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VIKAS KUMAR

Subject _____

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ELECTRONIC DEVICES

1. Introduction :

* Importance of Semiconductor Devices

These devices enhances:

- performance
- Reliability
- Cost - effectiveness

of

Energy Systems

Information Systems

- | | |
|-------------------|---------------------------|
| > Generate | > Store |
| > Distribute. | > process |
| > Regulate energy | > Communicate information |

Properties of Semiconductors :

- Polarity of charge carriers.
- Concentration of charge carriers.
- Transport of charge carriers
- interaction with electromagnetic field.

a) Polarity of charge carriers :

in semiconductors you can have both positive polarity and negative polarity that is one big difference between the semiconductors and the metals. In metals we have only negatively charged carriers

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that is electrons. The positively charged carriers in semiconductors are called holes.

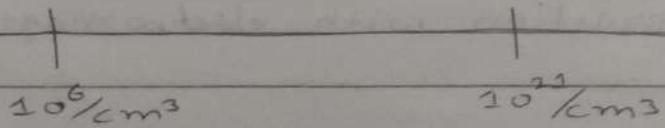
- Coming to the concentration:

In metals charge carrier concentration is beyond $10^{21}/\text{cm}^3$. So beyond 10^{21} we have the metals whereas below 10^6 we have the insulators and in between 10^6 and 10^{21} we have the semiconductors.

So the concentration of charge carriers in semiconductors varies over almost 15 orders of magnitude 10^6 to 10^{21} .

- Concentration can varied by:
doping, illumination & temperature variation.

Insulators \times Semiconductors \times Metals.



Concentration of carriers \rightarrow

- The transport of charge carriers in metals your current flows only because of drift, but in Semiconductors current can flow also because of what is called diffusion

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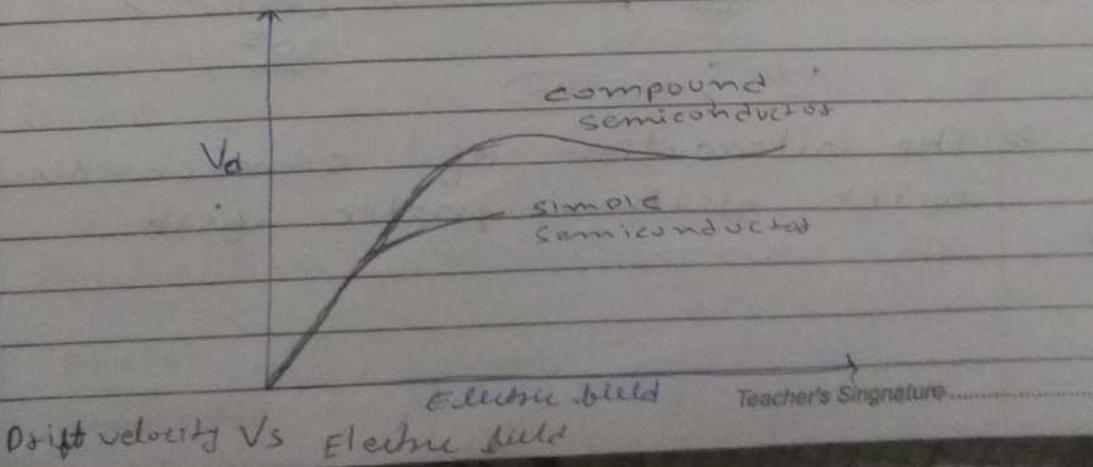
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temperature gradient called thermoelectric current.

- Drift is transport of carriers because of potential gradient.
- Diffusion is because of concentration gradient at different points.
- Another mechanism of current flow is because of temperature gradient called thermoelectric current.

Drift Transport:

drift current is associated with drift velocity. The drift velocity increases with increase in electric field, in the small electric field regions this variation is linear, but on increasing electric field this becomes sub-linear and ultimately the velocity tends to saturate.



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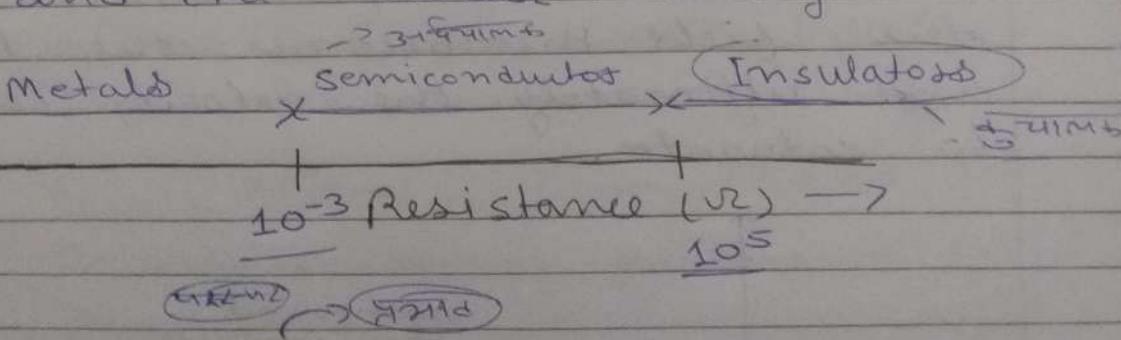
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In case of Compound Semiconductor an interesting kind of behaviour is found where the drift velocity increases with the electric field reaches a peak and then it falls before saturating. It is a situation of negative differential resistance because dI/dV is negative. This can be used to make oscillators.

• Mobility :-

The drift velocity by electric field ratio for small electric field i.e. linear region is a constant, so V_d/E is a constant and it is called mobility.

Mobility decides what is called the resistivity of sample, so resistivity depends on the carrier concentration and the carrier mobility.

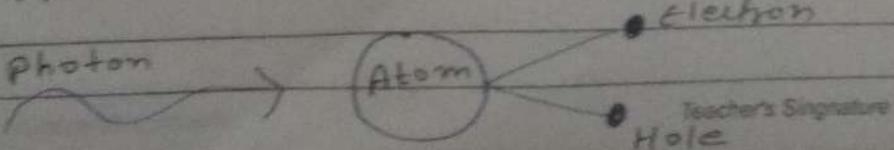


» The interaction of semiconductors with electromagnetic field.

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- when the light falls on any surface, part of it is reflected & part of it is absorbed.
- Because of light falling on an atom the bonds break and the result is an free electron and a hole, so electron + hole pair generation.
- As a result conductivity of the semiconductor must have enough energy to raise electrons across the band gap, or to excite the impurities within the band gap.
- As a result conductivity of the semiconductor changes and therefore this effect is referred to as photoconductivity
- To cause this, the light that strikes the semiconductor must have enough energy to raise electrons across the band gap, or to excite the impurities within the band gap.

Application: photodetector, solar cells



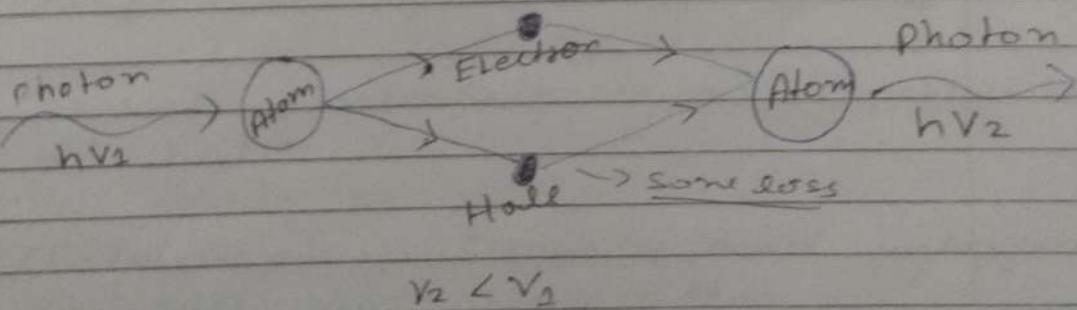
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Hole

- As we can have the situation where free electrons and holes in Semiconductors recombine and the energy is given away as light. This effect is called Electroluminescence.
- prior to recombination, electrons & holes may be separated either by doping the material to form a p-n junction or through excitation by impact of high-energy electrons accelerated by a strong electric field
- Examples of electroluminescent materials :-
 1. powdered zinc sulfide doped with manganese (producing orange-red colour)
powdered zinc sulfide doped with copper (producing greenish light)
or silver (producing bright blue light)
 2. Thin films zinc sulfide doped with manganese (producing orange red colour)
 3. naturally blue diamond , which includes a trace of boron that acts as a dopant.

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IV. Semiconductors containing group III & group V elements, such as indium phosphide (InP), gallium arsenide (GaAs), (Ga_xN_{1-x})_{As}

- Combination of effects that is light falling on an atom gives rise to electron hole pairs & if these electron hole pairs recombine & give rise to a light output where input is light and output is also light but obviously the frequencies of the two cannot be the same because there will be some energy loss, so $\nu_2 < \nu_1$ and this effect is called photoluminescence



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Topics

Some basic Concepts

- types of Semiconductor
- thermal equilibrium and steady state.
- wave particle duality

Intrinsic Semiconductors :

- Bond and band models
- Generation and recombination.
- Hole - the positively charged carrier
- Effective mass of a carrier

Extrinsic Semiconductors :

- Majority and Minority carriers
- Bond and band models.
- Fermi - Dirac statistics and Fermi level

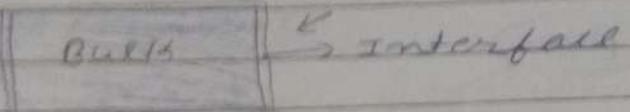
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Semiconductor Bulk

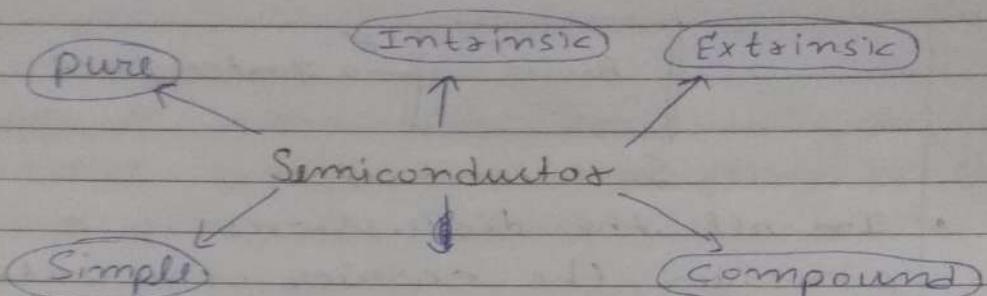


Semiconductor

- In all the discussions we will consider the carrier concentrations in the semiconductor Bulk.
- The semiconductor block , has the bulk and the outline is the interface
- A small 'white' region near the interface is to be excluded from the bulk because this region will be affected by the properties of the surface or the interface. We consider 'Bulk' as this area is large compared to interface.
- Though interface is as important as bulk.
- Understanding surfaces and interface is still not very clear

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Classification of Semiconductors



Example : Si, Ge.

Example: InAs, InP.
InGaAs

• Simple Semiconductor :-

→ In this kind of simple semiconductor one type of atom is regularly repeated & it is also called elemental semiconductor.

• Compound Semiconductors :-

→ In compound Semiconductors, we have more than one atom for constituting the semiconductor.

• Pure Semiconductors :-

→ In this semiconductor, we find that there is no impurities or defect.

So this is perfect crystalline arrangement. In this semi-con. we found regular arrangement of the atoms

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* Intrinsic Semiconductor :

In this type of semiconductor, semiconductor is not totally pure, they are may be some defect & impurities but the concentration of e^- & holes would be same that in the pure Semiconductor.

In this semiconductor ~~defect~~ defect are present but they are compensating each other. ^{or} ~~cancel~~

* that mean one type of impurities Compensate other type of impurities ^{cancel}

* So that concentration in this semi-conductor remains same that pure semiconductor.

* Compensation mean if there are some +ve defect so may be there are some -ve defect.

so the NET compensation in I-S equal = pure semiconductor
Intrinsic semiconductor

So the NET Concentration in this semicon = Concentration in pure

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* Extrinsic Semiconductors :-

- In this type of semiconductors where defects and impurities present and where concentration of hole and e^- will not be same under the equilibrium condition.

So in the semiconductor we will find higher number of e^- & hole at equilibrium condition.

So we can relate Extrinsic sem. to Doped semiconductors. Unless Doping of two type of impurities (Doping of e^- & Doping of holes).

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* Thermodynamic (THERMAL) Equilibrium &

In physics there is a general philosophy that is followed for modeling complex situations, and that is : treating a complex situation as a small deviation from the idealized situation which can be treated mathematically.

- For Example, Supposing you want to tell the location of some place to a person who does not know the place, very often you tell a landmark.
↳ at A
- you do not tell the person how far is that place from where you are.

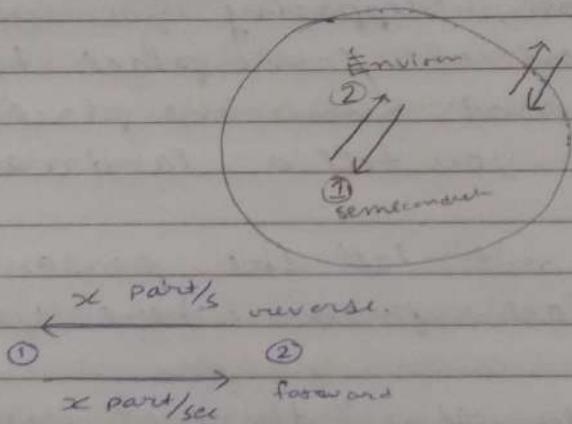
So this idea of "thermal equilibrium" is a convenient idealized condition which is not achievable in practice.

Many phenomena that we encounter can be modeled as small deviations from thermal equilibrium.
↳ Basis

So, we will find the word "quasi equilibrium" attached to the device analysis or modeling

* treating a Small deviation from Equilibrium condition

- The semiconductor is said to be in thermal equilibrium with its environment if for any process that may be going on between the Semiconductor and the environment, there is an inverse process going on at the same rate.
- It is also called the principle of the "Detailed Balance"



"Detailed Balance" mean, when you go far looking at the process in more and more detail, so at the every level of detail detail the Balance may be maintain

- Semiconductor is in thermal equilibrium if (Easy to understand compared to earlier conditions, much more defined) :

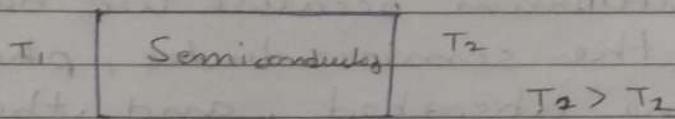
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1. No external excitations, much other than temperature.
2. No net motion of charge or energy.

Some examples of non equilibrium:

Temperature difference across the Semiconductor



$T_2 > T_1$
So flow of energy (heat)

→ No in equilibrium

Suppose we have a semiconductor; at one end you have a temperature T_1 , at other end you have a " T_2 . The first condition is satisfied here, there is no excitation other than temperature. However, if the temperature T_2 is more than temperature T_1 then there is a flow of heat from one end to the other end, that is flow of energy, and there is no reverse flow of energy to balance this. It is a one directed process from T_1 to T_2 so it is not under equilibrium.

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» Light falling on a semiconductor

- Supposing we have light falling on a semiconductor it may be falling on all sides or may be one side it does not matter.
- This semiconductor is not under equilibrium because we have ^{light} shining on the semiconductor, photons are being absorbed, and then that energy is being converted to another form of energy.
- There is no inverse process. It is not as though (Visible, infrared) a semiconductor is giving out light. That is interesting which means that if the semiconductor is visible it is not under equilibrium. So, the semiconductor should be under dark conditions. This is the implication of equilibrium.

» Semiconductor under electric field:

Supposing you have semiconductor and you apply electric field, so as current is flowing, now it is

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is obviously not under equilibrium because the First condition itself is not satisfied, there is excitation other than temperature.

Semiconductor

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- But, Semiconductor devices are only useful under Non Equilibrium condition, as you can't get anything out of a device if it is in equilibrium.

• Quasi Equilibrium Situations

- * Many practical situations for semiconductor may be treated as quasi Equilibrium (Small deviations from equilibrium) situations. Why? Consider a p-n junction.

$$P \subset N$$

- Across the PN Junction we have very large current density even under equilibrium condition for electrons as well as holes.

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- Current density in one direction is exactly balanced by current density in the other direction. So, no RESULTANT CURRENT. In other words, the Thermal equilibrium is not a static equilibrium: it is a dynamic equilibrium.
- * Equilibrium: No "NET MOTION of charge or energy", it does not say "No motion of charge or energy".
- Intense activity but not in any one direction.
- That is why this condition is a useful starting point because, if you now add any other excitations then you can treat this condition as a small deviations from equilibrium.
- ↳ So let us take this example for PN Junction one can show if you take for electrons, at the junction, there is a current of a 1000 A/cm^2 . So there is one tendency

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for electrons to go from P to N at the rate of $1000 A/cm^2$, and it is exactly balanced by another density density tendency.

- The current density under equilibrium conditions across the junctions has no net effect hence the net current is 0.
- ↳ So, we cannot get a current out a P-N junctions if it is under equilibrium.

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Strings \rightarrow E^{ATR}
 Streams \rightarrow E^{INT}

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Wave Partical Duality :-

- In this topic we learn how the particle behaves inside a Semiconductor.
- So it means, the energy or matter propagates in a form of string of particles, as a travelling waves.
or

particle stream	photon	Electron	phonon
travelling wave	Electro magnetic wave	De-Baglie	Elastic
Variable with ω and t	E, M field	Probability	Atomic Displacement
Name of the wave equation	Maxwell's $E\omega^n$	Schrodinger's $\psi\omega^n$	-

- Let us try to see the equations relating the particle and wave aspects.

$$F = h \times V \quad P = h / \lambda$$

- Here on L.H.S : E & P , these two parameters represent the properties of particles in the stream.
- On R.H.S : The parameters V (34157) & 1 represent the properties of waves (travelling) associated with the stream of particles

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- V is a parameter which represents variation with respect to time.
- λ is a parameter which represents variation with respects to distance
- E & P also represents minimum quantum of energy (momentum) that can propagate.
- ~~This~~ For example, let us take the energy of one electron volt (energy gained by one e^- when it falls from 1V)

$$E \Rightarrow 1eV = 1.6 \times 10^{-19} \text{ Joule.}$$

- Let us assume that we are talking of an electromagnetic wave having energy 1 ev.

$$P = h/\lambda ; E = h\nu \quad v = \nu \times \lambda$$

we can write;

$$P/E = \frac{1}{\nu} \times \frac{1}{\lambda} = \frac{1}{\nu\lambda}, \text{ so } P = E/\nu$$

$$\text{therefore } \lambda = h/\lambda = \frac{h \times \nu}{E}$$

Next, let us substitute the values.

$$d = \frac{6.020 \times 10^{-24} \text{ atoms}}{1.6 \times 10^{-19} \text{ J}} \times 3 \times 10^8 \text{ m/sec}$$

= 1.24 micrometers.

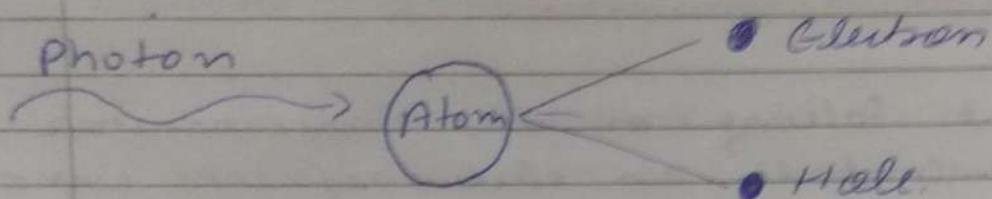
PARTICLE BEHAVIOR :-

- Light falling on the semiconductor is equivalent to an electromagnetic wave falling on the semiconductor.
- That is a photon or a stream of photons falling on the semiconductor atom, & then an electron hole pair generated.
- So, instead of regarding as a wave. Now this particular phenomenon can be interacting with an atom where things look more complicated, if the wave is converted into its particle stream regarded as a particle stream, then it becomes a simple problem in collision. So collision between a photon and an atom.
- Now treat this collision from energy momentum conservation point of view and see whether this photon can generate an EHP in the semiconductor? whether it can break a bond?

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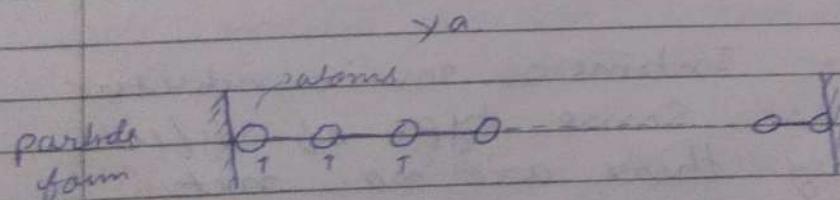
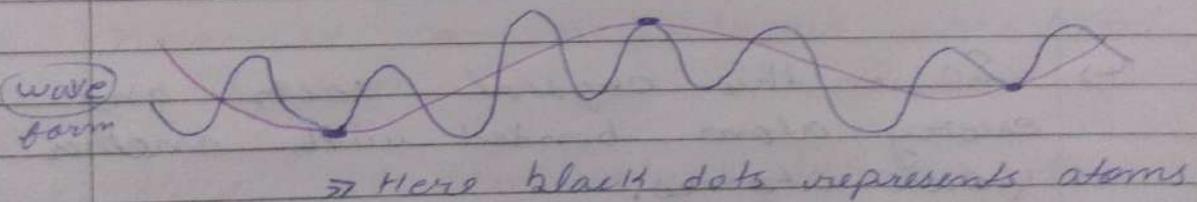
- Now, this particular phenomenon can be regarded as a collision of a photon with an atom in the particle equivalent particle system.



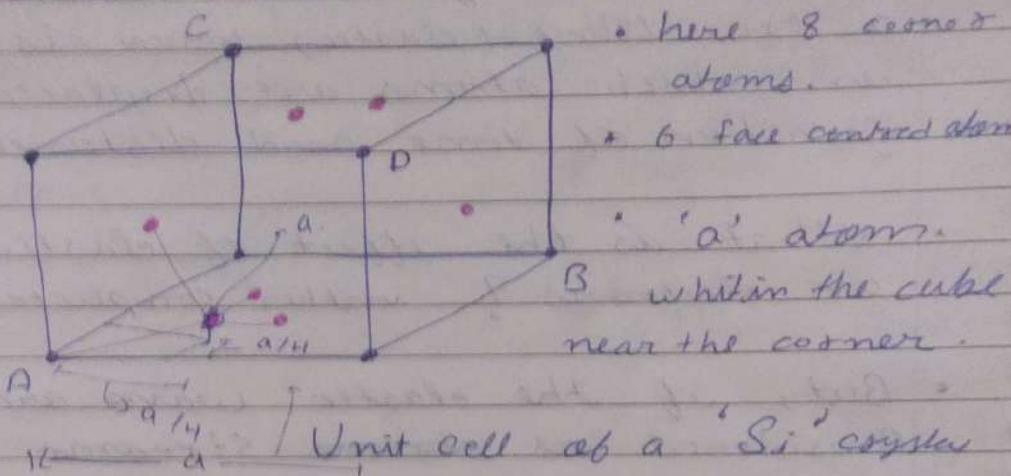
Another example of WAVE BEHAVIOR

- A semiconductor crystal $T > 0\text{K}$, the atoms are in agitation (vibration).
- Each vibrating atom gives rise to a travelling wave.
- Each vibrating atom is bonded to the next atom, and next atom is bonded to the next atom, the series of atoms which are bonded together can be regarded as a kind of continuous solid medium as an analogy (analogy).

