Semiconductor fundamentals

lec 04
15/7/15

Topics:
- Fermi-Dirac fraction
- Physical interpretation of fermi-level (E_F)
- Relation of n_i with E_g (Energy gap)
- Sources of carriers in extrinsic semiconductor
- Charge-balance equation
- Band model of extrinsic semiconductor
- Heavy doping effects on EBD
- Carrier transport
- Drift and diffusion current eqn's.
- Types of Scattering
- Method's of generating excess carriers
- Injection level concept.
- Effect of excess carriers on EBD
- Concept of Quasi-Fermi level
- Direct Vs Indirect Bandgap Semiconductor
- Carrier Lifetime

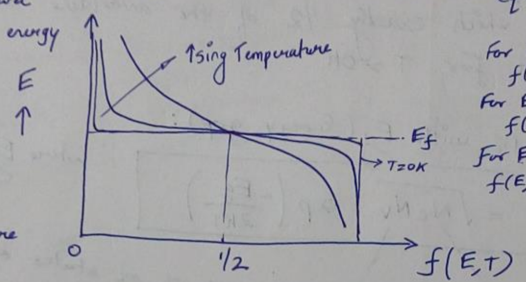
- Fraction of available states occupied at any E, T is

01

$$f(E,T) = \left[\frac{1}{1+\exp\left(\frac{E-E_F}{KT}\right)} \right] \text{ --- Fermi-Dirac fraction --- eq}^n \text{ (1)}$$

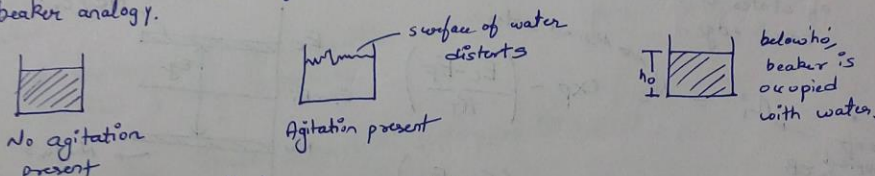
where E_F : Fermi level
KT : Thermal energy

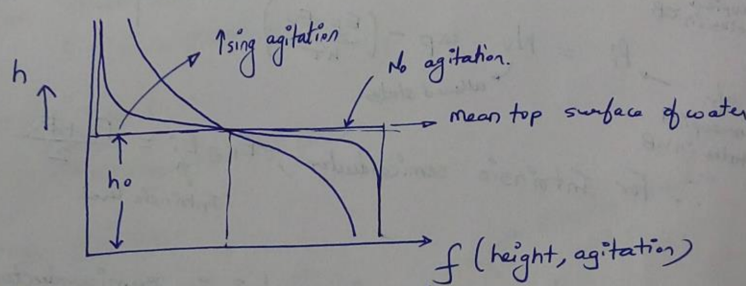
- Eq^n (1) tells that e^- from lower energies are moving to higher energies as Temperature ↑ses.



For $E \to \infty$
$f(E,T) = 0$
For $E = E_F$
$f(E,T) = 1/2$
For $E \to -\infty$
$f(E,T) = 1$

- To understand the shape of Fermi-Dirac function we use Water in beaker analogy.





f (height, agitation) → fraction of beaker volume occupied.

In this analogy,

Water in beaker ⟷ electrons
Beaker volume ⟷ allowed energies
height ⟷ energy
agitation ⟷ Temperature
fraction of beaker volume ⟷ fraction of occupied states
mean top surface ⟷ Fermi level.

• Physical significance of Fermi-level (E_F):

It is that

(i) Energy below (above) which all allowed levels are occupied (unoccupied). at $T = 0K$

(ii) Energy at which exactly 1/2 of the available states are occupied for $T > 0K$

• Relation of n_i with E_g (Energy gap):

$$n_i = \sqrt{N_C N_V}\ \exp\left(\frac{-E_g}{2KT}\right)$$

where $E_g = E_C - E_V$

Intrinsic e^- concn → n_i

N_C → Effective density of states at conduction (CB) band edge.

