1.1 eV)
(c) GaAs (1.43 eV)
(d) Cds (2.6 eV)

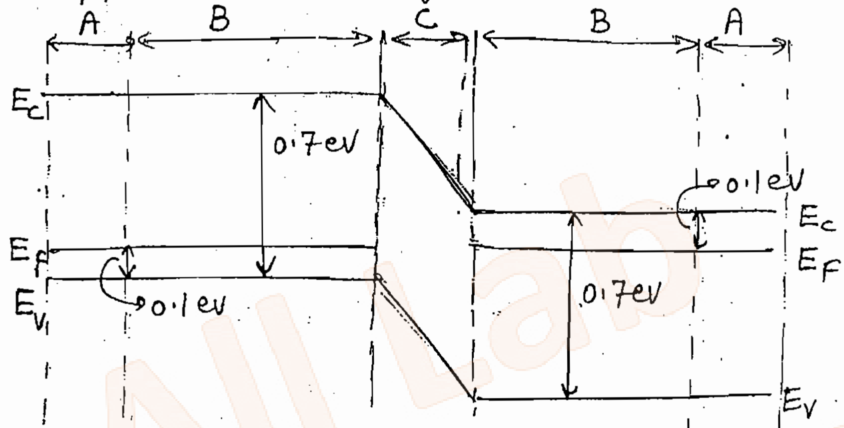
Also find In which region of EM spectrum, these W.L.'s would lie.

Q.14 :- A Si photodiode has an active light receiving area of dimension 0.4 mm X 0.4 mm when radiation of W.L. λ = 7000 nm & intensity of 0.1 mW/cm^2 is incident. It generates a photoconductor of 20 nA. Calculate

(a) Responsivity (R) in amp/w.

(b) Quantum Efficiency of photodiode at 700 nm (within an accuracy of 1%)

Q.15 :- Consider a band gap diagram of simple LED. Assume all recombination as direct & result in light emission. A. F.B. is applied on the junction.



(a) In which region would you expect the optical recombination rate to be greatest.

(b) What the approximate energy & W.L. of emitted photons.

(c) For the steady state current of $I = 10$ mA. Assuming that all photons escape. What is the optical output power consistent with your answer to part (b).

(d) What is the electrical power consumed if 1.4 V is applied at the jun^n.

(e) Quantum Efficiency of LED.