- So, if any one atom vibrates another atoms also get into vibration, so a travelling (elastic) wave is generated in which atoms are displaced as a function of time and distance.
- What is the effect of elastic waves on electrons? rather complicated picture.
- But, if the elastic wave are considered as ~~streams~~ streams of particles called phonons, this becomes a collision between phonons and electrons, which is easy to understand. How this collision affect movement (mobility) of e^- ?



Bond model of an Intrinsic Semiconductor



* So, we know that any crystal have a regular arrangement of atom. It involves that repetition of a atoms is called a unit cell

→ So in this crystal each and every atom bonded with another four atoms.

In the Intrinsic semiconductor there is some type of defect. But they there are no net defects ya impurity. it mean +ve number of defect = -ve no. of defect.

Properties of Silicon

Parameter	Units	Silicon	Gallium Arsenide
Group		IV	II-V
Atomic number		14	---
Valence e ⁻		4	
Atomic concentration, cm ⁻³		5×10^{22}	4.22×10^{22}
Crystal structure		Diamond	Zinc Blende
Lattice constant A°		5.43	5.65
Bond energy ev		1.12	1.42

→ Si crystal at $T=0\text{K}$ and $>0\text{K}$

At $T=0\text{K}$ there is no thermal agitation so, all atoms are bonded to four nearest neighbours, no bond is broken.

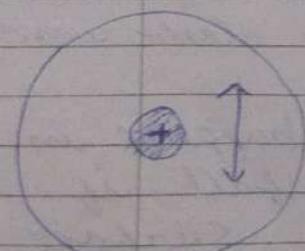
- Now, at temperature beyond 0K each atom starts vibrating about its mean position. whenever an atom vibrates it generates an elastic wave.
- This is analogous to what happens in a pond when rain drops fall. if there is no rain, the top surface of the pond is calm one. the rain start falling. whenever a

A rain drops fall from there
a ripple is generated (arrows)

- These ripples will originate from each of the drops and they will interfere.
- Similarly each of vibrating atoms generate a traveling wave and these waves will interf. interfere
- Looking at a wave-particle analogy we can therefore say that for $T > 0K$ we have phonons moving about in crystal

Q Why an vibrating atom generates and Electromagnetic Wave?

Electric Dipole §



An atom is vibrating

↗ A positively charged nucleus which is surrounded by a negative electron cloud corresponding to the electrons.

- » The black dot here and the horizontal line of the black dot represent the negative charge
- » There is a relative displacement between the centre of the e^- cloud and the positively charged nucleus.
- » This relative displacement of the positive and the negative charges creates an oscillating dipole.

Consequence of Breaking the Bond's

- » We know a bond is created between ^{the} two valence electrons between two electrons atoms.
- » The electrons jump out of the bond as shown in the diagram as a broken bond and an electron being set free.
- So in this point all the waves which are interfering with each other, suddenly they will make rise to the high amplitude and the bond breaks e^- Teacher's Signature generated.

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But there is no sufficient freedom for it to be outside the crystal it is free of the particular atom which was holding it; but it must ~~above~~ move about within the crystal. It does not belong to a particular atom.

- And there is a valancy left behind by the free electron.
- In the absence of a negative charge, the natural region will be acting like a positively charged called the Hole (valancy of electron).

Q) At $T > 0K$, there will be 4 types of particle in a semiconductor crystal (Si):

1. PHONONS : Elastic wave emanating from vibrating atom.
2. PHOTONS : Electromagnetic wave emanating from vibrating atoms.
3. FREE ELECTRONS : Generated as a large number

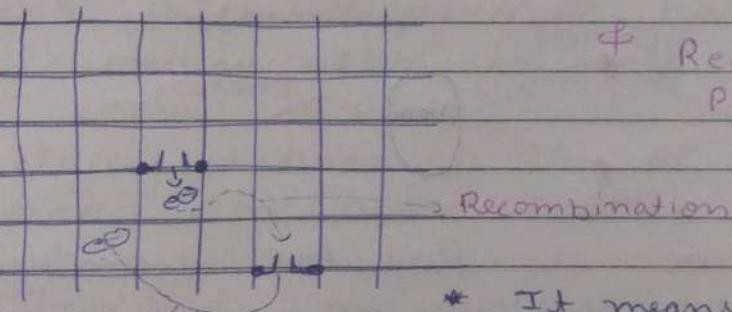
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of photons and phonons can converge onto a Si atom and if the total energy exceeds bond energy

4. Holes : Generated due to left over Valancy by electrons positively charged and can also move about in response to electric field. So can also be treated as carrier of current.

Generation process [Electron Hole pair]

* Recombination process



* It means the generation of e° & Recombination is always balance.

Detailed Balance :

photo generation \leftrightarrow Radiative Recombination.

- If the generation happens because of photons then we call the process as photo generation.
- Result light absorbed.

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- That means photons are alone participating in the process.

Then the thermal equilibrium implies that it should be exactly balanced by a process in which photons are being produced as a result of recombination, that is called radiative Recombination.

- Result : Light emitted

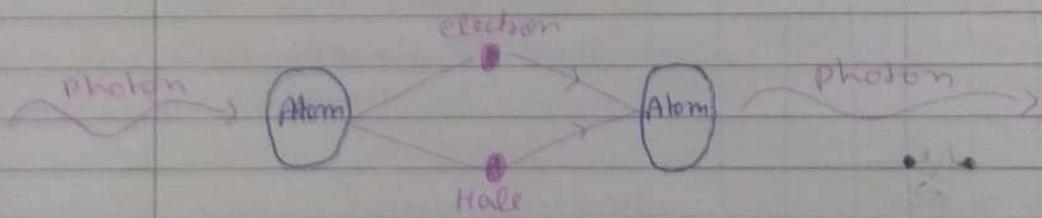


Photo generation

Radiative Recombination

Concentration of Carriers as Function of Temperature

Say $T = 300\text{ K}$

Under thermal equilibrium average energy.

$E = k \times T$, where k stands for Boltzmann constant.

$E = 0.026 \text{ eV}$ (average energy of a particle)

(Note) : Different particles have different energy, this is only average.

Now to break $\text{Si} - \text{Si}$ bond we need the bond energy 1.1 eV.

Therefore, no number of particles will be given by $\frac{1.1}{0.026} = 42$,

i.e. We need 42 particles to be converged at a single point.

Obviously this cannot happen at every Silicon atom, thus here comes probability

Supposing the probability that a particle collides is p .

- if 4^2 particles should collide then probability of such an event will be P^{4^2}
 - This probability is very small ($P < 1$).
- ** So two condition after bond break:
- 1) temperature high., so it make vibration between atoms and due to vibration bond Break.
 - 2) in this condition Bond break so ~~Bond breaks~~ it make free electron. and due to free electron bond break (4^2 particle break 1 si-si bond)

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* Now, we know $n_s(\text{Si}, 300\text{K}) = 10^{10}/\text{cm}^3$

* And silicon atom concentration

$$= 5 \times 10^{22}/\text{cm}^3$$

$$\text{So, } \rho^{42} = \frac{10^{10}}{5 \times 10^{22}} \Rightarrow \frac{1}{5 \times 10^{12}}$$

* One atom out of 5×10^{22} atom contributes for ECP generation.

> Now at different temp, $T = 400\text{K}$

> Number of particles will be = 31.5

* Fraction of Silicon atoms are going to contribute to e^- hole pairs = $\rho^{31.5}$

* So, when temp. rises, smaller and smaller number of particles need to be involved in this process, and the probability of the event starts increasing rapidly.

That is why conductivity of semiconductor is lower compared to metals where every atom contributed one electron.

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Reason for Log Scale for n_i and reciprocal of temperature

$$\left\{ n_i = N \cdot p^{\frac{E}{kT}} \right\}$$

where ' n_i ' is the atomic concentration in silicon, ' p ' is the probability that an atom is hit by a particle, ' E ' is bond strength & ' kT ' is the average energy of the particle at temperature ' T ' under equilibrium conditions.

- Here the probability $p < 1$, so if we write this equation using $\frac{1}{p}$ we get a quantity ≥ 1

$$n_i = N \left[\frac{1}{p} \right]^{-\frac{E}{kT}}$$

$$\log n_i = \log N - \frac{E}{kT} \log \left(\frac{1}{p} \right)$$

$$\left\{ \log n_i \propto -\frac{E}{kT} \right\}$$

therefore if we plot n_i on a log scale and $(\frac{1}{T})$ a reciprocal of temperature on the axis we will get a straight line.

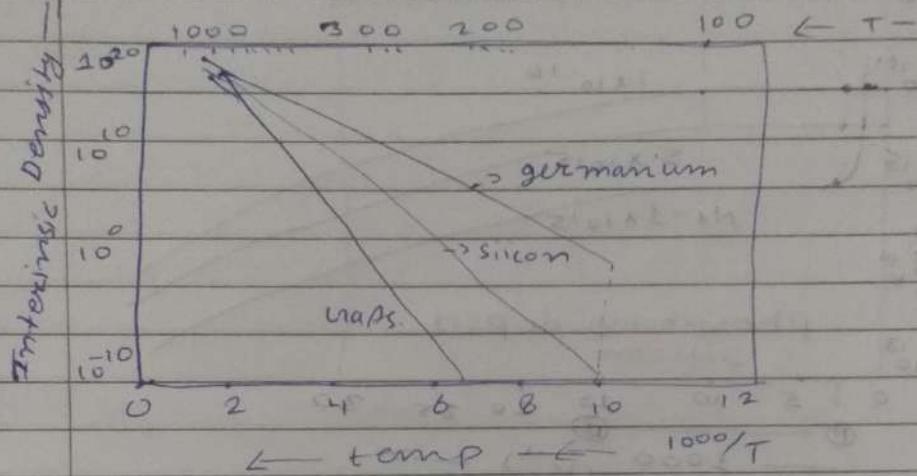
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$T \uparrow$ then $n_i \uparrow$

CARRIER CONCENTRATION VS INTRINSIC SEMI CONDUCTOR

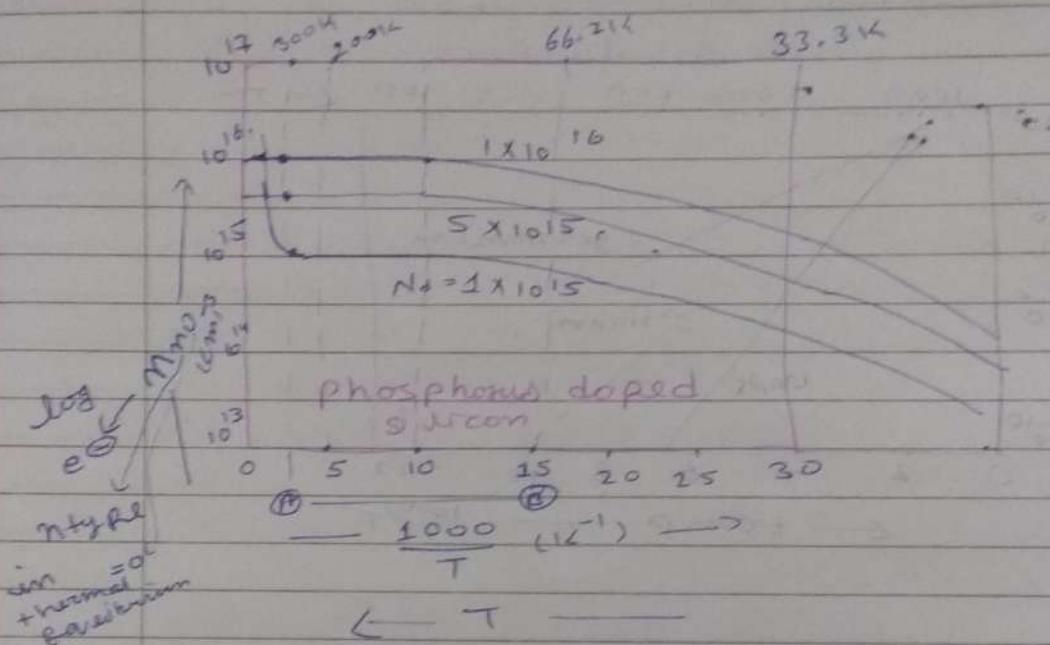


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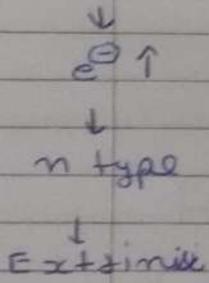
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Majority Carrier Concentration in Extrinsic Semiconductors



Donor (Phosphorous, n-type)



In Region -

(A) — (B), our device
is work properly.
because concentration
of n type (doped semicon)
is constant with temp.

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Experimental evidence of positively charged carriers & holes in a Semiconductor :-

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* Energy Band Model :

The energy band model tries to analyse the electron population in terms of the energies possessed by electrons.

How the electrons are distributed over energy at any temperature.

The basic tenets of this model are three:

1. The allowed energy states for e^- .
 - (i) e^- 's are only allowed in certain energy states.
 - (ii) e^- 's always tend to occupy the lowest energy states available.
 - (iii) No two e^- 's can occupy the same energy state. (Pauli's exclusion principle)

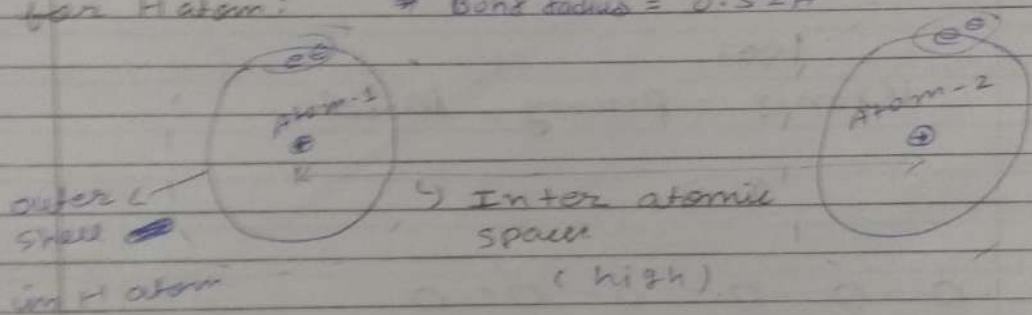
2. Distribution of allowed states over energy :

How many states are there and how they are distributed over energy.

- This distribution is represented using a function $N(E)$.

3. At equilibrium only a fraction of states are occupied at any time: not all the states will be occupied: Analogy
- This fraction is a function of energy and temperature $F(E,T)$.
 - This is normally called the Fermi-Dirac function.

for H atom: # Bohr radius = 0.52 Å

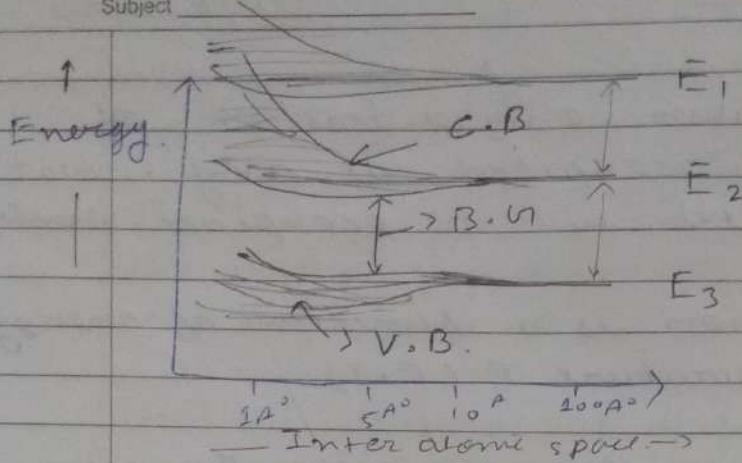


So when Inter atomic distance is high than the outermost shell e⁻'s does not observe any force due to the electric field.

(AND)

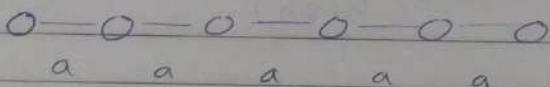
when Inter atomic space (ℓ) decrease than the electrons of outer shell e⁻ are disturbed and therefor the splitting of outer most energy level occurs.

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~~KO~~
Kronig - Peierls Model.

1-D

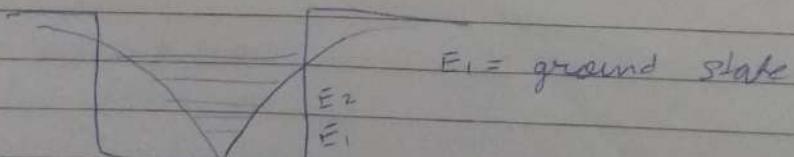


$$\text{the potential energy } V = \frac{k}{r} \frac{a_1 a_2}{r^2}$$

at nucleus $r = 0$.

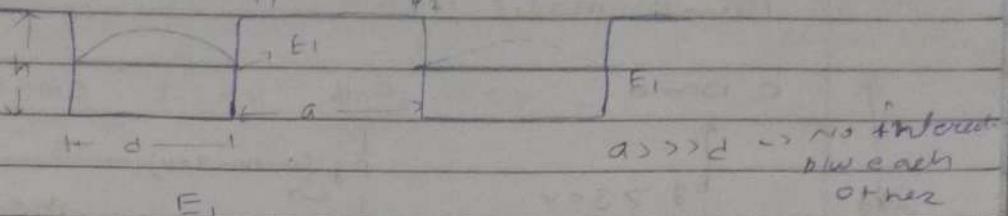
$$V \rightarrow \infty$$

the potential difference (V) approximated as rectangular periodic potential well.



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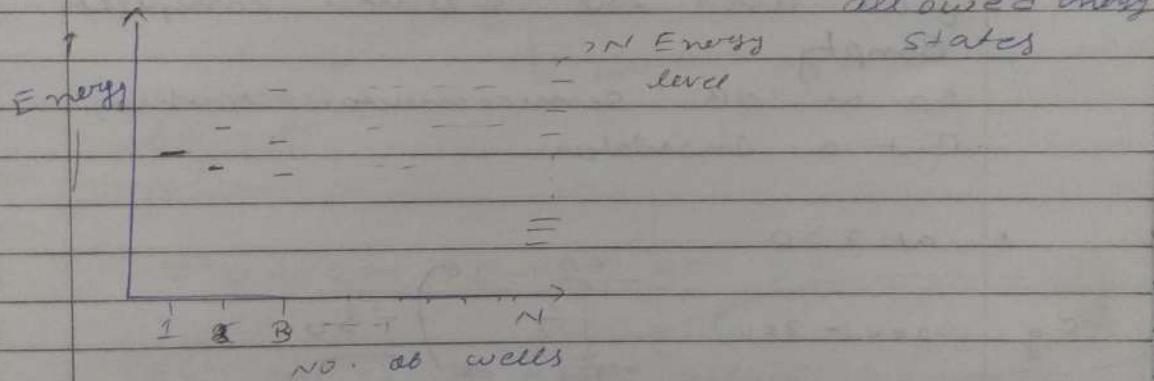
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_____Well 1 ψ_1 Well 2 ψ_2 

Two solution

$$E_1 < E_2$$

1 solution when $a \gg d$ 2 " " " $a \approx d$.3 wells \rightarrow 3 solution \rightarrow 3 Energy level. λ_1 " \rightarrow λ_1 " \rightarrow λ_1 " level

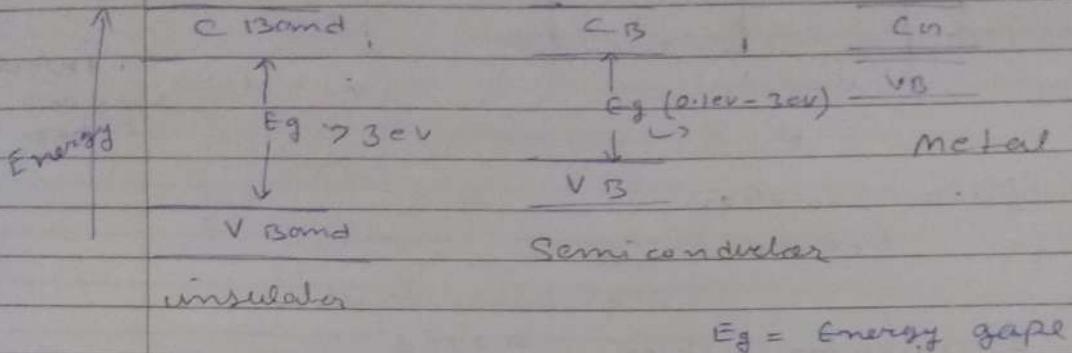
allowed energy states



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Band model :-



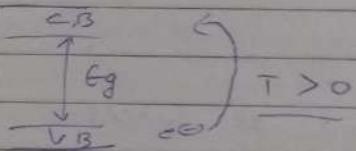
↳ Semiconductor :-

- In case of semiconductor at 0K the valence band is completely full and the 'C' band completely empty.

so at 0K semiconductor nothing
But a insulator.

- at $T > 0$

$$E_g = 0.1\text{eV} - 3\text{eV}$$



- * hole exist only at ~~VB~~ Valence Band.

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Ge, Si, Ge^+ at $T = 300\text{K}$
 $\downarrow \quad \downarrow \quad \downarrow$
 $0.67\text{eV} \quad 1.1\text{eV} \quad 1.42\text{eV}$
 (room temp)

according to Bloch

potential of electron varies periodically.
 the probability of finding an electron
 should also vary periodically.