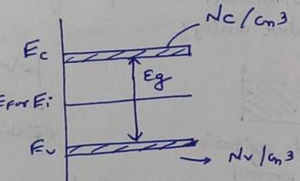
N_V → Effective density of states at valence band (VB) edge

• $n_i = N_C \exp - \left(\frac{E_C - E_F}{KT}\right)$

n_i → no of occupied states in CB; N_C → Allowed states

$p_i = N_V \exp - \left(\frac{E_F - E_V}{KT}\right)$

p_i → no of unoccupied states in V.B; N_V → allowed states

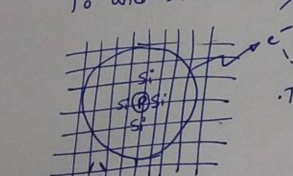


∴ For Intrinsic semiconductor, $E_F = E_i = \frac{E_C + E_V}{2}$

E_i → Intrinsic level

• Sources of carriers in extrinsic semiconductor:

To understand this, let consider Phosphorus doped Si (ie N type Si) → has 5 valence e^-s.



At $T > 0K$;

→ This e^- becomes free bcoz of thermal vibration of Si atoms

• The energy required to free this 5th e^- from the orbit is ionization energy.

$E_{ion(Ph)} = 0.045\,eV$ → (This is very small)

∴ Even at $T > 0K$ (lower temp), most of impurity atom (Ph) get ionized & each Ph atom will contribute to an e^- (which is available for conduction, but no hole is created)

At high tempr, Si-Si atom bond can break (Si ionization) ⇒ EHP created.

⇒ This is addn source of carrier.

∴ Sources of Carriers in extrinsic semiconductor:

Process	Result	Energy required (For Si)
Impurity ionization	only e^- or only hole	0.045eV
Silicon ionization or (Thermal generation)	EHP (Electron-hole pair)	1.1eV

↳ This much energy is required to break Si-Si bond

$N_d^+ / N_d \leq 1$

N_d^+ → concⁿ of ionized P atoms

N_d → concⁿ of P atoms (donor)

- At room temp, most of impurities are ionized, becoz energy reqᵈ for this is only 0.045eV.

Similarly, for Boron doped Si: (p-type Si):

$E_{ion}(B) = 0.045eV$

$\frac{N_a^-}{N_a} \leq 1$

N_a^- → concⁿ of ionized B atoms.

N_a → acceptor impurity concⁿ

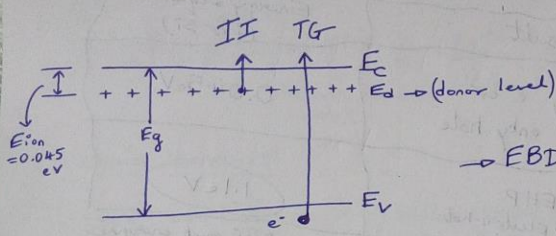
- Charge balance equation:

n-type (P, Gr V): $n_{n_0} = N_d^+ + p_{n_0}$

p-type (B, Gr III): $p_{p_0} = N_A^- + n_{p_0}$

- n_{n_0}, p_{p_0} → Majority carrier concentration
- N_d^+, N_A^- → Impurity ionization process
- p_{n_0}, n_{p_0} → thermal generation process → Minority carrier concⁿ