The probability of finding an e^- is
 equal $\propto = |\Psi|^2 \Rightarrow$ wave function
 $\sim \text{wave function}$ varies periodically.

$$\Psi_{k\ell}(t) = u_{k\ell}[x] e^{i k x}$$

$\int L$ product of a plane wave
 periodic function
 cell function

$$\nabla^2 \Psi + \frac{2m}{\hbar^2} (E - V) \Psi = 0$$

$E \rightarrow$ energy eigen values. \rightarrow
 $V \rightarrow$ periodic potential. periodic
 $m \rightarrow$ mass of electron

$$k = \pm \frac{\pi}{a}$$

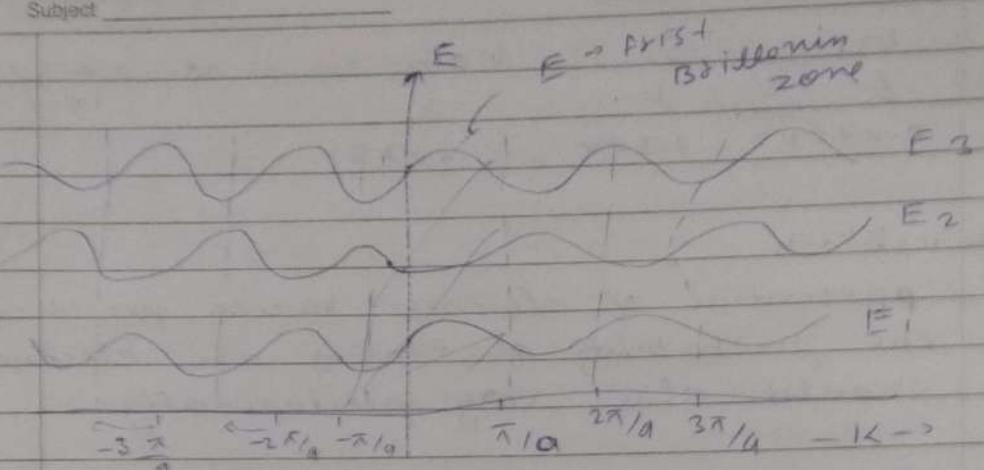
$a \sim$ inter atomic space

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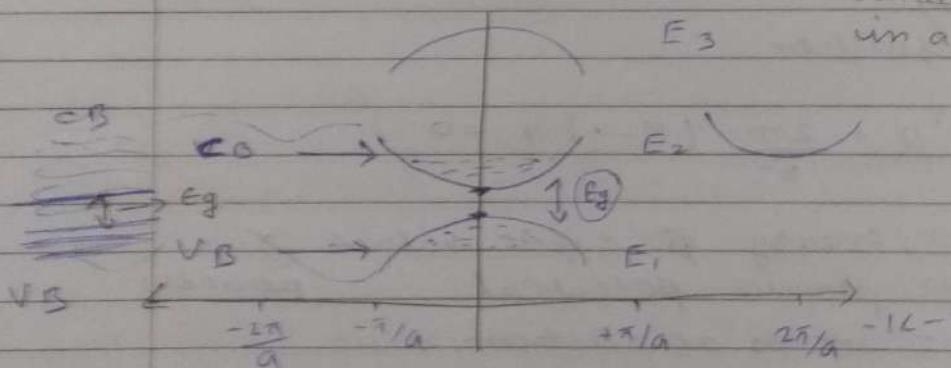
here \mathbf{k} being the momentum

- ① periodic zone picture & E_{as} + the energy. and
 - ② Reduced " "
 - ③ Extended " "
- we can say \mathbf{k} is a wave vector.

Reduced zone.

• Direct

Band gap
in a semiconductors



- * In this case when an e^- move from V.B to C.B. then e^- leave some Energy and that
- ↳ energy = Energy Band gap

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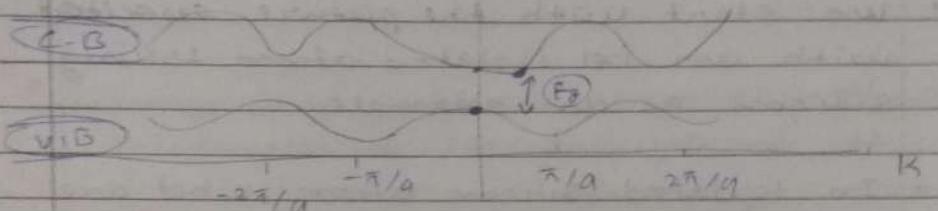
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+ E

Indered
Band gap
Semiconductor



In this case Energy band gap is not equal = Energy of e^-

$$I = J \times A$$

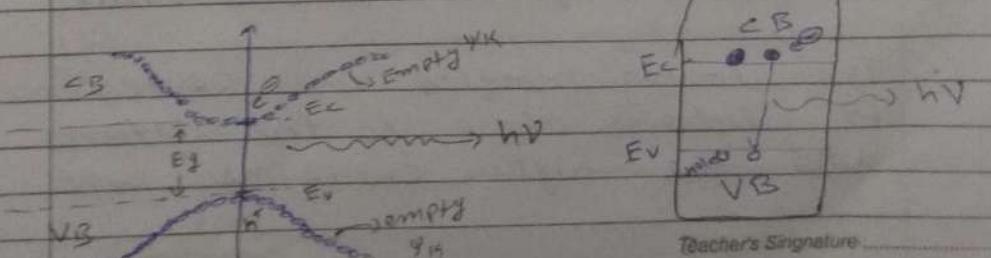
↓
current density

$J = n q M E$

carrier concentration carrier charge mobility

$n = \int_{E_C}^{\infty} n(E) dE$
carrier density.

$n(E) = f(E) \times f(E)$ Occupation probability
density of states total probability of finding e^- in state.



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* What are the allowed states?

- we start with the picture associated with an isolated atom taking silicon as an example.
- In isolated silicon atom what are the allowed energy states?
- Then we put together n atoms all regularly arranged and then start reducing the inter atomic distance between the n atoms and bring it down to the distance that we have in the crystal.
- we can sketch on a diagram where the x-axis denotes atomic separation and y-axis denotes available energies or electron energies?
- No silicon's atomic number is 14
- The ~~ses~~ distribution of these 14 electrons is written as $1s^2, 2s^2, 2p^6, 3s^2, 3p^2$ in terms of the various value
- The lower energies will correspond to electrons close to the atom and the higher energies will

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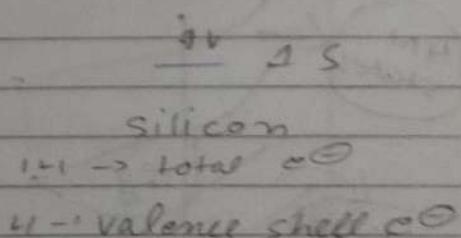
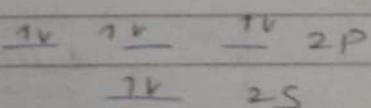
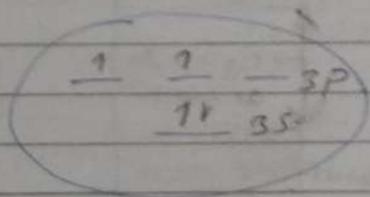
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correspond to electrons away from the atom.

* Energy band model is from the statistical mechanics. & the principle of these kind of distribution is define from quantum mechanics.

ALLOWED STATES IN SILICON:

- This is the picture for isolated atom.
- For $3p$, only 2 electrons are there in this although there are 6 states available.
- Considering $3s$ and $3p$ orbital together, there are n valence electrons and thus n vacant available states.



- For N atom system there will be $2N$ electrons in $1s$ state and so on

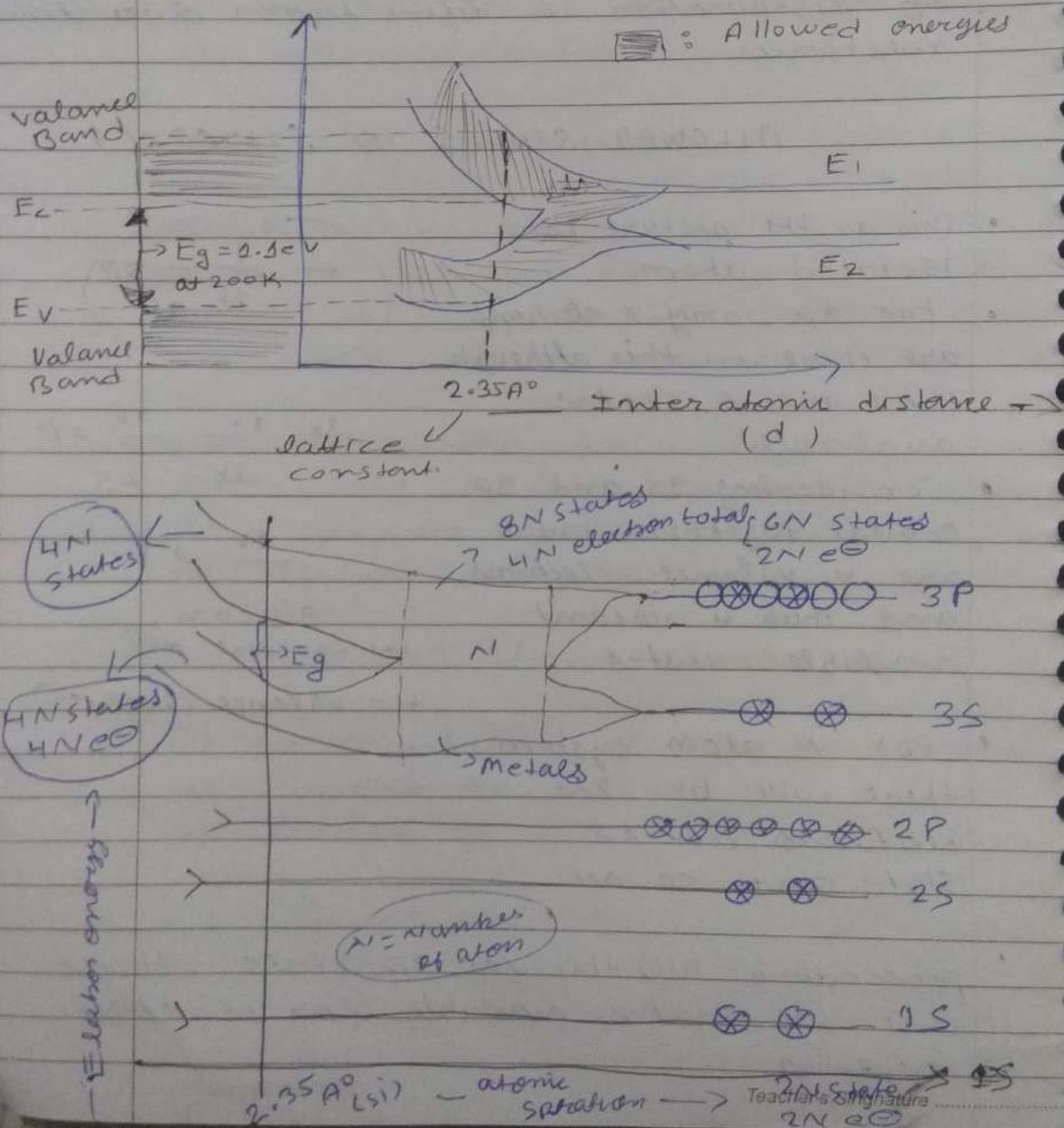
proceeding like this for $3p$ state there are $6N$ states available for N atom system.

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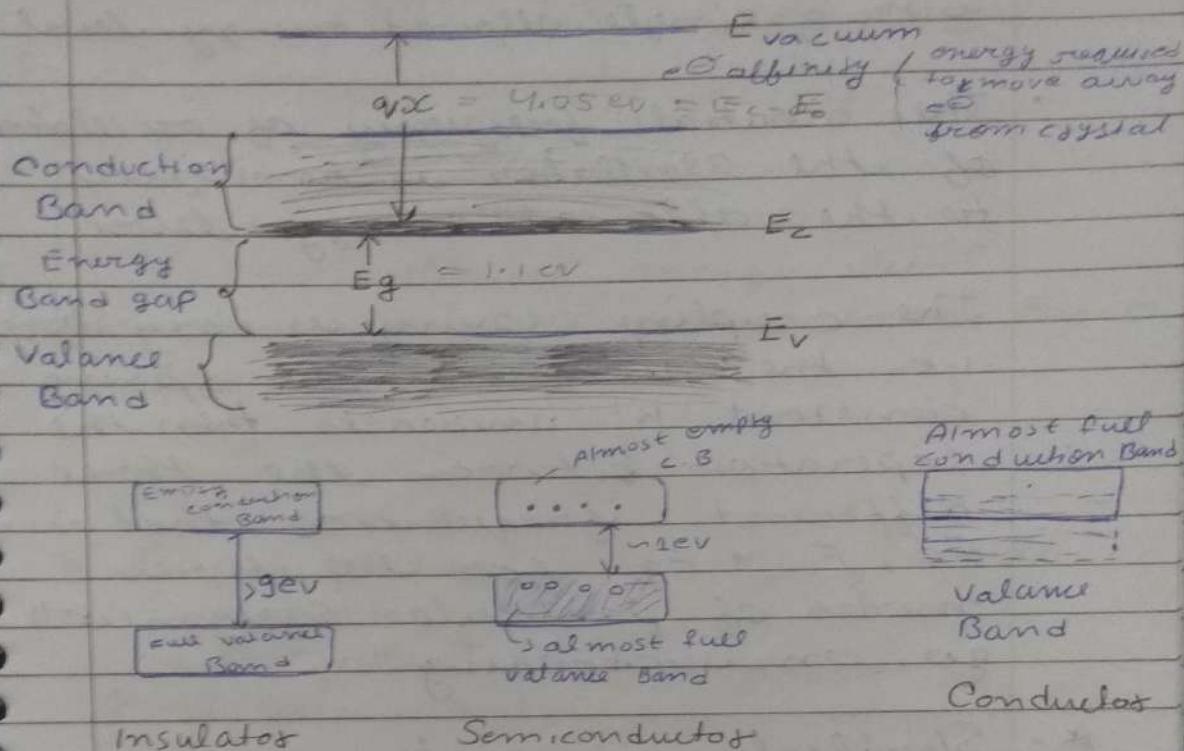
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therefore there are $4N$ vacant available states.

Formation of Bands as a function of Inter-atomic Distance



Simplified Energy Band Diagram :



Oscillator Analogy :

- * why is it that when the atoms come closer the energy level of an isolated atom splits into different energies when you coupling between various atoms then the energy level corresponding to the various atoms split and they are not the same

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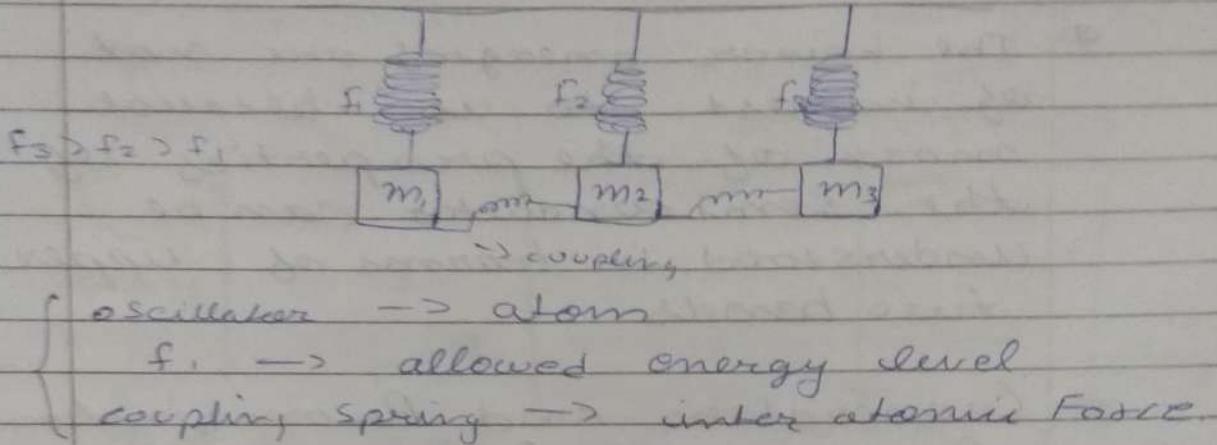
- The oscillator is analogous to atom with a single allowed energy level.
- The neutral frequency of oscillation of the oscillator is analogous to the allowed energy level.
- The coupling spring is very strong i.e. the strength of the spring constant 'K' increases then the separation between the three different frequencies that is F_0 , F_1 & F_3 for the three modes of particular system will go on increasing.
- * Similarly, if we bring the various atoms close together in a system then the coupling between the atoms increases or inter atomic forces increase.
- In that case the single level starts splitting into 'o' different levels for 'n' atom system.

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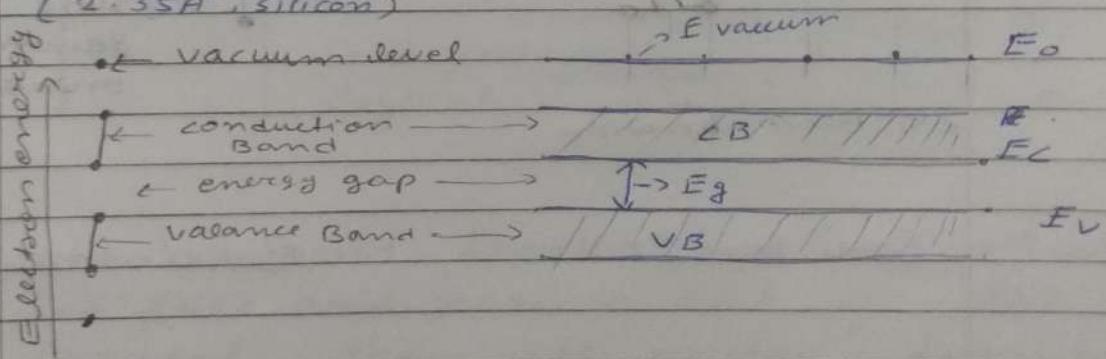
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* Band picture at the Atomic Separation :

(2.35 \AA , silicon)



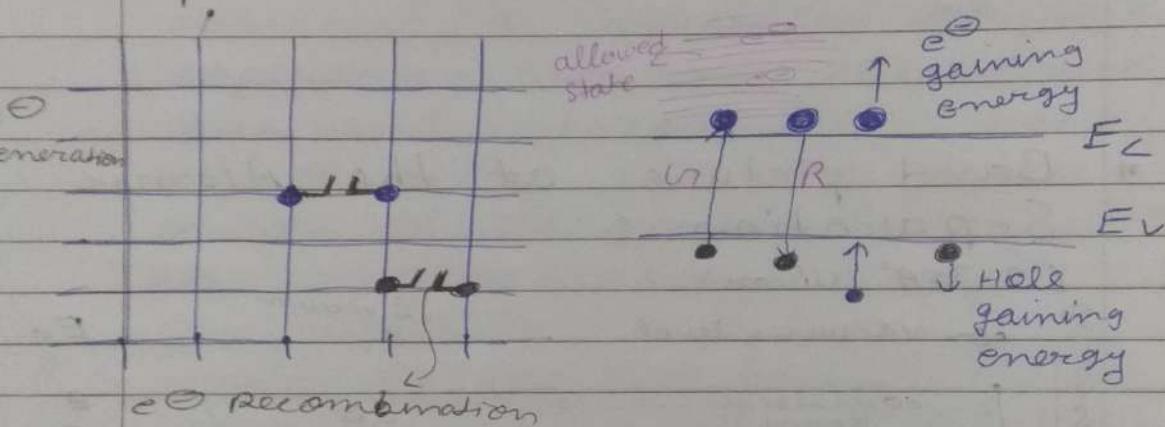
- ① It is difficult to work with a diagram on the left where the ends of this band are indicated as points.
- ② Thus, for simplicity instead of a point we draw a line

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- ④ The lower energies are not of interest to us because most of the properties of the semiconductors can be understood in terms of upper two bands.

Generation and Recombination Process in Band Model :



Bond module

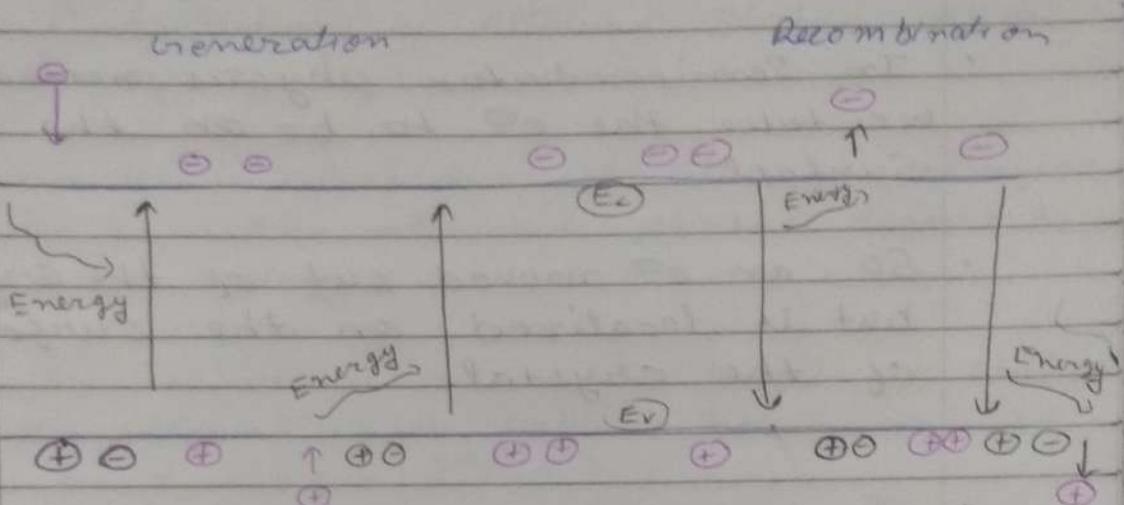
Band module

Electron

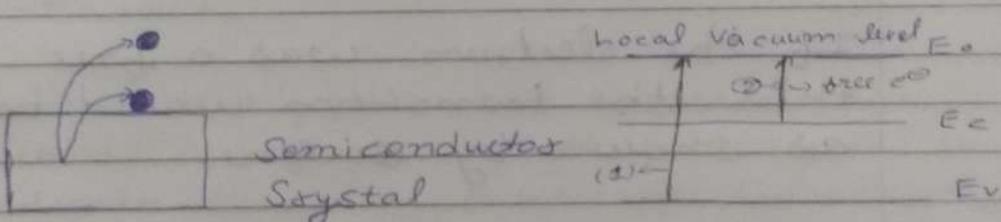
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• Electrons jumping up from valence band to E_e :



- when a bond breaks and an e^- is set free and moved out of the crystal, then its energy transition could be represented as electron jumping from valence band to the vacuum level (shown by 1. line)
- Now the question arises that whether the e^- is on the surface or far away from the silicon crystal

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- In Semiconductor physics normally we take the e^- to be on the Surface.
- So, an e^- moved out of the crystal but it localized on the surface of the crystal.
- That is why vacuum level is referred to as local vacuum level
- If the electron was a free e^- then the transition would be like as shown by ② line.

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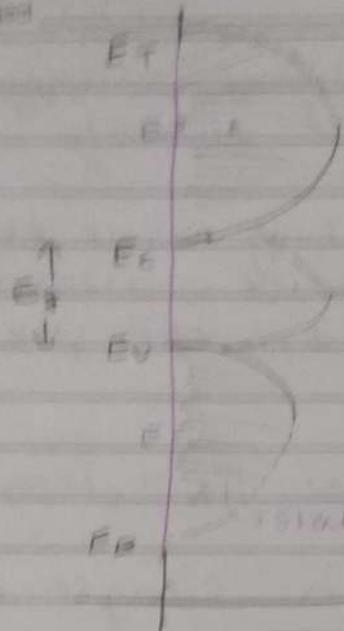
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= Distribution of Allowed States over Energy :

- We know what are the allowed energies so how the allowed states distributed over energy.
- In other words the total of states corresponding to valence band would be $= 4 \times 5 \times 10^{22} / \text{cm}^3$
 \hookrightarrow ^{atom} _{state in crystal / cm³}
- The allowed states are distributed as follows :
 1. we take the 'y axis' to indicate the allowed energies and the 'x axis' to indicate the distribution of the states over energy, (N(E) called density of states function).
 2. E_C & E_V are conduction and Valence band respectively.
 3. Let us say, the bottom of the valence band is called E_B and the top of the conduction band is E_T . So E_B to E_U is one allowed band.

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$$N(E) = \alpha_1 [F - E]$$

$$\alpha_1 = (8 \sqrt{2} \pi m^3) / h^3$$

Electrons fill up to E_F

$$N(E) = \alpha_2 [E_F - E]$$

$$\alpha_2 = (8 \sqrt{2} \pi m^3) / h^3$$

Electrons leave E_F

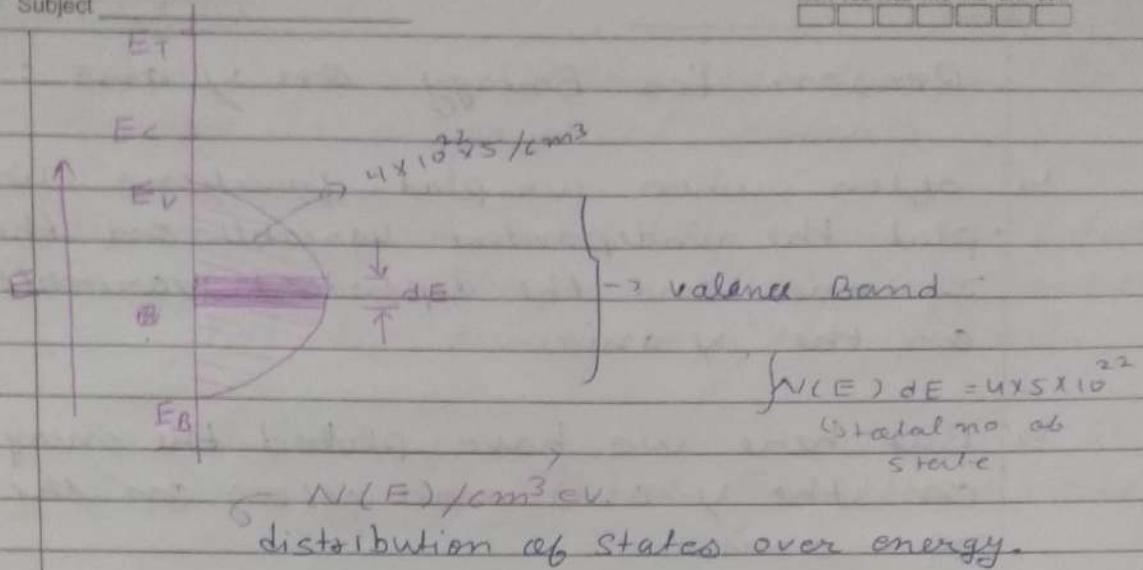
$$N(E) = ?$$

$$\left\{ \begin{array}{l} \alpha_1 = \frac{8 \sqrt{2} \pi m^{3/2}}{h^3} \\ \alpha_2 = \frac{8 \sqrt{2} \pi m^{3/2}}{h^3} \end{array} \right.$$

Fraction of Available states Occupied at any Energy and Temperature :

- Available state at any energy E , within an interval dE
- This is given as Fermi Dirac Function, $F(E, T)$.

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- ↳ If we take a small interval dE , at some energy E , then the number of states in the energy interval would be given by shaded area.
- ↳ Now if we integrate this particular function over the interval which means if we take the total area under this particular function, then that area will be equal to $4 \times 5 \times 10^{22}$.
- ↳ Also we have a small number of states near the edges of the band. As we move towards the middle of the band we will have a larger number of states within an energy interval.
- ↳ So the available states over are not uniformly distributed over energy.

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Reason for Energy on y axis :

- ↳ often, when we plot functions, we plot the independent variable on the x-axis and the dependent variable on the y-axis.
- ↳ But here we have plotted the energy on the y-axis and $N(E)$ on the x-axis.

There are some reasons for following this convention in Semiconductors physics

- ↳ One is, in the energy band diagram or allowed energy diagram, we had kept the energy on the vertical axis, so it is useful to align all other diagrams to this diagram.
- ↳ Also there are strong reasons for plotting energy on the y axis.
- ↳ if we consider potential energy for example.
 a body which is at a greater height has higher potential energy so somehow we are used to this kind of a convention

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when we are talking of energy. So energy is a physical quantity

- Higher the location of body more the potential energy. and therefore it makes sense to plot the energy on the Y axis.

∴ Density of States Function - N(E)

- We cannot have a single equation for this function.
- Only the function near the edge of the band is of interest to us which can be represented as a parabolic equation.
- The constant "a" is slightly different for the conduction band than the valence band
- a_1 represents the constant for the conduction band and a_2 represents the constant associated with the valence band

Therefore for the valence band, the constant a_2 depends on the effective mass of the hole m_p and \hbar is the planck's constant.

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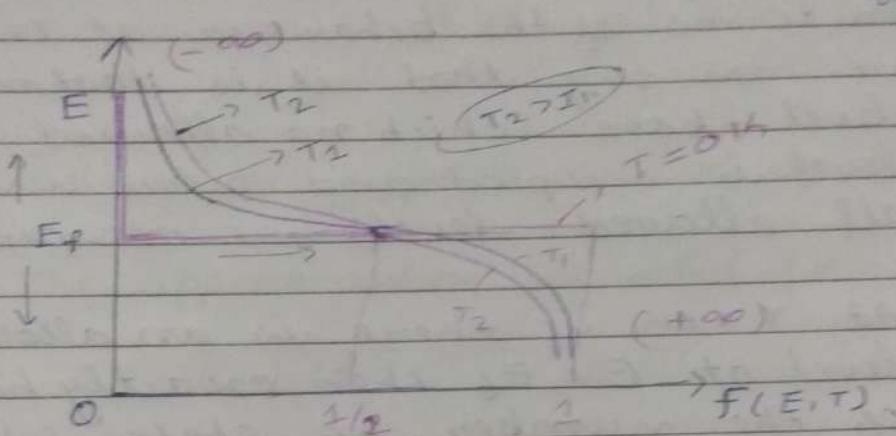
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$$F(E, T) = \frac{1}{1 + e^{\frac{(E - E_F)}{kT}}}$$

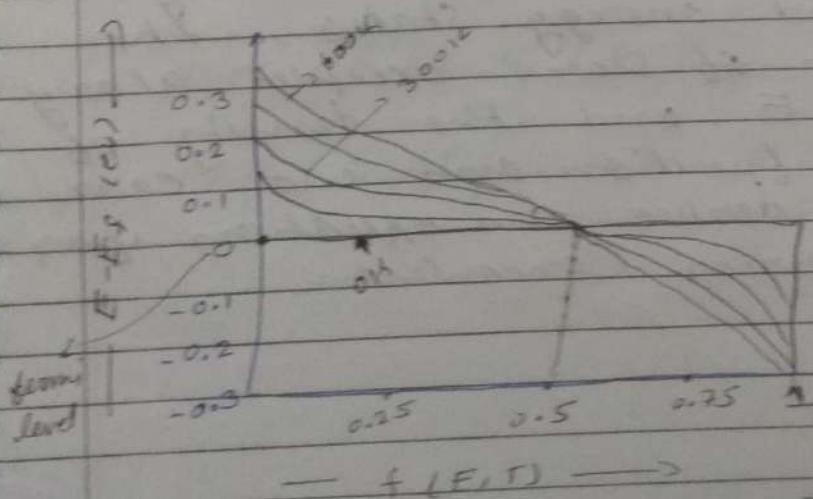
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where E_F
is stands
for Fermi
level



- at $T=0$, fermi level means all states are filled, so probability of finding $e\ominus$ at fermi level ($p(e)$) = 1
- at $T>0$, fermi level means always half states are filled : so $p(e) = \frac{1}{2}$

Fermi - Dirac Function



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Physical Significance of E_F

- In terms of the behaviour at $T=0K$ we can say that it is that energy level above which no allowed level is occupied and below which all allowed levels are occupied.
- At $T > 0K$ if there is an allowed level at $E = E_F$ then exactly half of the number of states which are available will be occupied.
- * So it is energy at which exactly half of the available states are occupied at $T > 0K$

Now we can put our information together namely the allowed energy states, The fraction of states occupied at any energy E , and the density of states function and we can try to derive an equation for the carrier concentration,

$$f(E, T) = \frac{1}{e^{(E-E^*)/kT} + 1}$$

* Boltzmann approximation of $f(E, T)$

- The approximation is valid for

$$(E - E^*) / kT \gg 3$$

$$\text{or } E < -3$$

$$f(E, T) \approx \frac{1}{1 + \exp\left(\frac{E-E^*}{kT}\right)}$$

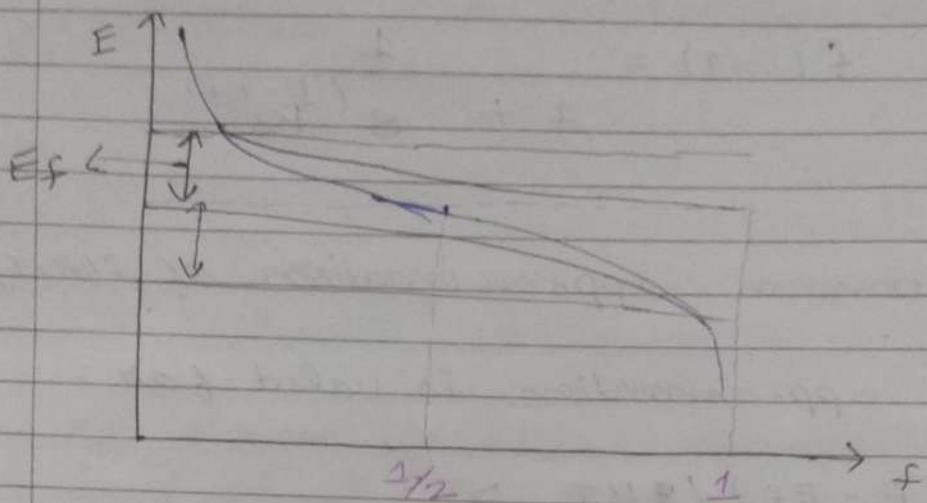
- Therefore

$$\text{For } E - E^* > 3kT$$

$$\hookrightarrow e^{\left(\frac{E-E^*}{kT}\right)} \gg 1 \Rightarrow f(E, T) \approx \exp\left(-\frac{E-E^*}{kT}\right)$$

$$\text{For } E - E^* < -3kT$$

$$\hookrightarrow \exp\left(\frac{E-E^*}{kT}\right) \ll 1 \Rightarrow f(E, T) \approx 1 - \exp\left(\frac{E-E^*}{kT}\right)$$



Physical difference between Fermi Dirac function and Boltzmann function.

- * The Fermi Dirac function derivation assumes that no two electrons can occupy the same energy whereas Boltzmann derivation assumes that any number of e⁻'s can occupy the same energy.

Estimation of the Concentration (n_i)

We can write the number of electrons in the conduction band at any temp (n_i) \Rightarrow

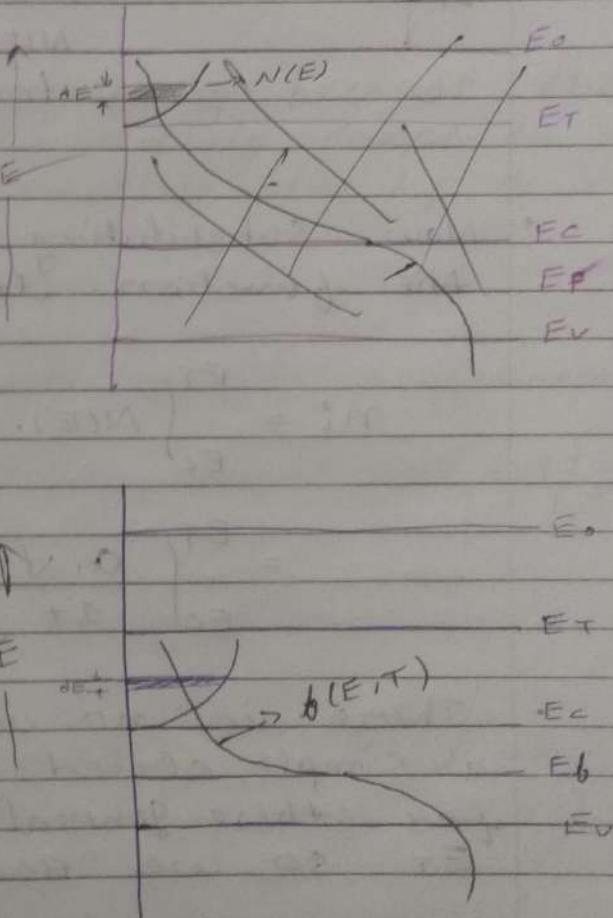
$$n_i = \int_{E_c}^{E_T} N(E) dE \cdot f(E, T)$$

number of \odot

in intrinsic semiconductors

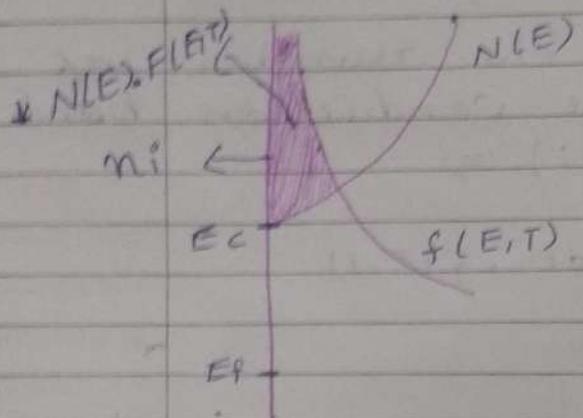
Here all three aspects have been shown: the allowed energy levels, the distribution of available states over energy and the fraction of state.

One portion is the number of electrons in the energy interval dE and integrating this gives us total number of \odot



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Multiplication of $N(E) f(E,T)$:



- * The boundary of the red region, is $N(E) \times f(E,T)$ at any temperature.

- Now, substituting all the terms the function looks like :

$$n_i = \frac{E_T}{E_C} \int_{E_C}^{E_T} N(E) \cdot dE \cdot f(E,T)$$

$$= \frac{E_T}{E_C} \int_{E_C}^{\infty} \alpha_1 \sqrt{E - E_C} \frac{dE}{1 + e^{\left(\frac{E-E_F}{kT}\right)}} + \int_0^{\infty}$$

$E_{vacuum} = 0$

$\alpha_1 \text{ activation energy} = 0$
 $\alpha_1 \text{ conduction} = 0$

- There is no way we can get a simple closed form equation for these general limits E_C and E_T so we uses some approximation.

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4. Boltzmann approximation is

$$\rightarrow f(E,T) \approx \exp - \left(\frac{E-E_F}{kT} \right), \text{ for } E-E_F > 3kT$$

$$\rightarrow f(E,T) \approx 1 - \exp \left(\frac{E-E_F}{kT} \right), \text{ for } E-E_F < 3kT$$

2. Replace E_F by infinity because this function $f(E,T)$ rapidly drops to 0 much before reaching the top of the conduction band.

3. parabolic Density of States approximation

$$N(E) = \alpha_2 \sqrt{E-E_C}, \text{ where } \alpha_2 = \frac{8\sqrt{2}\pi m_e^{3/2}}{h^3}$$

~~$n_i = \alpha_2 \sqrt{2\pi m_e k T} \delta(E-E_C)$~~ is after three

$$n_i = \alpha_2 \left[\frac{2\pi m_e k T}{h^2} \right]^{3/2} e^{-\left(\frac{E_C-E_F}{kT} \right)}$$

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physical Interpretation of formula
for N_i :

$$N_i = \frac{2}{h^2} \left(\frac{2\pi m_n kT}{3/2 - (E_c - E_f)} \right) e^{-\frac{(E_c - E_f)}{kT}}$$

↑
 $f_B(E_c, T)$

Number of states occupied at conduction Band.
 at conduction Band.

- The N_i represent the occupied conduction band states.
- $f_B(E_c, T)$ is the Boltzmann approximation to the Fermi Dirac function at $E=E_c$ and Temperature T .
- That means this term represents the fraction of states occupied for energy E_c within an interval dE at any temperature.
- So we could effectively interpret N_c and as the number of available states at E_c .

E_F

Effective Band Picture

→ conduction band.

 E_C E_C E_V E_V E_B

N_c/cm^3 (effective density
of states at
conductive band
edge)

} valence band

- Fraction of electrons present at E_C can be find out by multiplying the states with the fraction given by the Boltzmann approximation.

- Now all of us knows that the equation is

$$n = 2 \left[\frac{2\pi m kT}{h^2} \right]^{3/2} e^{-\frac{(E_C - E_F)}{kT}}$$

- But from the above equation how do we know that the Boltzmann approximation is valid ??

- Hence we have to derive a formula for E_F and check whether indeed E_F is below 3 times kT .

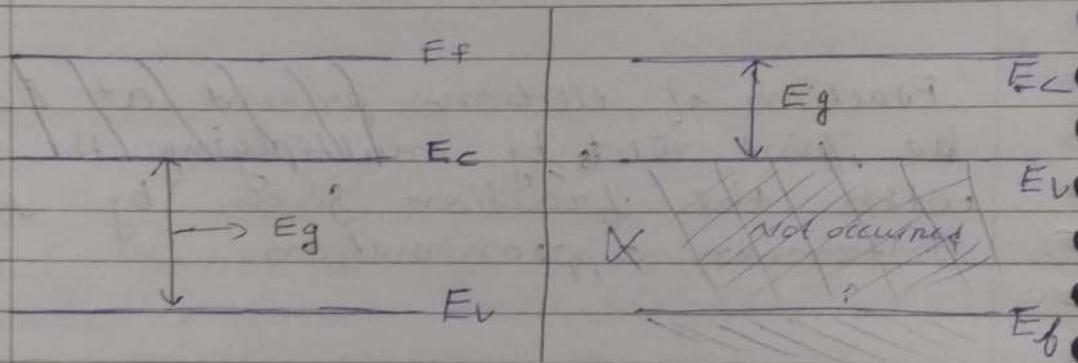
- Now we have to locate the fermi level in an intrinsic semiconductor in the next slide.

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→ Location of E_f by Simple Reasoning

- * We all know that the Fermi energy level is that level above which no level is occupied and below which all available states are occupied at $T=0\text{K}$



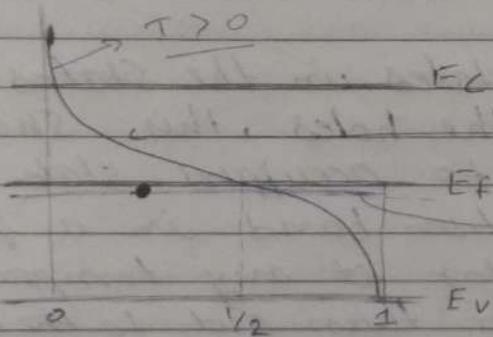
- Supposing E_f was in conduction band, then what it means is that below E_f whatever states are there which are allowed they must be occupied.
- Now if we assume the E_b to be in the valence band, then all states above E_f should be unoccupied but we know that at $T=0$ the entire valence band is occupied.
- This means there must be conduction electrons at $t=0$ which is NOT TRUE.

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- Hence E_F should be somewhere between E_C & E_V at $T = 0 \text{ K}$.
- Now at T at higher temp. the fermi energy is away from the valance band but close to the conduction band.



By use of this function we can find out the e^- 's concentration using the equation

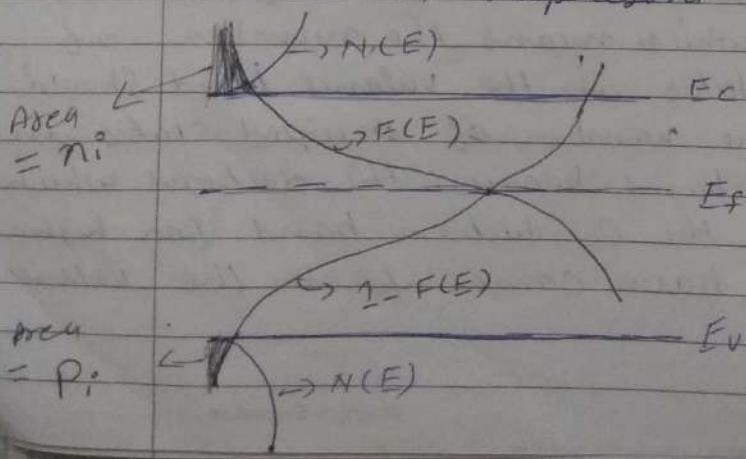
- Here E_F is close to the C_B and away from the V_B .

- all the electrons have to come from the valance band, which means the number of unoccupied states in the valance band should be equal to the number of occupied states in the conduction band because the electrons which have come to the Conduction band for higher temperatures have come from the valance band.

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- Hence as E_f is close to E_c and far from E_v , hence it has been concluded that the no. of unoccupied states in valence band will be less than the no. of occupied states in conduction band or we can mention it as $N_i > p_i$
- Unoccupied states in the states valence band are the holes, this should be equal to occupied state in the conduction band in a pure Semiconductor at any temperature. if this two turn out to be not equal for a certain choice of E_f then that choice of E_f is Not correct.
- The number of holes n_i is given by

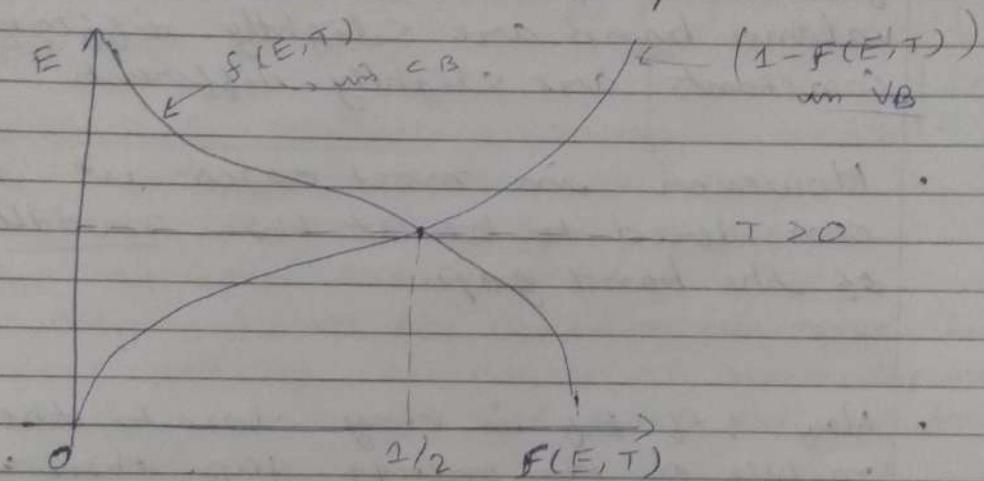
$$n_i = \int N(E) \cdot dE [1 - f(E, T)]$$
- $1 - f(E, T)$ represent unoccupied states.



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$$p_i = \int_{E_B}^{E_F} N(E) \cdot dE [1 - F(E, T)]$$

So it is very clear that if E_F is close to the conduction band edge then area n_i will be less than area p_i .



So if the two constants in the density of states functions for the conduction and valence bands are exactly same then it is clear that $\text{area } p_i = \text{area } n_i$

that is E_F is exactly in the middle of the energy gap.

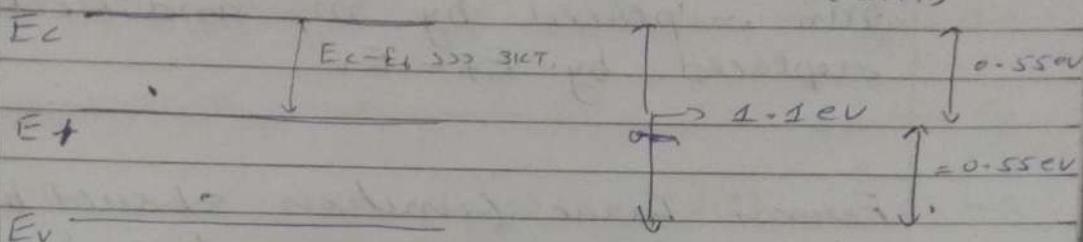
If E_F is exactly in middle of valence band and conduction band then it has been stated that $n_i = p_i$. But it is not exactly at the middle of the energy gap because the effective mass of electrons and holes is not the same.