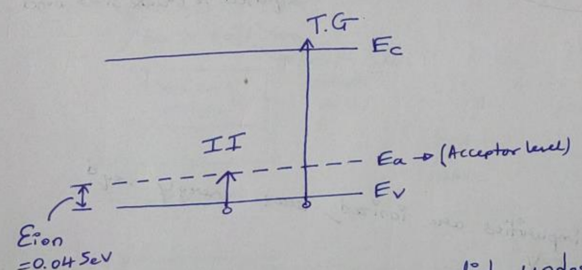
• Band model of extrinsic semiconductor



II → Impurity ionization

TG → Thermal generation

→ EBD of ntype Si

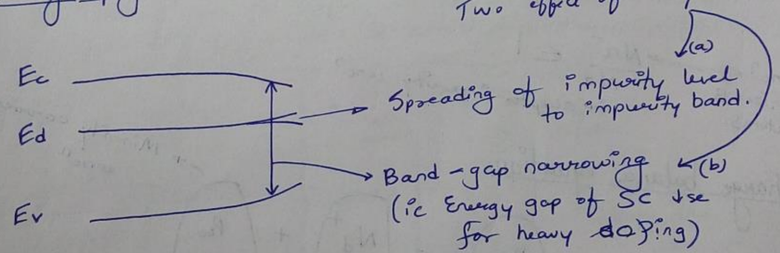


→ EBD of ptype Si

→ The above EBD picture is valid under Moderate doping.

• Heavy doping effects on EBD:

Two effect of heavy doping



· Impurities starts interacting when doping is heavy, beco z distance between impurities starts reducing. As a result, single level impurity will spread into a band.

- $p_{n_0} n_{n_0} = N_c N_v \exp -\left(\frac{E_g}{KT}\right) = n_i^2$ --- Law of mass action

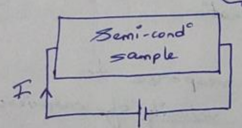
For n type Semiconductor: $p_{n_0} = \frac{n_i^2}{n_{n_0}} \simeq \frac{n_i^2}{N_d}$ $\quad (n_{n_0} = N_d)$

(p_{n_0} → minority carrier conc^n)

- **Carrier transport:**

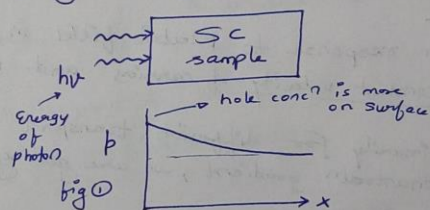
Let's see some examples of various modes of transport

1. Flow of current in SC is due to 'drift' here (due to potential gradient)



Drift transport

2. Light falling on SC sample



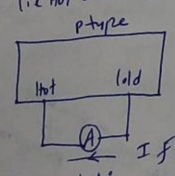
Diffusion transport

- Here hole current is due to conc^n gradient (i.e. due to diffusion)
- Diffusion transport

If $h\nu > E_g$, such that EHP is created. Light (photon) is being absorbed within a short distance from surface, excess/extra carriers will be created near the surface. ← How?

∴ conc^n of carriers near the surface will be higher than in the bulk. Thus conc^n gradient of carriers is established (shown in fig①).

3. Sample with two contacts (i.e. Hot & cold contacts)

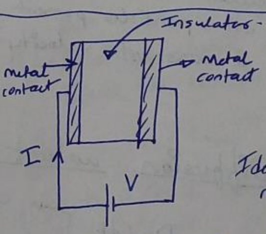


← I flow thr Ammeter

Thermo-electric current).

- Here, current I is established becoz of temperature gradient.

4.



Ideally, there shld be no current.

- However, if insulator is v.thin (few nm), then u find current flowing in response to voltage.
- This current flowing thr insulator is becoz of tunneling → (It is a Quantum mechanics phenomenon)

[we will cover it in some details later!]

- **Einstein relation** (It shows that both drift & diffusion are based on random thermal motion)

Diffusivity = Mobility × Thermal voltage (V_t)

(Diffusivity: constant associated with diffusion transport; Mobility: constant associated with drift transport)

$$V_t = \frac{kT}{q}$$

$$D = \mu V_t$$

↳ holds under quasi-equilibrium.