- which is reflected from different shape of $N(E)$.
- Hence, the parabolic density of states functions for conduction band and valence band are slightly different constants are slightly different.
- However in most cases it is considered to be at the middle of the band gap.
- Now, if E_F is very close to the middle of the energy gap, then what is the distance between E_F & E_C ?
- The energy gap in silicon is 1.1 electron volt. Half of that would be 0.55.
- Let us take $E_g = 1.1 \text{ eV}$, then $\frac{1}{2}$ of it would be 0.55 electron volt. That is $E_C - E_F$.
- Now, $kT = 0.026 \text{ eV}$ so $3kT = 0.078 \text{ eV}$ if we compare 0.55 eV and 0.078 eV we will always find that $(E_C - E_F)$ in a pure semiconductor like silicon and in many other semiconductors

will always be more than $3kT$ at any temperature. So, Boltzmann approximation is valid.

$$\text{For } EB \Rightarrow E_c - E_F \gg 0.078 \text{ eV}$$

$(3kT)$



Now, from the equation we have to find out E_F , because until know the value of E_B , we could not find out the value of n_i .

$$n_i = 2f \left[\frac{2\pi m n kT}{h^2} \right]^{3/2} \cdot e^{-\left(\frac{E_c - E_F}{kT} \right)}$$

$$p_i = 2 \left[\frac{2\pi m p kT}{h^2} \right]^{3/2} \cdot e^{-\left(\frac{E_F - E_v}{kT} \right)}$$

$E_T = +\infty$
 E_c

E_F

$E_B = -\infty$

use Boltzmann approximation to the fermi Dirac function and then use parabolic density of states approximation and we replace the bottom of the valence band by negative infinity and then our result will be exactly analogous to this. So we can write down the result for p_i simply from the result of n_i .

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- The formula for n_i should be the same as the formula for n_i with the replacements of m_n replaced by m_p and $E_c - E_f$ replaced by $E_f - E_v$.
- Fermi - Dirac function should be ≤ 1 , therefore the negative sign is kept outside and the term inside the bracket should be positive.
- So, $E_c - E_f$ & $E_f - E_v$ should be positive.

Now we can eliminate the E_f between these two results by
 $n_i \times p_i$

$$n_i \times p_i = 4 \left[\frac{2\pi kT}{h^2} \right]^3 (m_n m_p)^{3/2} e^{-\left[\frac{E_c - E_f}{kT} \right]} \cdot \underbrace{n_i}_{m_i} \cdot \underbrace{N_c N_v}_{e^{-\left[\frac{E_f - E_v}{kT} \right]}}$$

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$$n_i = \sqrt{N_A N_V} e^{-\left[\frac{E_g}{2kT} \right]}$$

Properties of Silicon & InAs

Parameter Symbol (unit) Si InAs

Band gap E_g (eV) 1.12 1.42Electron affinity X (eV) 4.05 4.07Intrinsic concentration N_i (cm^{-3}) 1.5×10^{10} 1.8×10^6 Effective density of states N_A (cm^{-3}) 2.8×10^9 4.7×10^{17}
 N_V (cm^{-3}) 2×10^9 7×10^{18} Dielectric constant ϵ_r 11.7 12.9

These values that are being shown are valid at room temperature 300 K.

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We can use these values of n_i at $T = 300\text{K}$ and then you can use the formula to find out the value at any other temperature.

- The expression of n_i as a function of temperature.

$$\# n_i = B \cdot T^{3/2} \cdot e^{-\left[\frac{E_g}{2KT}\right]}$$

Now we know the value at 300K . So using that value to get the constant 'B' which is independent of temperature, and then using the constant and we can find n_i at any other temperature.

- Now;

$$\# \frac{n_i(T)}{n_i(300\text{K})} = \left(\frac{T}{300}\right)^{3/2} e^{\left[-\frac{E_g}{215} \left(\frac{1}{T} - \frac{1}{300}\right)\right]}$$

\therefore This is how we can estimate n_i at any other temperature.

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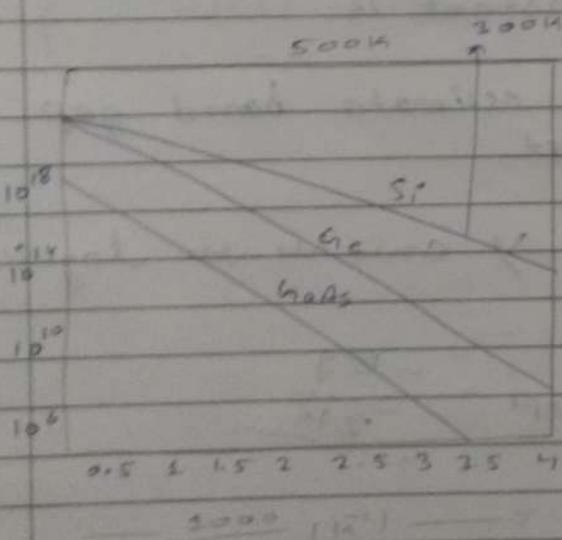
Effective mass of Silicon & GaAs

Parameter	Symbol	Si	GaAs
-----------	--------	----	------

Conductivity effective mass	m_n/m_0	0.26	0.09
	m_p/m_0	0.38	—

Electron affinity	m_e/m_0	1.18	0.068
	m_h/m_0	0.82	0.56

Carrier Concentration in Intrinsic Semiconductors



$$n_i = \sqrt{N_c N_v} e^{-\frac{E_g}{2kT}}$$

$$n_i = B_0 T^{3/2} e^{-\frac{E_g}{2kT}}$$

$$\log n_i = \log B_0 + \frac{3}{2} \log T - \frac{E_g}{2kT}$$

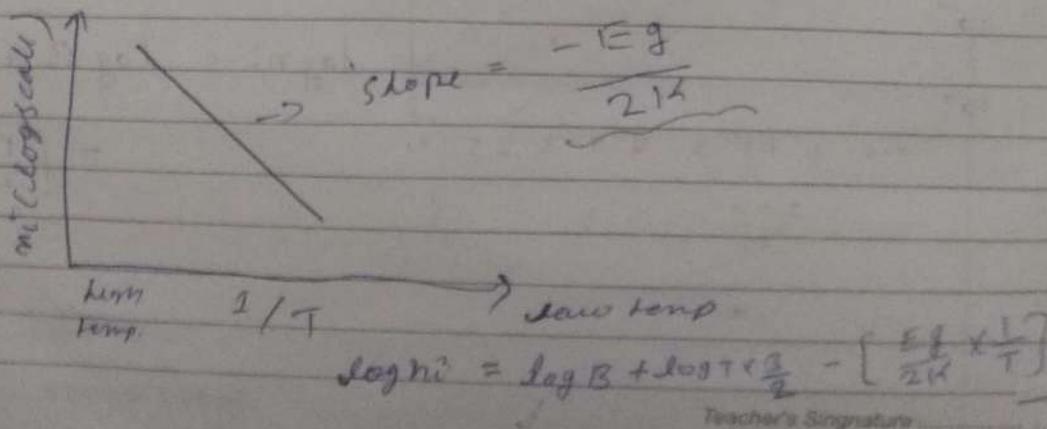
$$- \left[\frac{E_g \times 1}{2kT} \right]$$

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Now this log of π is dependent on temperature but this variation with temperature is very small because it is logarithmic dependence on temperature whereas it depends on $1/T$ varies much more rapidly.

Hence, log n_i vs $1/T$ term would be a straight line.

- In log n_i vs $1/T$ graph slope of the straight line is $Eg/2k$. Thus depends on the energy gap and Boltzmann constant k .
- So we can estimate band gap from this plot.
- That is why Y axis is in log scale



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- The slope can be used to get the energy gap of the Semiconductor.
- Now from n_i and p_i , E_f has been calculated.

$$E_f = \frac{E_c + E_v}{2} - kT \ln \sqrt{\frac{N_c}{N_v}} \quad [n_i = p_i]$$

∴ The second term depends on temperature. But this dependence on temperature is negligible because $\sqrt{\frac{N_c}{N_v}}$ quantity is small.

{ So E_f is approximately equal to $\frac{E_c + E_v}{2}$ }

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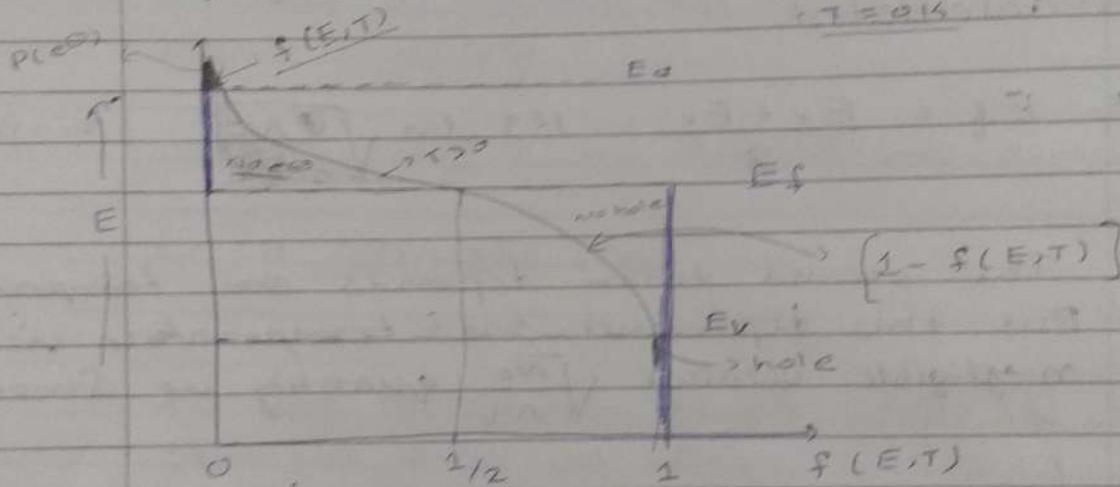
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$$\text{Fermi function } f(E, T) = \frac{1}{1 + e^{\frac{(E - E_F)}{kT}}}$$

E_F = fermi level



at $T = 0$:

valence band completely full by e^-

↪ probability of occupation = 1

CB:

↪ probability of occupation = 0

$$f(E, T) = \frac{1}{2} \quad (E = E_F)$$

↪ for all temp.

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Quasi Fermi Level: Junction Device (P-n Junction)

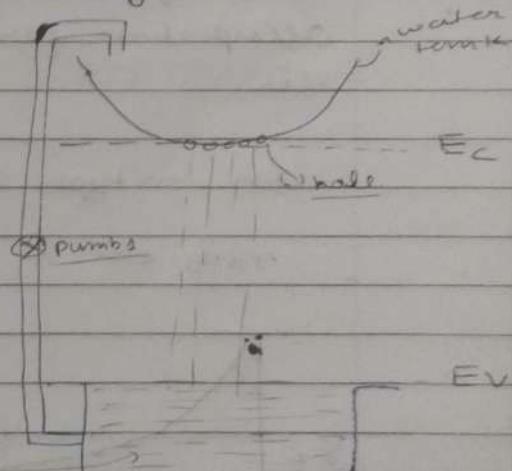
refers to the two quasi fermi level which describe the probability of occupation in the CB and VB, in quasi-equilibrium.

One fermi level describe the occupation probability in conduction band and another describe occupation probability in V.B

Thermalisation:

Electron \rightarrow Drop water

Hole \rightarrow air Bubble



at pump off ($T=0$)

contains full ($V_B \text{ full}$) at $T=0$
 full

\rightarrow pump on ($T > 0$) after
a finite temp (stationary state)

after some time

water in container walls
is equal water in tank

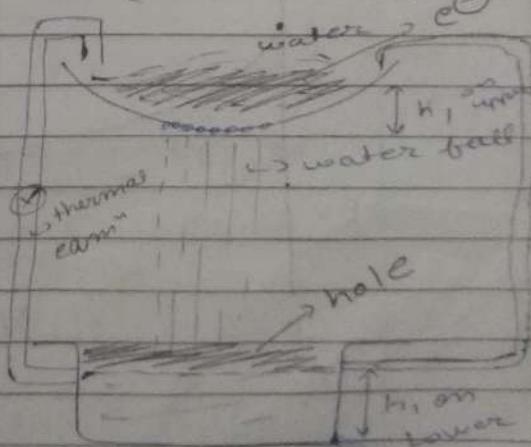
Water = e^-

at high temp

e^- ions

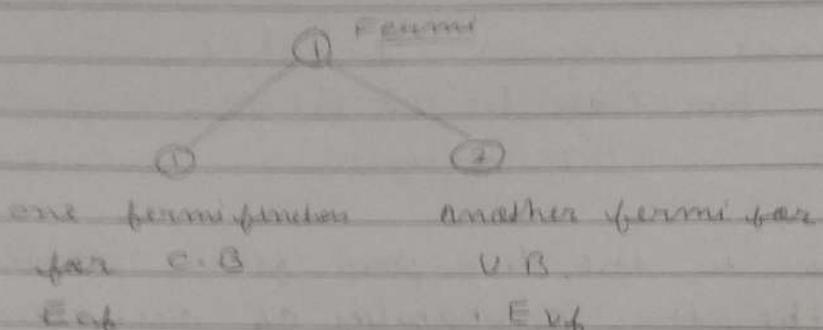
\rightarrow hole in VB

$V_B \text{ column} = \text{hole}$



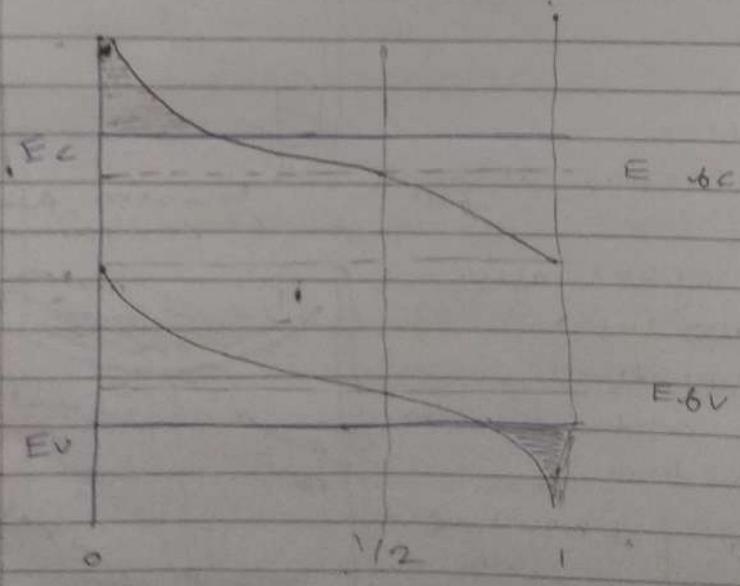
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- 4) The carrier density is so large in both the conduction band and valence band, that we required a two fermi level to describe the occupation probability in C.B and V.B

in n-type Sem. in p-type Sem.
no. of e⁻ is high no. of hole high



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$$f_c(E, T) = \frac{1}{e^{\frac{(E - E_{Fc})}{kT}} + 1}$$

$$f_v(E, T) = \frac{1}{e^{\frac{(E_{Fv} - E)}{kT}} + 1}$$

$$n = Nc \cdot e^{\frac{(E_F - E_c)}{kT}}$$

$$P = Nv \cdot e^{\frac{(E_v - E_{Fv})}{kT}}$$

~~$$n_e = Nc \cdot e^{\frac{-E_F - E_c}{kT}}$$~~

$$n_p = Nv \cdot Nc \cdot e^{-\frac{E_F}{kT}} \left(\frac{E_{Fc} - E_{Fv}}{kT} \right)$$

$$\text{in}^2$$

$$f_c(E, T) = \frac{1}{e^{\frac{(E - E_{Fc})}{kT}} + 1}$$

$$f_v(E, T) = \frac{1}{e^{\frac{(E_{Fv} - E)}{kT}} + 1}$$

$$n = Nc \cdot e^{\frac{-(E_c - E_{Fc})}{kT}}$$

$$P = Nv \cdot e^{\frac{-(E_{Fv} - E_v)}{kT}}$$

$$n \cdot P = Nc \cdot Nv \cdot e^{\frac{(E_{Fc} - E_{Fv})}{kT}} \cdot e^{\frac{-(E_c - E_{Fc})}{kT}}$$

$$n \cdot P = Nc \cdot Nv \cdot e^{\frac{(E_c - E_v)}{kT}} \cdot e^{\frac{(E_{Fc} - E_{Fv})}{kT}}$$

$$n \cdot P = (Nc)^2 \cdot e^{\frac{(E_{Fc} - E_{Fv})}{kT}}$$

$$\text{In } E_{Fc} = E_{Fv} \quad E_F = E_c = 0$$

$$n \cdot P = n \cdot c^2 \quad \Rightarrow \quad n \cdot P > 0$$

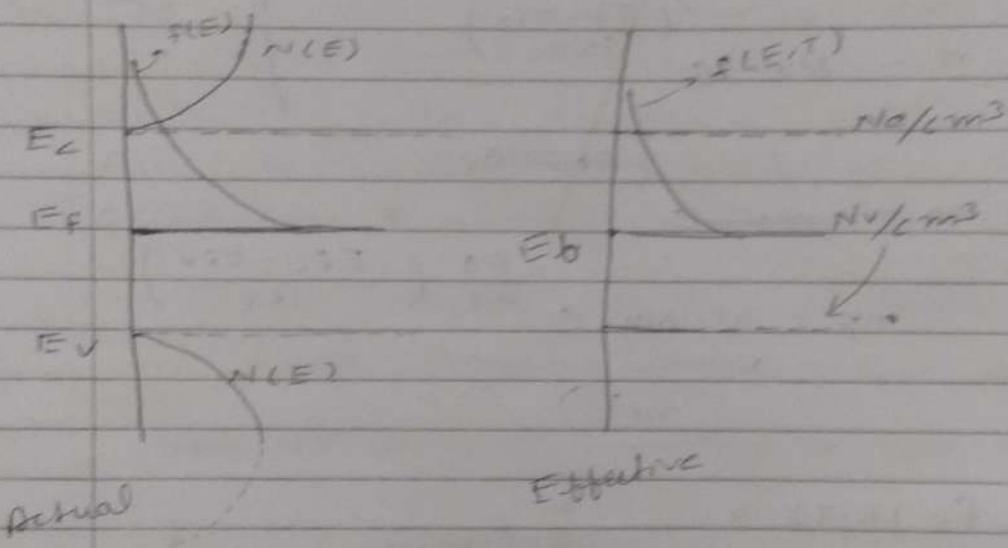
$n \cdot P = n \cdot c^2$ (at room temperature, $E_F = E_c = 0$)

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How the weather for the sun

Under Quasi-equilibrium mass action law is not valid

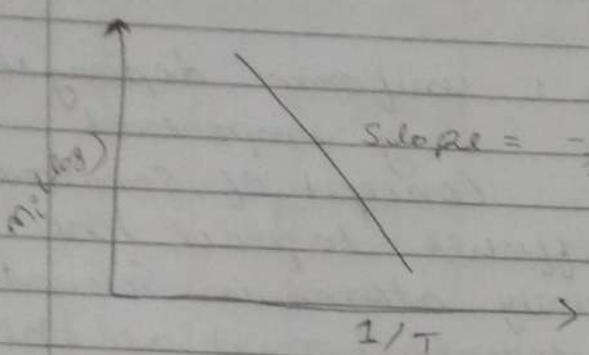
- Allowed level and Density of States plot:



$$\left\{ \begin{array}{l} n_i = N_c e^{-\left(\frac{E_c - E_i}{2kT}\right)} \\ p_i = N_h e^{-\left(\frac{E_f - E_i}{2kT}\right)} \end{array} \right.$$

$$E_b = \frac{E_c + E_f}{2} - kT \ln \sqrt{\frac{N_c}{N_h}}$$

$$n_i = \sqrt{N_c N_h} e^{-\left(\frac{E_b}{2kT}\right)}.$$



* Carrier Concentration in Extrinsic Semiconductor :-

↳ Minority Carrier concentration

$$= (\text{Intrinsic carrier concentration})^2$$

Majority carrier concentration

$$\therefore P_{no} = \frac{n_i^2}{N_{no}} \quad \text{for n-type}$$

n type under equilibrium

$$\ast n_{po} = \frac{n_i^2}{P_{po}} \quad \text{for p-type}$$

Bond model of the Extrinsic Semiconductor :-

- Uniform Doping means no defects only impurities.

• Uniform Doping : uniform doping is very important concept of Semiconductors. It is very difficult to place the uniform impurity atoms in Semiconductors at regular intervals : just as the Silicon atoms in a Silicon Crystal at regular intervals it is not possible to have impurity atoms placed at regular intervals that easily. This is because the process that are used to introduce impurities normally result in random location of the impurity atoms.

• Suppose the concentration of impurity atoms is $10^{16}/\text{cm}^3$

$$\text{Defect} \pm \sqrt{10^{16}/\text{cm}^3}$$

$$\text{average} = 10^{16}/\text{cm}^3$$

$$\text{Range for impure} = 10^{13} - 10^{16}$$

III Band model of the Case of Silicon doped with phosphorus impurity :

• p' atom can be located exactly in the place of Silicon or it can also be between two Silicon

$$F = \frac{q^2}{4\pi\epsilon_0 E_s \delta^2}$$

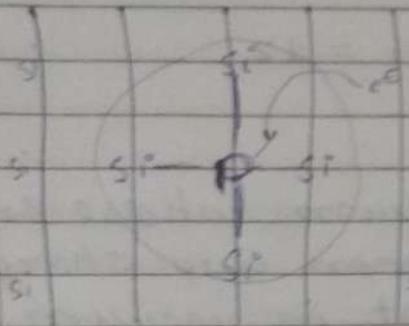
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$$F \propto \frac{1}{E_s}$$

$$E \propto \frac{1}{E_s}$$

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HOW THE MED THIS PAPER GET DOWN



- At $T=0K$, the phosphorus module has 5 electrons in the outermost orbit and among them 4 electrons will participate in bonding with 4 neighboring silicon atom.

- Only one electron will simply revolve around the phosphorus.
- Without this particular electron the phosphorus atom is positively charged. The radius of the orbit is rather large and that is because the medium here is silicon and not vacuum.
- Now if we consider the effect of the dielectric constant of the medium in which this particular electron is orbiting, the force between this positively charged phosphorus and the negatively charged electron F is proportional to $\frac{1}{E_s}$.

$$F = -\frac{q^2}{4\pi\epsilon_0 E_s \delta^2}$$

$$F \propto \frac{1}{E_s}$$

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here $\epsilon_s > 1$; $\epsilon_s = 1$ vacuum.

for Silicon $\epsilon_s = 12$

- In a dielectric medium whose $\epsilon_s > 1$ then the force between two charges will be less than that in vacuum. here ϵ_s for Silicon is about 12 which implies that the force between two charges, assuming some distance r , will be 12 times smaller in silicon than in vacuum.
- The energy of the electron in the orbit using the Bohr model of the hydrogen atom is proportional to $\frac{1}{(\epsilon_s)^2}$ which reflects that, the energy of this electron orbiting around the phosphorus atom in Silicon would be 144 times less (because the $\frac{1}{(\epsilon_s)^2}$ for silicon would be $\frac{1}{(12)^2}$ than that of a hydrogen atom).
- Now this energy of the electron is actually energy required to free the electrons from this particular orbit and take it to infinity. So this is called the Ionization Energy by definition.

 E_{ion}

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$$\text{Fion} \propto \frac{1}{(\epsilon_0)^2}$$

The energy required to free this is electron. Fion infinity $\frac{1}{(\epsilon_0)^2}$, thus due to presence of Silicon medium the phosphorus atom can be ionized rather easily with respect to vacuum medium.

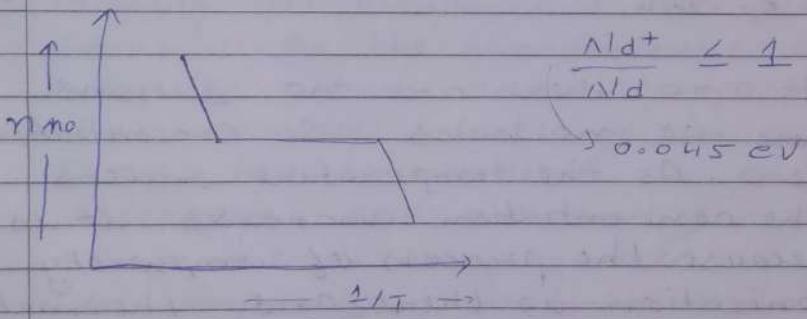
- The same phosphorus atom when move out of silicon its ionization energy will be much larger, typically about 0.045 ev.
- A silicon - Silicon (si---si) bond, to break this, the energy required is 1.1 ev. Now as a result the electron which is orbiting around the phosphorus atom at $T = 0K$, can be freed very easily when the temperature beyond $0K$. For $T > 0K$ this electron becomes free of this phosphorus atom because of thermal vibrations of Silicon atoms.

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Sources of pairs in Extrinsic Semiconductors :

process	Result	Energy Required (for silicon)
Impurity ionization	Only electron or only hole	0.045 eV
Silicon ionization or Thermal generation	EHP	1.1 eV

Concentration vs Temperature Dynamic



Suppose, in an n-type semiconductor in a phosphorus doped crystal the electrons will be in majority. Electrons are created by impurity ionization as well as by silicon ionization as thermal generation whereas holes are created only by thermal generation. So, electrons are in a majority. So it is majority carrier concentration N_{no} Versus T/T .

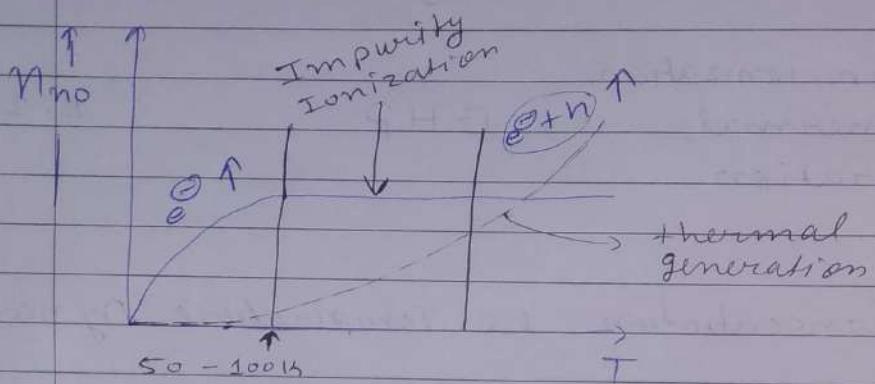
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$$E = 15 \times T = 0.026 \text{ eV}$$

\hookrightarrow H₂ particles \hookrightarrow 1.1 eV $\xrightarrow{\text{Si-Si}} e^{\circ}$

Impurity Ionization And Thermal Generation Curve for phosphorus doped Si :



- At $T = 0$ there are no electrons and no holes, so concentration is 0. As the temperature raises the concentration increases, it is because the process of impurity ionization is there and thermal generation is there.
- But it has been obvious that the impurity ionization process will always dominates over thermal generation because of the small energy. So while a temperature may be around 50K to 100K the exact temperature

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depends on the value. So, for different impurities we have different ionization energies. By this time all the impurities are ionized or Nd^+/Nd becomes almost = 1.

- So once that happens the concentration has becomes almost constant because although this particular process of is going on unceasing with temperature, the concentration is very small compared to that concentration.
- Already all impurities are getting ionized by the temperature which is less than room temperature so we are reaching in saturation though the component is going on unceasing the thermal generation component is very small compared to impurity ionization because of the different energies associated And beyond the temperature the thermal generation is becoming comparable to the impurity ionization

So beyond 50-100K the impurity ionization has saturated, thermal generation is increasing and it is going beyond so the carrier concentration now starts exceeding

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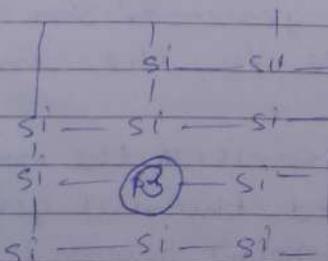
that is how the plot can be explained as an increasing portion in the beginning then a flat portion of the concentration and then again an increasing portion.

Bond model for the case of Silicon doped with Boron Impurity:

For the P type boron doped silicon boron is group 3 impurity. The ionization energy of boron is also about 0.04 electron volts.

Here in the following figure the phosphorus is being replaced by boron. At $T=0\text{ K}$ there is a hole revolving around a negatively charged boron atom.

$\hookrightarrow \text{P(hole)} \uparrow$



Boron is a group third element

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Boron has three electrons in the outermost orbit, therefore, there are 3 bonds; however one bond will be broken, because boron does not have a 4^{th} electron whereas Si has a 4^{th} electron here.

- Now for $T > 0\text{K}$, it is possible for an electron from any one of this bonding processes, electrons located in any of the silicon-to-Silicon bond jump into it and fill in the place and establish this bond, if that happens the electron which is coming to this boron atom will make this boron negatively charged.
- But since the electron has come from somewhere nearby, it will leave behind a vacancy there. Such a thing will happen only at $T > 0\text{K}$. So for $T > 0\text{K}$ the absence of an electron near the boron side results in a broken Si-bond somewhere else because the boron atom likes to accept an e^- in order to fill the bond. So $T > 0\text{K}$ each boron atom is ionized, will contribute to a hole, after breaking of a bond for this reason Boron atom is called the ACCEPTOR ATOM.

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Difference between phosphorous atom and Boron atom:

- The only difference between phosphorous and boron is that at $T=0K$, the phosphorus atom is equivalent to a positively charged nucleus because it has the 4^{th} electron from somewhere else and a hole or a positive charge revolving around it.
- The another statement is that because of the presence of the Silicon medium the ionization energy of boron reduces drastically, energy proportional to $\frac{1}{E_0^2}$ and that energy turns out to be 0.415 electron volts.
- Similarly, there is a parallel process of Silicon ionization which result in a hole and an electron pair. in the case of boron we are getting holes by two mechanisms. one is impurity ionization and other is the thermal ionization or Silicon ionization.

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Therefore the holes are in a majority and for this reason this Semiconductor will be called p-type Semiconductor.

Sources of pair pairs in Extrinsic Semiconductor :

Process	Result	Energy required (for Silicon)
---------	--------	----------------------------------

Impurity ionization	only electron or only hole	0.045 eV
---------------------	----------------------------	----------

Silicon ionization	EHP	1.1 eV
--------------------	-----	--------

Thermal generation		
--------------------	--	--

- Impurity ionization in the case of boron resulting in only hole does not give rise to a free electron. Energy is 0.045 eV; you have Silicon ionization which results in electron hole pair generation and energy 1.1 eV. This result will be similar like phosphorus, the only difference being this N_{nn} will be replaced by P_{pp}.

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position of Fermi Energy level due to change in Temperature and Doping :

C.B

E.F.

V.B

Intrinsic S.C.

C.B

E.Fm ↓

⇒

(T↑)

C.B

E.Fm

V.B

V.B

Intrinsic S.C.

① $E_{Fm} \downarrow \Rightarrow T \uparrow$ $E_{pp} \uparrow$ $\Rightarrow T \uparrow$

y ↘

(Tc)

 $E_F \rightarrow E_{Fi}$ Intrinsic
Semiconductor

Doping :

N.D ↑ ($e^- \uparrow$)

C.B

N.A (hole ↑)

C.B

E.Fi

V.B

Esi

Extrinsic S.C.
n-type

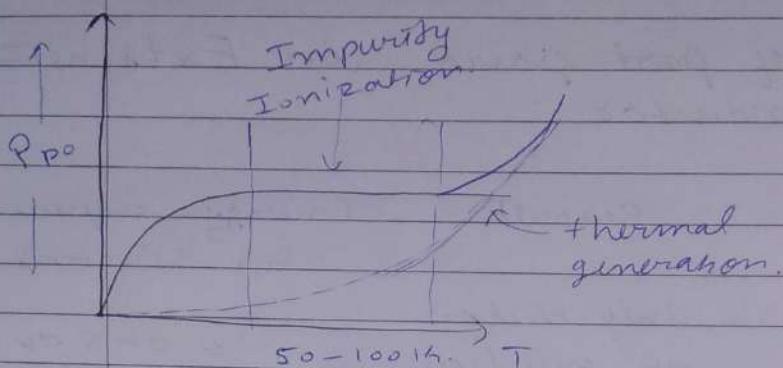
V.B

Extrinsic S.C.

P-type

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Impurity Ionization and Thermal Generation Curve for Boron doped Si.



- Impurity ionization boron atoms getting ionized and ultimately, almost fully ionized with in the range of $50\text{K} - 100\text{K}$ which is much lower than room temperature and then saturation so impurity ionization has saturated here. Na/Na^+ , "Na" is the impurity concentration ; "a" stands for acceptor because boron accepts an electron it is called as a group 3 acceptor . And Na^- "—" superscript indicates that fraction of Na which are ionized So, $\text{Na}^-/\text{Na} \approx 1$ after 50K to 100K Na/Na^+ is almost 1 . So the curve has been saturated The process of thermal generation Similarly taking place.

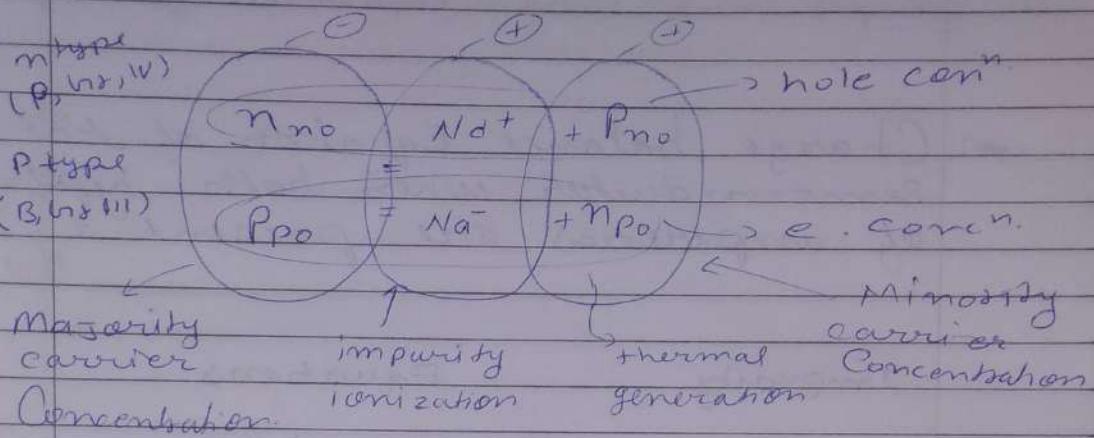
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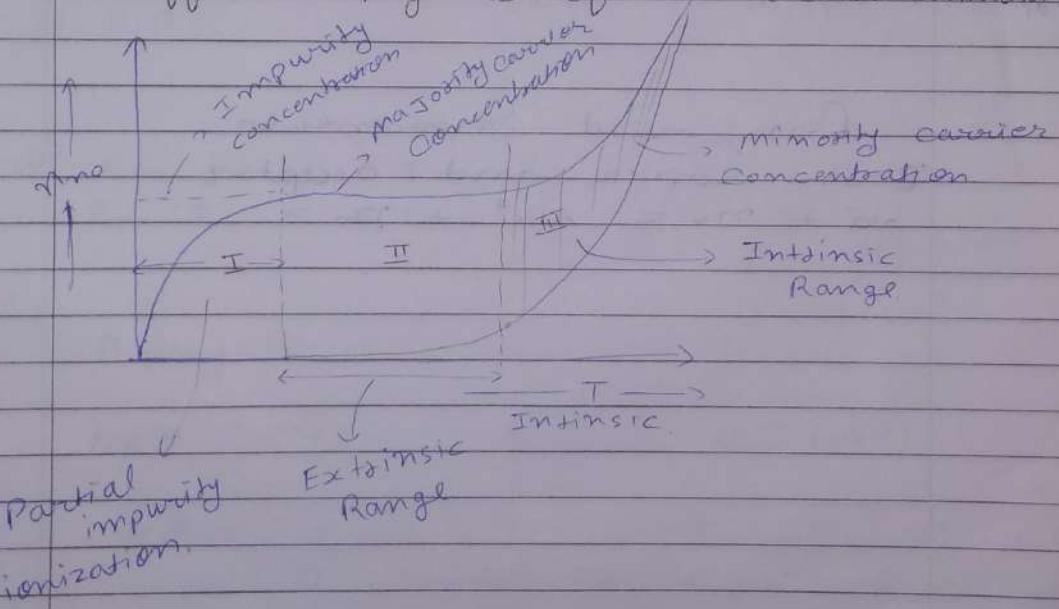
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Charge Balance Equations:



Different Regions of Carrier Concentration:



Region I : impurity concentration

Region II : Extrinsic Range (Majority Carrier concentration)
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Region III : Intrinsic Range (Minority carrier concentration)

Charge balance Equation of the Semiconductor when both type of impurities are present :-

Impurity

Equations.

n_{type} \leftarrow Donor

$$n_{no} = N_d^+ + P_{no}$$

P_{type} \leftarrow Acceptors

$$P_{po} = N_a^- + n_{po}$$

Compensated Semiconductor.
Both donor and acceptor
 $N_a^- + n_o = N_d^+ + p_o$

if we increase the donor (e^-) more than probability of finding e^- is also increase so

increases the acceptor (hole) concentration then probability of finding hole is also ↑

C.B

C.B

E.Si

↑

E.Si

V.B

↓

V.B

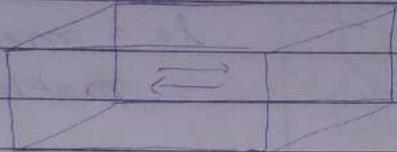
(i) n-type

(i) p-type

$E_Fm \uparrow$ when $N_d \uparrow$ $E_Fp \downarrow$ when $N_d \uparrow$ } Extrinsic
Semiconductor.

Carrier Transport in a Semiconductor

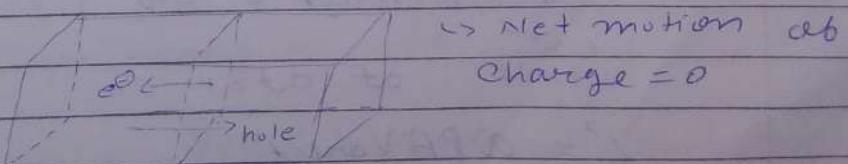
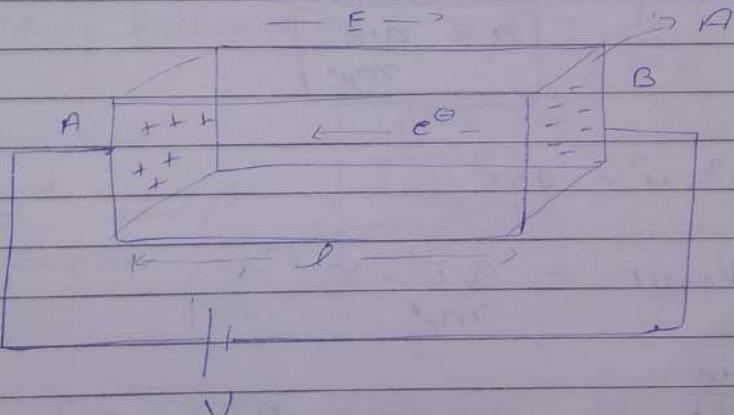
thermal Equilibrium:



- 1) No net motion of charge
- 2) No external excitation
in light, voltage, temperature

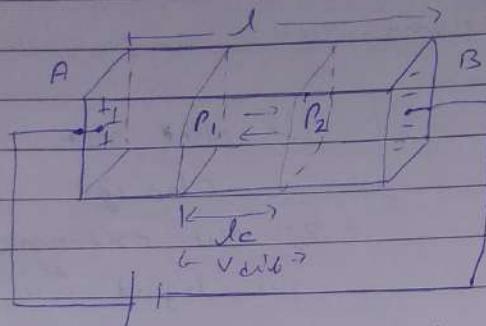
Carrier transport

- Drift Transport → Due to potential difference
- Diffusion " → Due to carrier concentration difference
- Thermoelectric " → Due to temp Difference

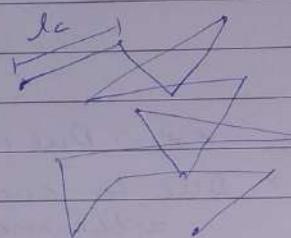


Subject _____

$$E = \frac{V}{l}$$



l_c = mean
path length



Thermal velocity
 v_{th}

$$\vec{F} = m\vec{a} = \rho \vec{E}$$

$$\vec{a} = \frac{\rho \vec{E}}{m_p^*}$$

$$v^2 - u^2 = 2as$$

$$V_{drift} = \frac{\rho E^2 \cdot \gamma}{m_p^*}$$

$$j = \frac{da}{dt}, \quad \text{Volume} = A \cdot V_{drift}$$

$$A \cdot P \cdot A \cdot V_{drift} = dq$$

converging
at hole at $dt = 1$

$$C = \rho PA V_{drift}$$

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$$v^2 - u^2 = 2as$$

final velocity initial velocity

$$v^2 - v_{th}^2 = 2a_{dc}$$

$$v^2 = 2a_{dc} + v_{th}^2$$

$$v = \sqrt{v_{th}^2 + 2a_{dc}}$$

$$v = v_{th} \sqrt{1 + 2a_{dc}} \quad v_{th} \text{ is very large}$$

$$v = v_{th} \left[1 + \frac{2a_{dc}}{2v_{th}^2} \right]$$

$$v = v_{th} \left[1 + \frac{a_{dc}}{v_{th}^2} \right]$$

$$\left. \begin{aligned} &= v_{th} + \frac{a_{dc} \times a}{v_{th}} \\ &\text{accelerated velocity.} \end{aligned} \right\}$$

$$\left. \begin{aligned} &v = v_{th} + a_{dc} \end{aligned} \right\}$$

$$\# \tau = \text{Relaxation time} = \frac{a_{dc}}{v_{th}} = \tau_c$$

when $v = 0$ net motion = 0 $\xrightarrow{10 \text{ m/s}}$ when $v \neq 0$ $\xleftarrow{10 \text{ m/s}}$ when $v \neq 0$ $\xrightarrow{12 \text{ m/s} \text{ (1)}}$
 $\xleftarrow{8 \text{ m/s} \text{ (2)}}$

net motion

$$\Rightarrow 12 - 8 = 4 \text{ m/s}$$

$$\left. \begin{aligned} v_1 &= v_{th} + a_{dc} \\ v_2 &= v_{th} - a_{dc} \end{aligned} \right\}$$

$\hookrightarrow \text{net velocity} =$

$$\left. \begin{aligned} v_2 \text{ avg} &= v_{th} - \frac{a_{dc}}{2} \end{aligned} \right\}$$

$$\left. \begin{aligned} v_1 \text{ avg} &= \frac{v_{th} + v_{th} + a_{dc}}{2} = v_{th} + \frac{a_{dc}}{2} \end{aligned} \right\}$$

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net velocity of carrier = a_v

$$V_{drift} = \frac{a_v \cdot E}{m_p^*} v.$$

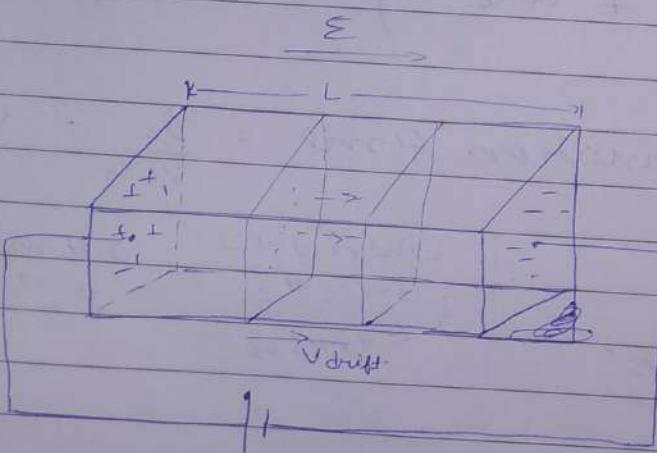
↑
hole

* $\vec{V}_{drift} = \left[\frac{a_v}{m_p^*} \right] \cdot \vec{E} = M_p \cdot \vec{E}$

↑
Mobility = M_p

* $V_{drift} (\text{electron}) = \left[\frac{a_v e}{m_n^*} \right] \cdot \vec{E}$

" = $M_n \cdot \vec{E}$



$$V_{drift} = \frac{a_v E}{m_p^*} v. \text{ m/s}$$

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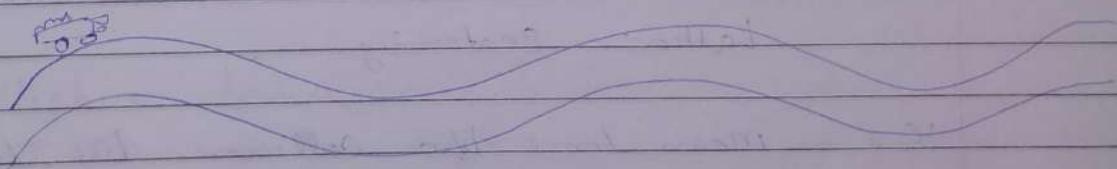
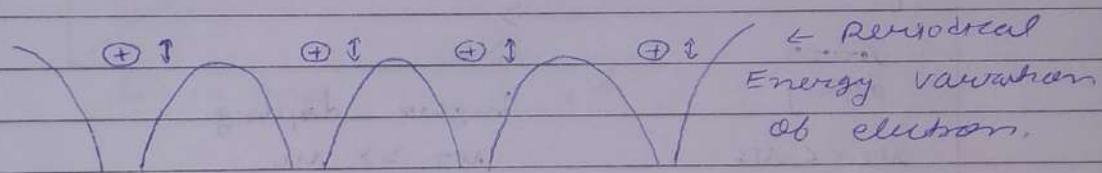
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~~Mobility~~ Effect :

- Collision
- Scattering

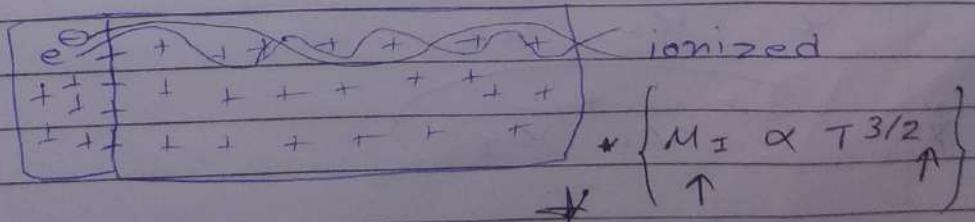
- {
- Ⓐ phonon Scattering / Lattice Scattering
 - Ⓑ Ionized Impurity Scattering



(A) * $\downarrow M_L \propto T^{-3/2} \uparrow$

* mobility of due to lattice scattering

(B) Ionized Impurity Scattering :-



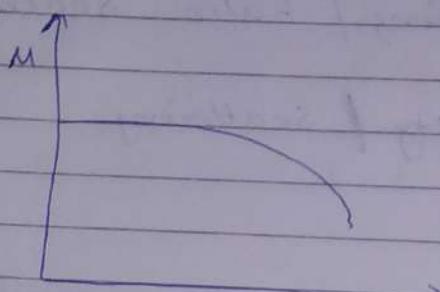
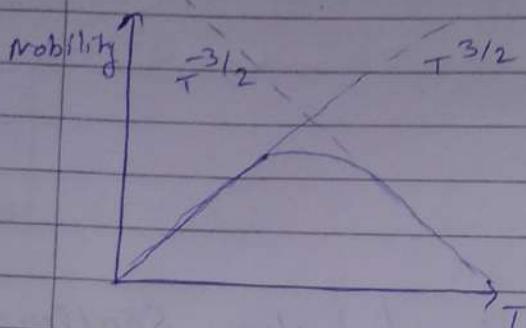
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$$M_L \propto T^{-3/2}$$

$$N_d \uparrow \rightarrow M_I \downarrow$$



$$M_I \ll M_L$$

$$M_I \gg M_L$$

τ_L = Mean time b/w collision due to
lattice scattering.