Facts:

1) In response to Electric field in drift transport, we are getting constant velocity of carriers and not acceleration

2) Simarily for diffusion transport also, in response to concentratn gradient, we are getting constant velocity of carriers.

why?

In semiconductor, we have other particles surrounding the e^-, & e^- is being scattered, that is why it is undergoing random thermal motion.

- It is becoz of this random motion that, e^- is not able to continuously accelerate (as e^- is encountering frictn during its moment becoz of other particles present in crystal). Thus, it can only acquire a constant velocity.

- **Drift and Diffusion current eq^n s.**

In p type SC:

$$J_{p\,diff} = -q D_p \frac{dp}{dx}$$ ($\frac{dp}{dx}$ → concn gradient)

$$J_{p\,drift} = -q p \mu_p \frac{d\psi}{dx}$$

$$J_{p\,drift} = q p \mu_p E$$

where $E = -\frac{d\psi}{dx}$ (E → E-field; ψ → gradient of potential)

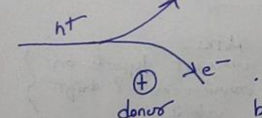
* Types of scattering:

1. Ionized impurity scattering. (for doped semiconductors)
2. Phonon / Lattice scattering. (e^- colliding with phonons) → vibrating Si atoms or Lattice site.
3. Carrier–Carrier scattering. (involves e^- & holes)

As Temp ↑, LS ↑ses

- phonons (Lattice scattering) → (Physical collision betⁿ carriers & Lattice site.)
- Ionized impurities (II scattering) → (It is becoz of action at a distance, it need not involve a physical collision)
- electrons, holes } (Carrier-Carrier scattering)
- In scattering, direction of motion of particle which has encountered a 'collision' cannot be predicted exactly.

Ionized impurity scattering



- II scattering changes directⁿ of particle.
- It takes place becoz of force of attractⁿ or repulsion betⁿ particle & this charge.

→ More the number of ionized impurities, greater is the chance of carriers getting scattered.

- For ↑sing temp, the scattering events will be less (becoz of ionized impurities)
- So, higher the concⁿ of impurities, higher is the chances of scattering

i.e II Scattering is most at lower temperatures.

Carrier–Carrier Scattering (CCS)

- e^-s by e^-s
- e^-s by h^+
- h^+ by e^-
- h^+ by h^+

] 4 events in CCS

- CC scattering is not important for carriers of same polarity.
- But C-C scattering by carriers of opposite polarity ⇒ definately effects the current.

Let us see how?

If a e^-/hole is colliding with other e^-/hole, it will transfer its momentum & energy to other e^-.

Now, current is not affected, since current is result of (energy & momentum of entire population) in any directⁿ.

For current to flow, it should be the directed component of momentum.

- Carrier-Carrier Scattering affects only the minority carriers mobility in a semiconductor. (except at v.high doping levels)
  CC scattering can affect the mobility of both e^- & holes

- Conductivity (σ)

$$\sigma = q n \mu_n + q p \mu_p$$

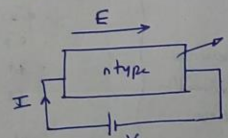
For ntype semiconductor:

$$\sigma = q n_{no} \mu_n + q p_{no} \mu_p \qquad (\because p_{no} << n_{no}) \text{ in ntype}$$

$$\sigma \simeq q n_{no} \mu_n$$ (This means that only majority carriers conc^n decides the conductivity)

- Methods of generating excess carriers:-
  1. Impact ionization
  2. Photo-ionization
  3. Injection mechanism
  4. Band to band tunneling

1. Impact ionization

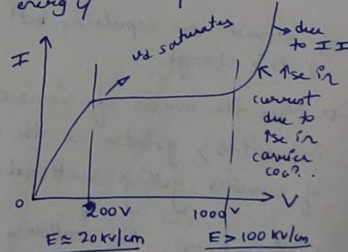


Assume semiconductor sample to be uniform.