τ_I = Mean time b/w collision due to
Ionized impurity impaction.

Probability of collision in this time.
 $\rightarrow dt$

$$\frac{dt}{\tau} = \frac{dt}{\tau_L} + \frac{dt}{\tau_I}$$

$$\frac{1}{\tau} = \frac{1}{\tau_L} + \frac{1}{\tau_I}$$

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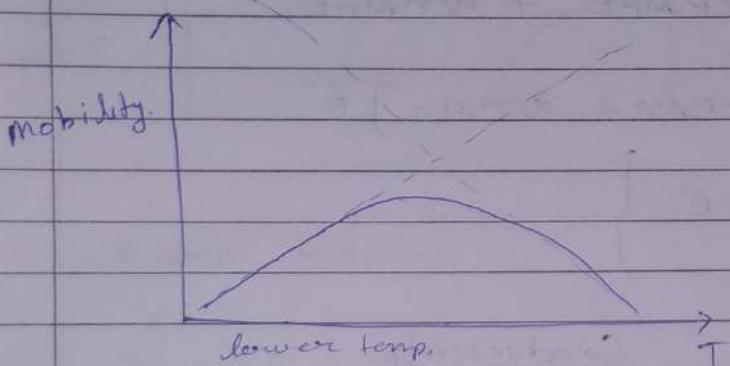
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 $M_{\text{L}} \ll M_{\text{I}}$

$$M_n = \frac{n_e}{m_n^*}$$

$$M_p = \frac{n_e}{m_p^*}$$

$$\left\{ \frac{1}{M} = \frac{1}{M_n} + \frac{1}{M_I} \right\}$$



At lower temp
 $M_L \ll M_I$

Higher temp

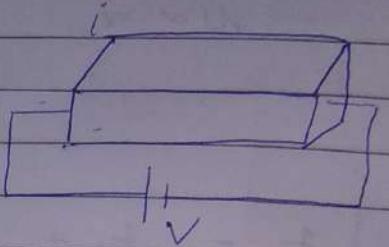
$T \uparrow \rightarrow S \uparrow M \downarrow$

$$\frac{1}{M} = \frac{1}{M_L} + \frac{1}{M_I}$$

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Recap :

$$J_{\text{drift}} = J_P + J_m$$



$$J_{\text{drift}} = J_P + J_n$$

$$J_{\text{drift}} = \sigma P M_p \vec{E} + \sigma n M_n \vec{E}$$

$$J_{\text{drift}} = [\sigma P M_p + \sigma n M_n] \vec{E}$$

$$\left. \begin{array}{l} J_{\text{drift}} = \sigma \vec{E} \end{array} \right\}$$

Conductivity.

$$R = \frac{PL}{A}$$

$$\rho = \frac{1}{\sigma}$$

Resistivity

$$\left. \begin{array}{l} \frac{1}{\mu} = \frac{1}{\mu_L} + \frac{1}{\mu_I} \end{array} \right\}$$

Drift Current is mainly due to majority carrier.

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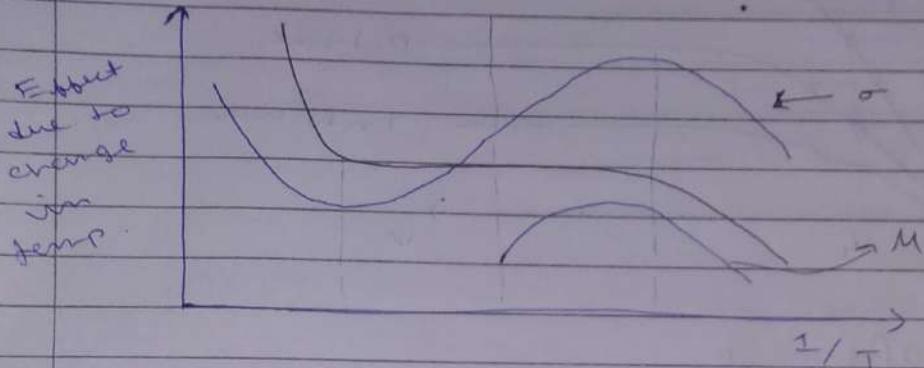
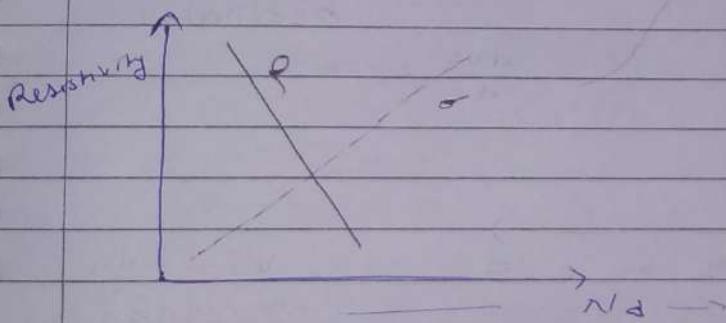
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_____*n Type :*

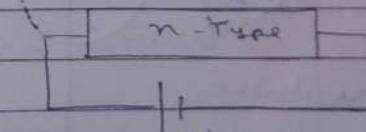
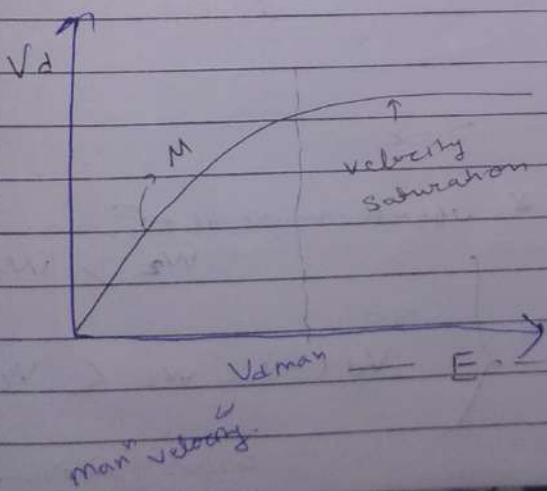
$$J = \frac{e \sigma n m}{\sigma} \vec{E}$$

$$n \gg p$$

$$\sigma = n n M n$$

*Effect - Doping*

$$\vec{V}_d = \vec{M} \vec{E} \quad V_d \propto \vec{E}$$

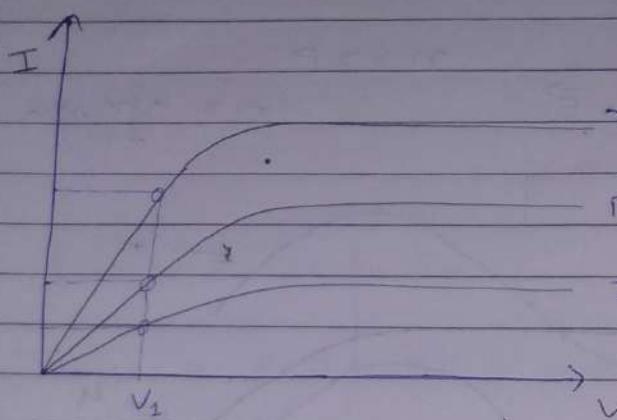


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Mobility

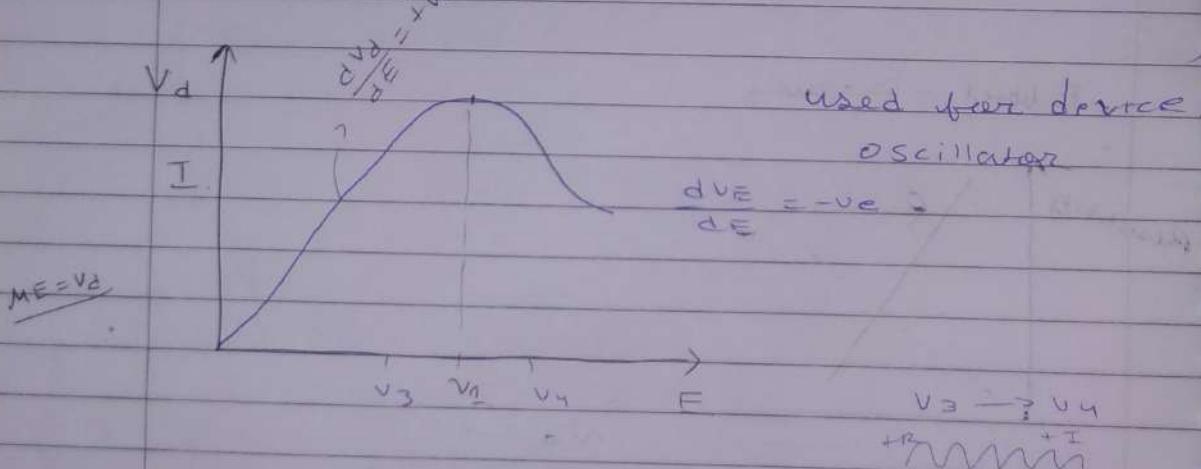
$$* M_n > M_p$$

n -type

p-type

Intrinsic

GraAs.



{ Discrete Band S.C }

Curvature..

$$W_2 > W_1$$

* work mass of e^- in

$$W_2 > W_1$$

*

SO

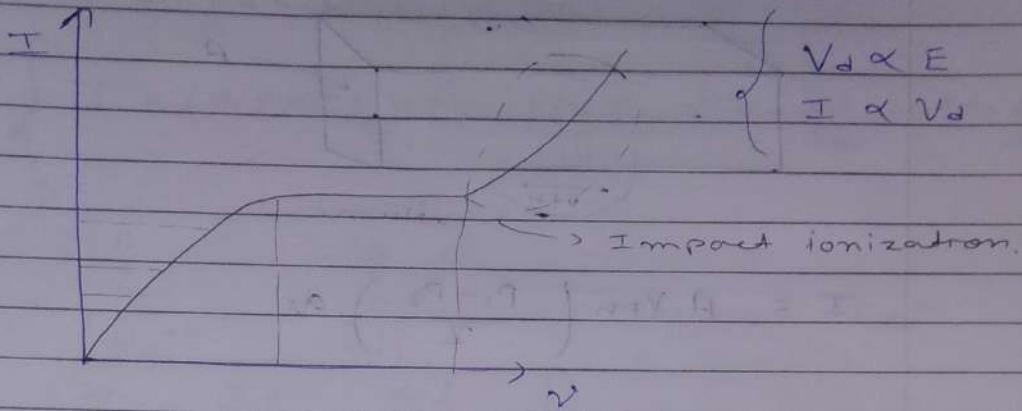
$$V_d (I)_{in W_2} < W_1$$

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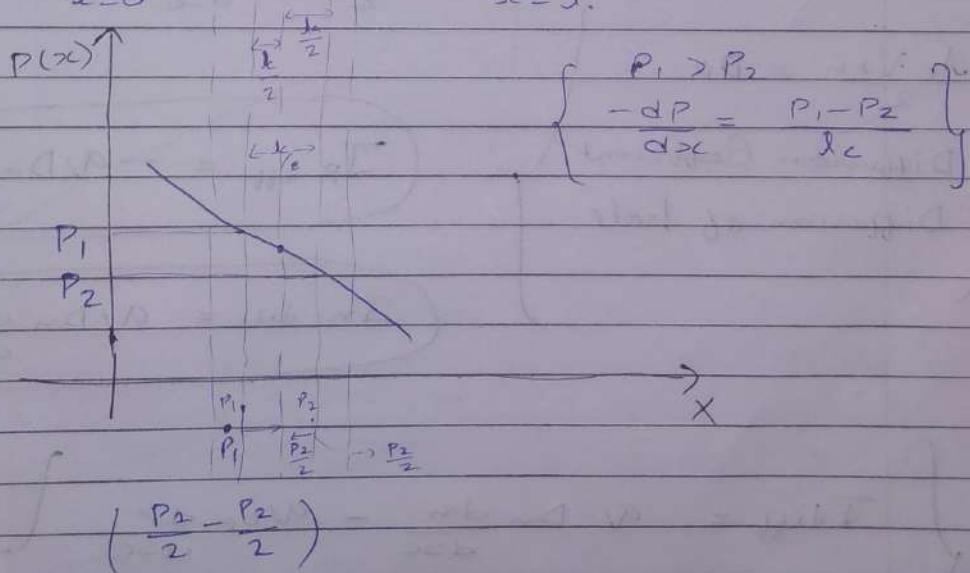
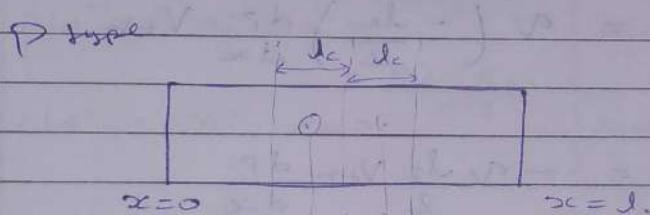
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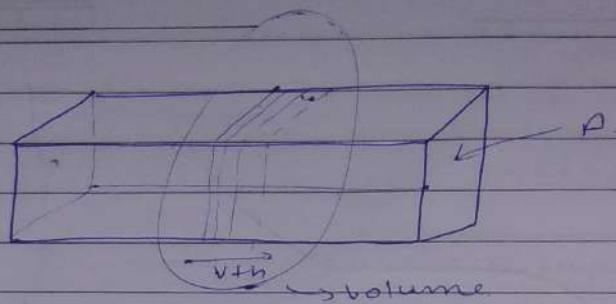
Diffusion Current : due to concn gradient.



$$\left\{ \begin{array}{l} P_1 > P_2 \\ -\frac{dP}{dx} = \frac{P_1 - P_2}{l_c} \end{array} \right\}$$

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$M = \frac{cm^2}{sec}$
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$$I = A \cdot V+n \left(\frac{P_1 - P_2}{2} \right) \cdot a$$

$$J_{\text{diffusion (hole)}} = a \left(\frac{P_2 - P_1}{2} \right) \cdot V+n$$

$$\frac{cm^2}{sec} \quad J_P \text{ diff} = a \left(- \frac{dc}{2} \right) \frac{dp}{dc} \cdot V+n$$

$$J_P \text{ diff} = - a \frac{dc}{2} V+n \frac{dp}{dx}$$

$$\frac{dc \cdot V+n}{2} = DP$$

Diffusion Coefficient

Diffusion of hole

$$J_P \text{ diff} = - a V D_P \frac{dp}{dx}$$

$$J_n \text{ diff} = a V D_n \frac{dn}{dx}$$

$$J_{\text{diff}} = a V D_n \frac{dn}{dp} - a V D_P \frac{dp}{dc}$$

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$$J = (J_{\text{diff}}) + (J_{\text{drift}})$$

$$\star \left\{ J = (\nu P M_p + N n M_n) e + \nu V_{dn} d_n - \nu V_{dp} d_p \right.$$

A B
 \downarrow \downarrow
 n_i n_i

$N_{d^{++}}$	N_{d^+}
--------------	-----------

$$x_{\infty} \quad I \leftarrow \Delta L = l$$

Thermal Eq

$$I = 0$$

$$n_o = n_i \exp \frac{E_b - E_{bi}}{kT}$$

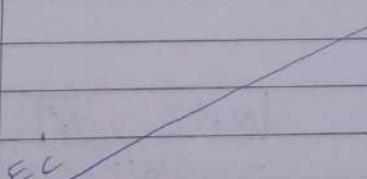
$$n_o = n_c \exp \frac{E_b - E_c}{kT}$$

$$N_{d^{++}} = n_i \exp \frac{E_b - E_{bi}}{kT}$$

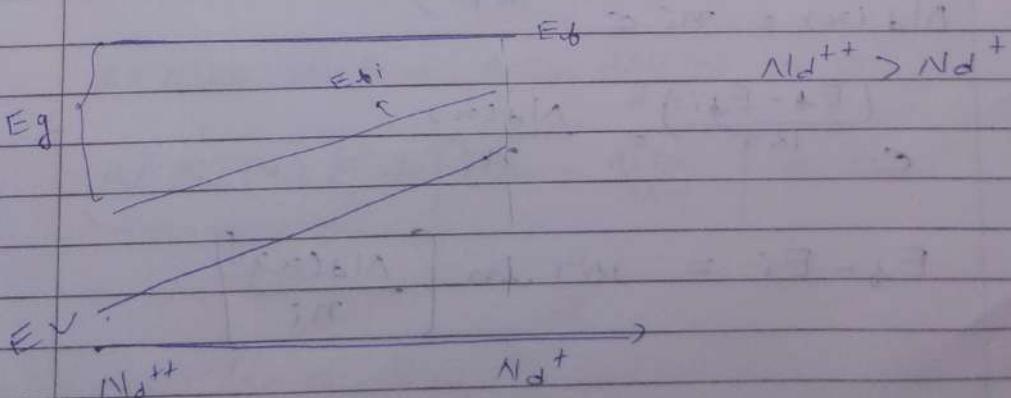
$$N_{d^{++}} = n_c \exp \frac{E_b - E_c}{kT}$$

$$N_{d^+} = n_i \exp \frac{E_b - E_{bi}}{kT}$$

$$N_{d^+} = n_c \exp \frac{E_b - E_c}{kT}$$

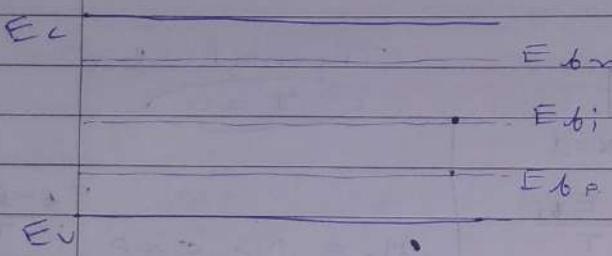
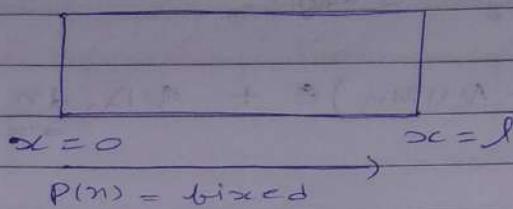


$$- (E_b - E_{bi})$$

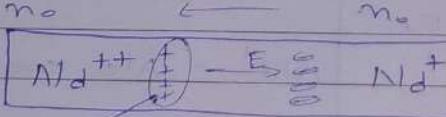


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A ↑ B ↓



→ Immobile charge

$n_o = n_i e \quad \left(\frac{E_b - E_{bi}}{kT} \right)$

$\frac{[Nd^{++} \quad Nd^+]}{Nd^{(o)}} \rightarrow$

$n_a = Nd(x) \quad \left(\frac{E_b - E_i}{kT} \right)$

$Nd(x) = n_i e \quad \left(\frac{E_b - E_i}{kT} \right)$

$$e \left(\frac{E_b - E_{bi}}{kT} \right) = \frac{Nd(x)}{n_i}$$

$$E_b - E_i = kT \ln \left[\frac{Nd(x)}{n_i} \right]$$

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$$-\frac{dE_{bi}}{dx} = \frac{M}{V} kT \cdot \frac{dNd(x)}{dx}$$

$$\Rightarrow \boxed{\frac{dE_{bi}}{dx}} = -kT \cdot \frac{dNd(x)}{dx}$$

$$\text{Electric Field } = \vec{E} = -\frac{dV}{dx} = -\frac{1}{q} \frac{dE}{dx}$$

$$\therefore \vec{E} = -kT \cdot \frac{dNd(x)}{dx}$$

Under Equilibrium $I = 0$

$$\vec{I} = \vec{J}_{drift} + \vec{J}_{diff}$$

$$= J_{ndrift} + J_{pdrift} + J_{pdiff} + J_{ndiff}$$

$$J_{ndrift} + J_{ndiffusion} = 0$$

$$\partial n \frac{Mn \vec{E}}{\partial x} + \partial Dn \frac{dn}{dx} = 0 \quad n \approx Nd(x)$$

$$\partial Nd(x) MnE + \partial Dn \frac{dNd(x)}{dx} = 0$$

$$\underbrace{\partial Nd(x) \cdot E}_{\neq 0} + \left[Mn - \frac{\partial Dn}{kT} \right] = 0$$

$$Mn = Dn \frac{a}{kT}$$

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$$\left\{ \frac{D_n}{M_n} = \frac{kT}{q^2} \right\} \leftarrow \text{Electron}$$

Relation b/w D_n and M_n

$$T = 300 \text{ (K)} \cdot (n - t)$$

$$\Rightarrow \frac{D_n}{M_n} = 26 \text{ mV} \rightarrow \text{Thermal voltage}$$

$$\left\{ \frac{D_p}{M_p} = \frac{kT}{q^2} \right\} \leftarrow \text{hole.}$$

$$\frac{D_n}{M_n} = \frac{1}{40}, \text{ at room temp.}$$

(SI)

$\left\{ \begin{array}{l} \text{Drift Current} \rightarrow \text{Majority carrier} \\ \text{Diffusion Current} \rightarrow \text{Minority carrier} \end{array} \right.$

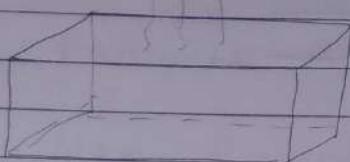
$\left\{ \begin{array}{l} \text{Drift Current} \rightarrow \text{Majority carrier} \\ \text{Diffusion Current} \rightarrow \text{Minority carrier} \end{array} \right.$