- Excess carriers are generated under the influence of high E-field by Impact ionization.

{ Note: current depends on carrier conc^n & drift velocity }

→ Betn any 2 collisions, carriers are gaining energy from the E-field.
i.e This energy i.e gained is so large, that the carriers when it collides with Si atom, it can break a bond & can generate excess EHP.
So, this is the situation of Impact ionizatn.

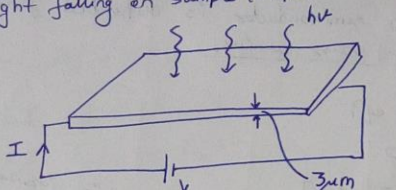


- Excess carriers: means carriers over & above the equilibrium value.

Note: Generally, excess carrier are created in pairs.

2. Photo-ionization / generation:-

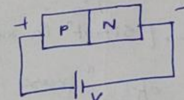
eg Light falling on sample (ntype)



Here, each photon having energy $h\nu > E_g$, can participate in breaking of Si bond & creating an excess EHP.

3. Injection mechansim:

. Consider a p-n junction



Forward junction biased.

• Here, p region (n) will inject extra holes (e⁻s) into n-region (p).

Thus, excess e⁻ & holes are created by appl^n of Voltage.

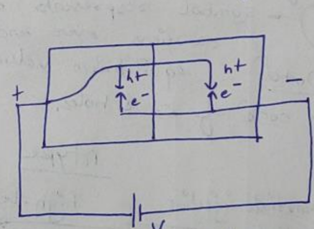
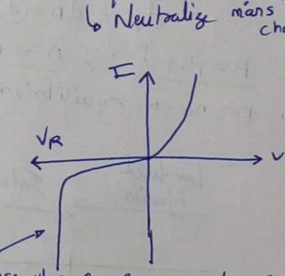


fig: Process of injection

Unique situat^n in SC ↳ Neutraliz means 'zero charge'!

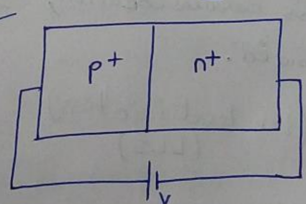


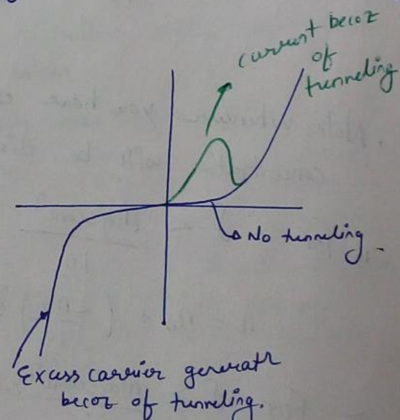
(For reverse vtgs, rise in current signifies generat^n of excess carriers)

. For this reverse vtg, a high E-field is created near the J^n (junction), which may give rise to excess EHP becoz of impact ionization or 'Tunneling'.

4. Band-to band tunneling:

. This eg shows a heavily doped p & n regions





. We will explore this type Later while encountering a device.

- **Injection level concept:**

  refer to
  The extend to which semi-conductor is disturbed from equilibrium becoz of excess carriers.

- Let's consider charge-balance eqn:

$$\delta[p + N_d^+ - n - N_a^-] = 0$$

ie $\delta p - \delta n = \delta[N_a^- - N_d^+]$ → If change in ionization of impurities is negligible, then $\delta p \approx \delta n$

≈ 0 — This is

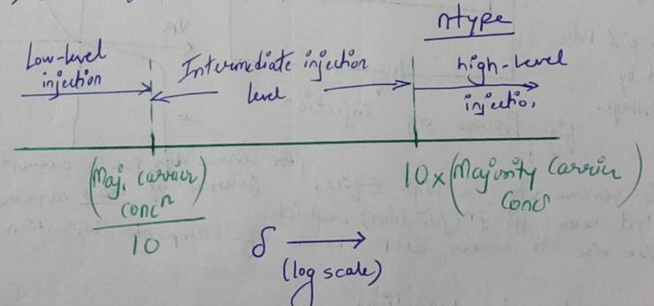
$\delta p \approx \delta n$ → (situatn in most SC)

This is the meaning of "excess carriers are generated in pairs!"

$\delta p \approx \delta n = \delta$ → symbol represents excess carriers over and above the equilibrium value.

ie $p = p_0 + \delta$; $n = n_0 + \delta$

where p_0, n_0 → equilibrium concn of e's & holes.



- Note: Whenever you have excess carrier creation, minority carrier concentration will be distributed.

→ For $\delta < \frac{\text{Maj.concn}}{10}$ (Low level injection) (LLI)

$$n = n_0 + \left(\frac{< n_0}{10}\right) \simeq n_0$$

→ For $\delta > \text{Maj.concn} \times 10$ (High level injection) (HLI)

$$n = n_0 + \underset{\delta}{(> 10 n_0)} \simeq \delta$$

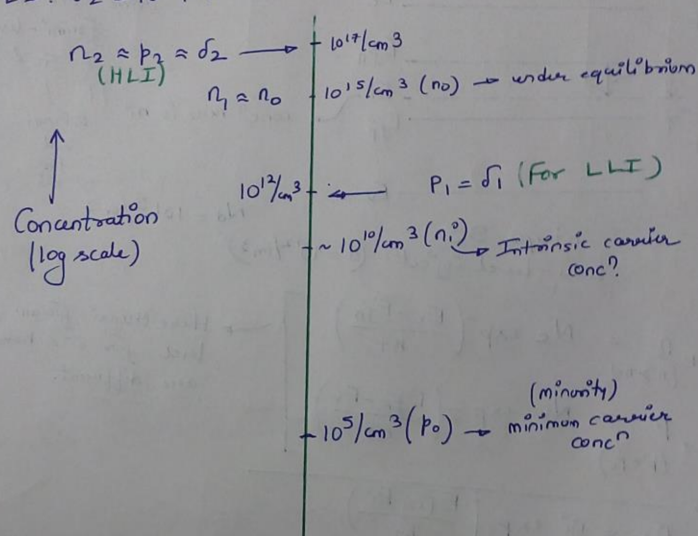
$$p = p_0 + \delta \approx \delta$$

Let us take an example to understand LLI & HLI:

n-type, $N_d = 10^{15}/cm^3$, Phosphorous doped Si

LLI : $\delta_1 = 10^{12}/cm^3$

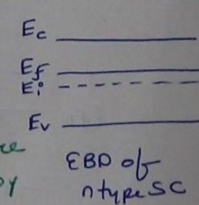
HLI: $\delta_2 = 10^{17}/cm^3$



Inferences from above discussion are:

1) For LLI, minority carrier conc^n is disturbed, while maj. carrier conc^n is almost same as in equilibrium.

2) For HLI, both majority and minority carrier conc^n are almost same.



- **Effect of excess-carriers on EBD:**

$$n_0 = N_c \exp -\left(\frac{E_c - E_F}{KT}\right)$$

$$p_0 = N_v \exp -\left(\frac{E_F - E_v}{KT}\right)$$

} Both n_0 & p_0 are characterized by same Fermi level

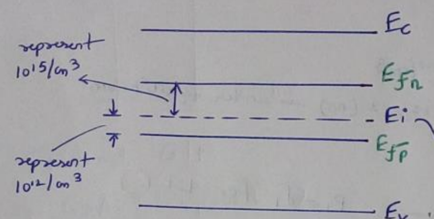
$$n_0 = n_i \exp\left(\frac{E_F - E_i}{KT}\right)$$

$$p_0 = n_i \exp\left(\frac{E_i - E_F}{KT}\right)$$

} n_0 & p_0 in terms of deviation from intrinsic SC

- The effect of excess carriers on EBD is different Quasi Fermi levels for e^- & holes:

- Quasi-Fermi level (under LLI and HLI):



Here, Fermi-level splits intwo two Quasi-Fermi-levels. (E_{fn} & E_{fp})
E_{fn}: Q. Fermi level for e^-s
E_{fp}: Q. Fermi level for holes

$N_d = 10^{15}/cm^3$

ntype SC
Low-level inject^n ($\delta = 10^{12}/cm^3$)

conc^n of e^-: $n = N_c \exp-\left(\frac{E_c - E_{fn}}{KT}\right)$ $(n > n_0)$

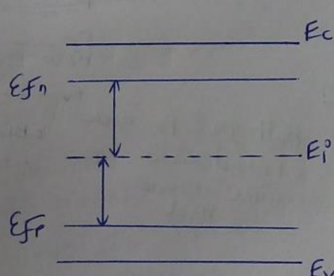
conc^n of holes: $p = N_v \exp-\left(\frac{E_{fp} - E_v}{KT}\right)$ $(p > p_0)$

→ Here Quasi-Fermi level for e^- & holes are different.

$$n_0 = n_i \exp\left(\frac{E_{fn} - E_i}{KT}\right)$$

$$p_0 = n_i \exp\left(\frac{E_i - E_{fp}}{KT}\right)$$

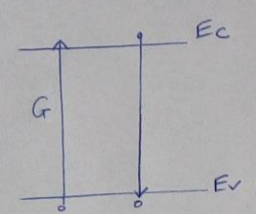
Note: Quasi-Fermi level are for (Quasi) Non-equilibrium conditions.



- Under HLI, excess hole and e^- conc^n will be same.

ntype SC
High-level injection ($\delta = 10^{17}/cm^3$)

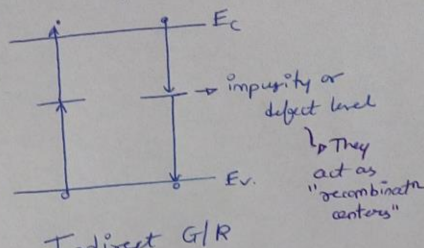
• Mechanism's of Generation-recombination phenomena:-



Direct G/R

eg GaAs (Compound SC)

· Here, wherever an e^- meet a h^+, a Recomb^n occurs.



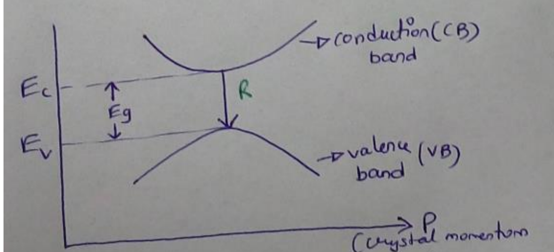
Indirect G/R

eg Si

· In Si, 'R' occur via impurity sites within the energy gap.

(So, near certain defect/impurity level within a SC, if e^- & h^+ meet, R can occur)

• Direct Vs Indirect Bandgap semiconductors:-



Direct band gap semiconductor

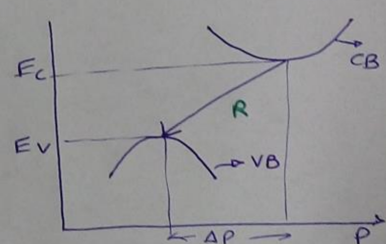
eg GaAs

· Here, momentum change is zero for the transition. & thus can be given to a photon

→ hence suited for opto-electronic devices

· Here, recomb^n process is radiative (direct)

· Uses for making LEDs



Indirect band gap SC

eg Si.

· Here, during transistion (e^- from CB to VB), there will be a change in momentum (ΔP).

· Here, recomb^n process is non-radiative.

· That means we cannot use Si for emitting light.

· Here, momentum can only be dissipated to a phonon or e^-.