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Excess Carrier



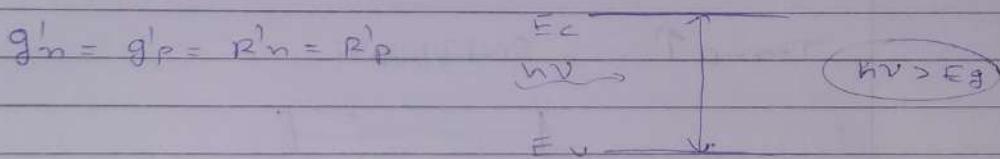
$$h\nu > E_g$$

Non-Equilibrium
Condition

① Equilibrium

$$G_{P_0} = G_{n_0} = R_{P_0} = R_{n_0}$$

② Non-Equilibrium



Excess Carrier Generation

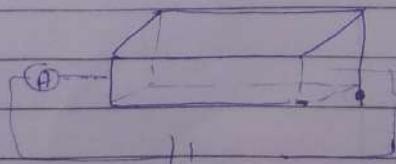
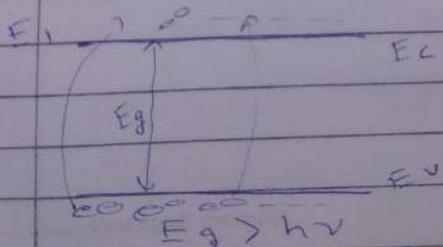
→ photo generation

→ Phonon generation

→ Impact Ionization

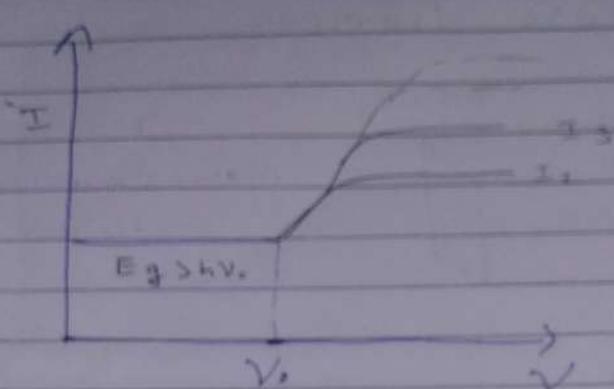
① photo generation (light)

$$h\nu_1 < E_g < h\nu_2 < h\nu_3$$



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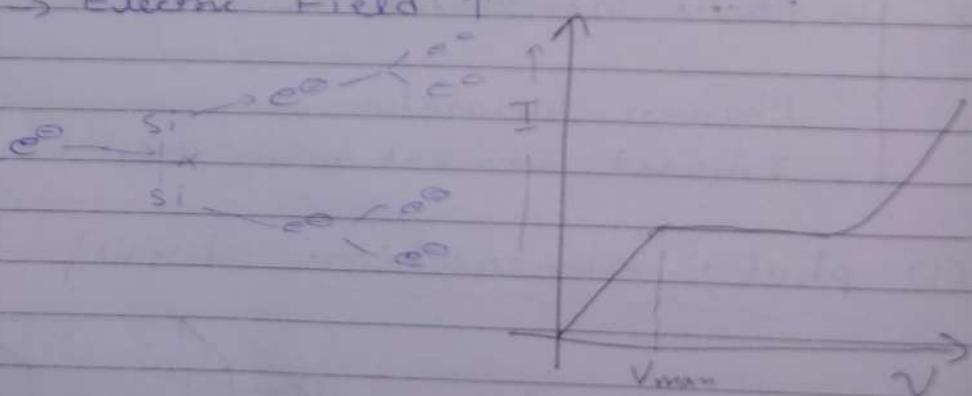


- ② phonon generation

Temp T Si \rightarrow $\text{Si} + \text{Si}$

- ③ Impact Ionization

→ Electric Field \uparrow



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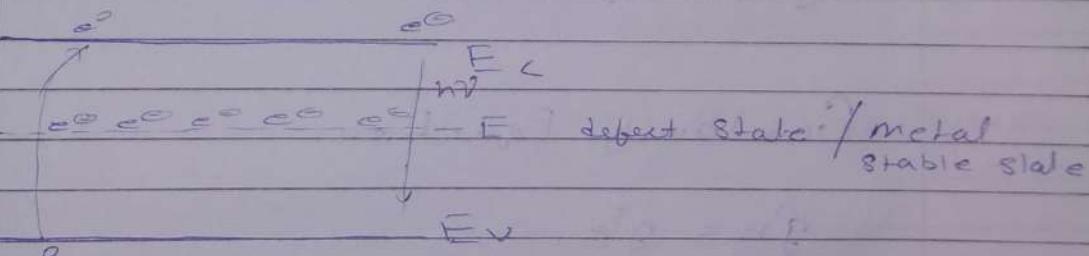
Recombination :

- Radiative Recombination (Direct Band)
- Non-Radiative Recom. (Indirect Band gap)

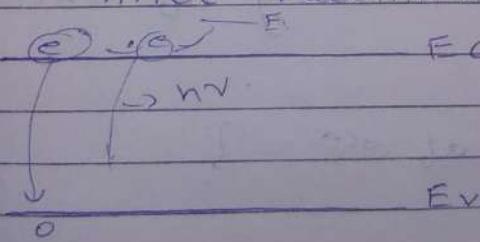
$$Si \rightarrow E_g = 1.1 \text{ eV}$$

$$E_C - E_V = 0.67 \text{ eV}$$

SRH Recombination



After Recombination



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_____*n type*

$$R_P' = \frac{S_P}{\kappa_P} = \frac{S_n}{\kappa_P}$$

$$\kappa_n = (\alpha \cdot P_0)^{-1} \quad \text{and} \quad \kappa_P = (\alpha_0 \cdot n_0)^{-1}$$

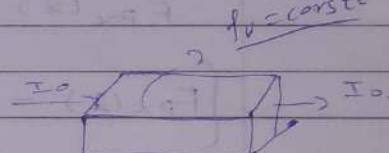
Continuity Eqn / Charge Conservation Eqn

 ρ_v = charge density

$$\vec{J} \cdot d\vec{s} = - \frac{d\rho}{dt}$$

$$\oint \vec{J}_s \cdot d\vec{s} = - \frac{d\rho}{dt}$$

$$\int_{\text{Vol.}} \nabla \cdot \vec{J} \cdot dV = - \frac{d}{dt} \int_{\text{Vol.}} \rho_v \cdot dV$$



$$\left\{ \nabla \cdot \vec{J} = - \frac{d \rho_v}{dt} \right\}$$

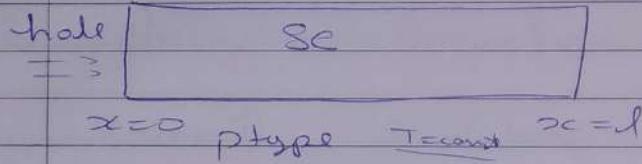
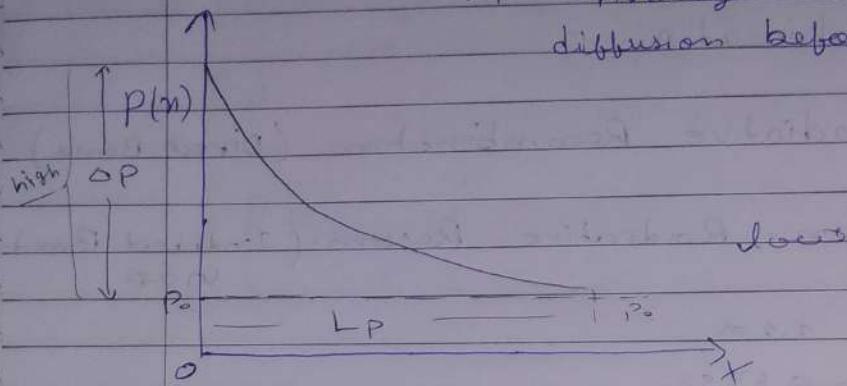
$$\frac{d \rho_v}{dt} = 0$$

$$\nabla \cdot \vec{J} = 0$$

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L_p = Average distance a hole
diffusion before recombination



Diffusion length = L_p = The distance at which the excess (hole) distribution is reduced to $1/e$ of its value at the point of injection.

Continuity Equation.

$$g'n = g'p$$

1, Rate of generating of excess electron.

Rate of change of e^{\ominus} = ?

$$\frac{dn}{dt}$$

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Rate of Recombination \propto conc of electron
of electron
 \propto conc of hole

Non - Equilibrium

$$n = n_0 + \delta n$$

Excess electron

$$P = P_0 + \delta P \sim \text{hole}$$

$$= P_0 + \delta n$$

T = constt

$$\frac{dn}{dt} = \frac{d\delta n}{dt}$$

$$n_i^2 = n_0 P_0 \quad \text{initial conc} = (n_i)^2$$

$$\frac{d\delta n}{dt} = \frac{d\delta n}{dt}$$

$$\frac{d\delta n}{dt} = \alpha_r [n_0 P_0 - (n_0 + \delta n)(P_0 + \delta P)]$$

↳ Rate of change of excess carrier

$$\frac{d\delta n}{dt} = -\alpha_s [\delta n (n_0 + P_0 + \delta P)]$$

$$\frac{d\delta n}{dt} = -\alpha_s \delta n [n_0 + P_0 + \delta P]$$

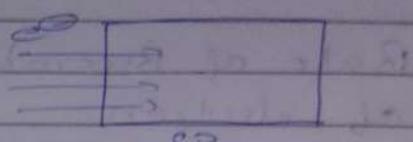
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① P type Si

$$P_o >> n_o$$



SP.

② low level injection

$$S_p \ll P_o$$

$$\frac{dS_n}{dt} = -\alpha_s (S_n) [P_o]$$

$$\left\{ \begin{array}{l} \frac{dS_n}{dt} + \alpha_s P_o (S_n) = 0 \\ \end{array} \right\}$$

↳ first order differential eqn

$$S_n(t) = S_n(0) e^{-\alpha_s P_o t}$$

$$S_n(t) = S_n(0) e^{-t/\tau_n}$$

τ_n = life time of the minority carrier
 $\tau_n = (\alpha_s P_o)^{-1}$

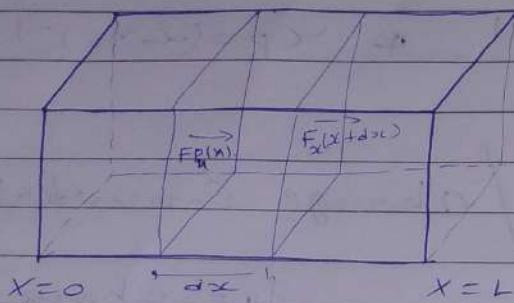
$$R'_n = - \frac{dS_n}{dt}$$

$$\begin{aligned} \frac{dS_n(t)}{dt} &= - \frac{S_n(0) \cdot e^{-t/\tau_n}}{\tau_n} \\ &= \frac{S_n(t)}{\tau_n} \end{aligned}$$

$$R'_n = R'_p = \frac{S_n(t)}{\tau_n} = \frac{S_n}{\tau_n} \quad (\text{P type})$$

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P-type



Carrier flux = No. of carrier/cm²s

$$F_{P_{x+dx}}(x) > F_{P_x}(x+dx)$$

$$\left[F_{P_x}(x) - F_{P_x}(x+dx) \right] \cdot dx \cdot dy \cdot dz = \frac{d}{dt} \Phi (dx \cdot dy \cdot dz)$$

$$\left\{ \frac{d F_{P_x}(x)}{d x} = - \frac{d P}{d t} \right\}$$

$$\nabla \cdot \vec{J} = - \frac{d (\rho v)}{d t} \quad \text{--- (1)}$$

$$\nabla \cdot \vec{F}_{P_x} = - \frac{d P}{d t} \quad \text{--- (2)}$$

$$J = \frac{I}{A} = \frac{\phi}{A \cdot t}$$

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$$\frac{dF_{Px}}{dx} = -\frac{dP}{dt} + g_P - \frac{P}{k_{Pt}}$$

Space and time.

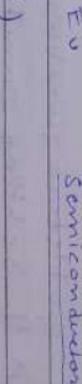
$$\frac{dP}{dt} = -\frac{\partial F_{Px}}{\partial x} + g_P - \frac{P}{k_{Pt}}$$

$$\frac{dn}{dt} = -\frac{\partial F_{nx}}{\partial x} + g_n - \frac{n}{k_{nt}}$$

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JunctionsNote work functionKey Ideas

Need to draw bending E_F
 diagrams. i.e. how does E_F change
 the energy band bend



Ans : Energy = ψ (potential)
 hence the gradient is
 indicative of electric field.

Some pointers :

- 1) Fermi levels will align.
- 2) Work functions for metal and silicon. Ability for Semicon conductor are material properties. They are not affected by device design.
- 3) Far from the junction, nothing interesting happens.
- 4) Watch for how the electrons move and how the conduction band edge will change with respect to the Fermi level to accommodate the new electron concentrations.
- 5) Solve Gauss law (poisson's Equation) to obtain the field and potential profile.

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Junctions

SC - SC

Intrinsic

Homojunction

SC - M

Schottky Junction

Heterojunction

Ohmic

Schottky Junction

* $Sc - \text{N} \times Sc \rightarrow \phi$ is a const but ϕ may be variable.

* Metal $\rightarrow \phi$ is a const.

JunctionsDensity of states, $g_1 + g_2$ $\rightarrow [m_1] m_2 \leftarrow$ Fermi functions, $f_1 + f_2$ $f_1 f_1 \quad g_2 f_2$ Free e^\ominus concn, $n_1 = f_1 g_1$
 $n_2 = f_2 g_2$ $n_1 \quad n_2$ $(1-f_1) g_1 \quad (1-f_2) g_2$

Hole concn

$$P_1 = (1-f_1) g_1 \quad f_1 = \frac{1}{1+e^{(E-E_F)/kT}}$$

$$P_2 = (1-f_2) g_2$$

at thermal Eqilibrium, the flux across the junction from L top = R top

$$n_1 P_2 = n_2 P_1$$

$$(f_1 = f_2) \rightarrow \begin{matrix} \text{fermi level} \\ \text{align} \end{matrix}$$

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Poisson's Equation

$$\frac{dE}{dx} = \frac{\rho}{\epsilon}$$

ρ = charge concentration per unit volume

ϵ = permittivity of the material

E = electric field.

Since $E = -\frac{d\phi}{dx}$ ^{potential}

$$\frac{d^2\phi}{dx^2} = -\frac{\rho}{\epsilon}$$

$$E = \int_{x_1}^{x_2} \frac{\rho(x)}{\epsilon} dx$$

↳ ~~Region~~ Region that is located at lower energy has got a higher potential, as compared to the regions located at higher energy.

If I have a Fermi level and I increase the potential of that so, let us say there is a metal and if I increase the potential of the metal, I increase the V, therefore the fermilevel will start moving downward.

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P-Si		n-Si
------	--	------

Immobro
charge. E_C

initially

 E_C E_{dm} E_{dp} E_V E_V

$\rightarrow J_{\text{diffusion}}$
 $\leftarrow J_{\text{drift}}$

At Equilibrium.

$$J_{\text{diffusion}} + J_{\text{drift}} = 0$$

$$\frac{dE_{dp}}{dx} = 0$$

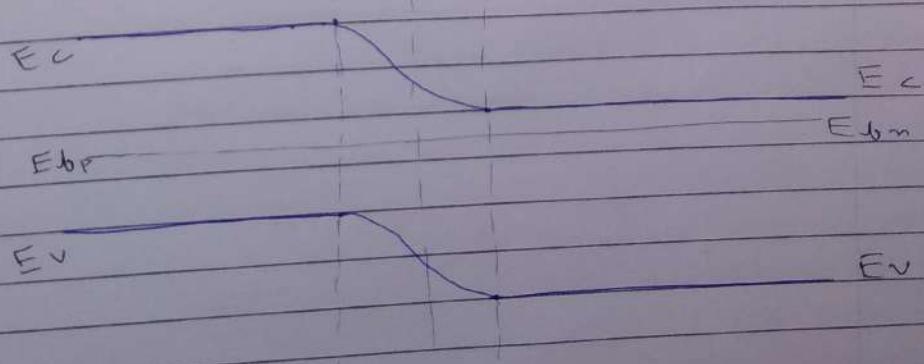
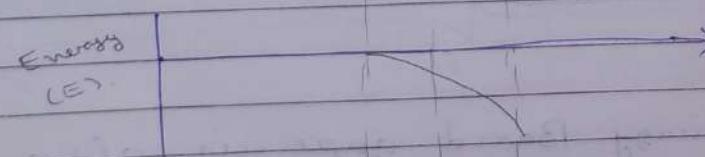
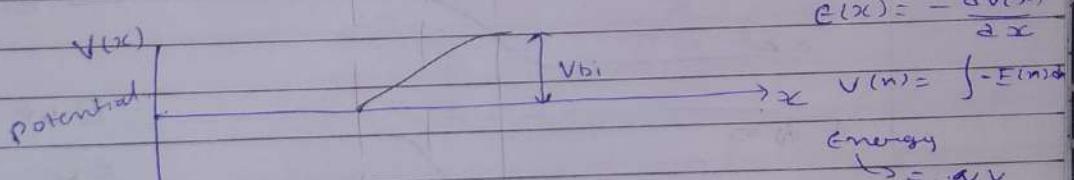
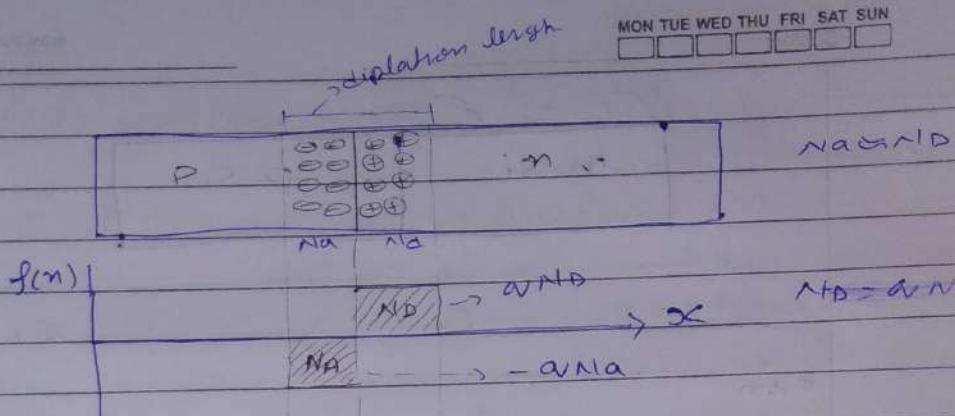
\hookrightarrow Fermi level is const

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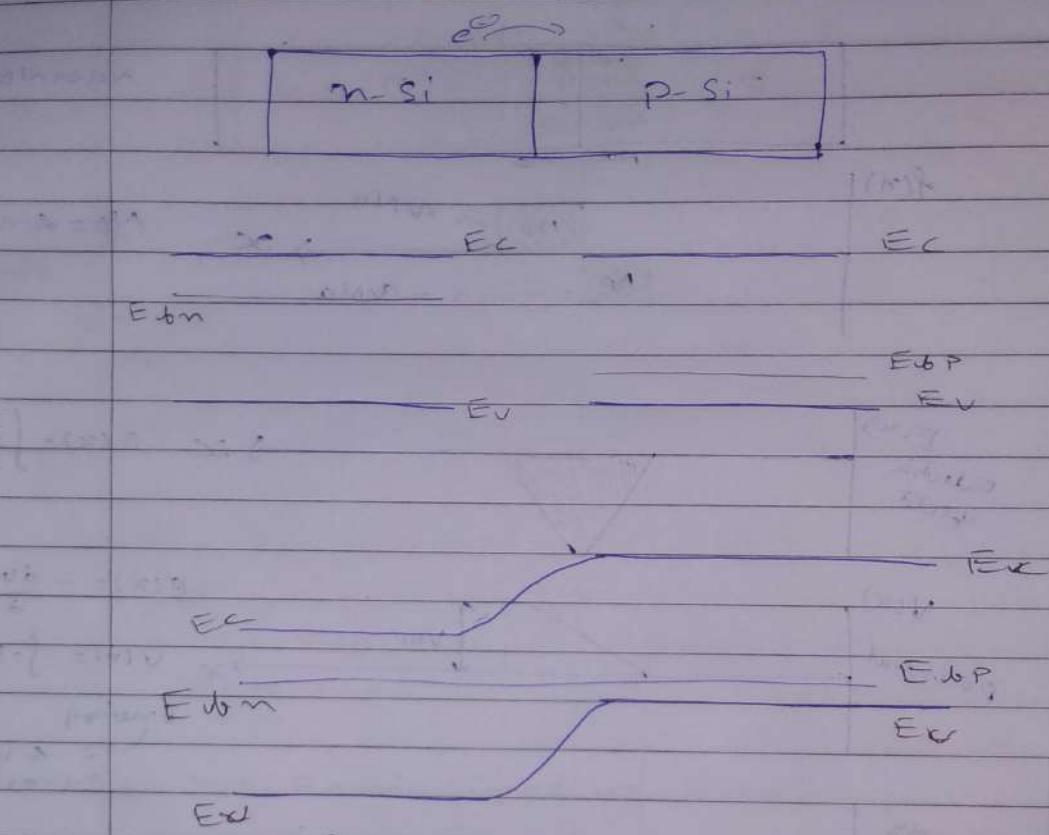


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- * (i) Energy Band gap is also constant.

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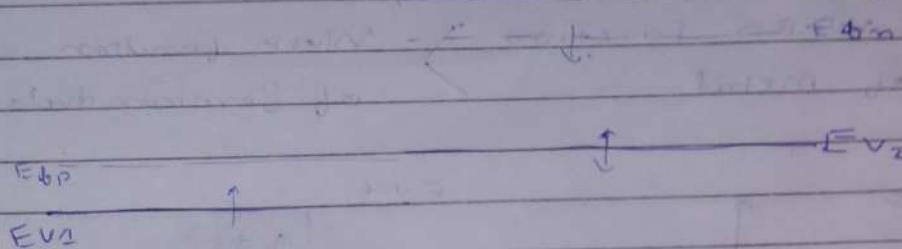
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Heterojunctions :

E_{C2} P Alnarts

Energy bands

E_{C2} E_{V2}



E_{C1}

$|E_{C2} - E_{C1}|$

E_{C2}

E_{b2}

E_{b1}

E_{V2}

E_{V1}

100mV

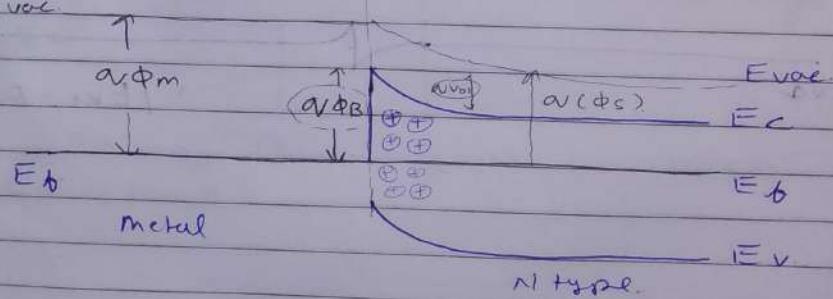
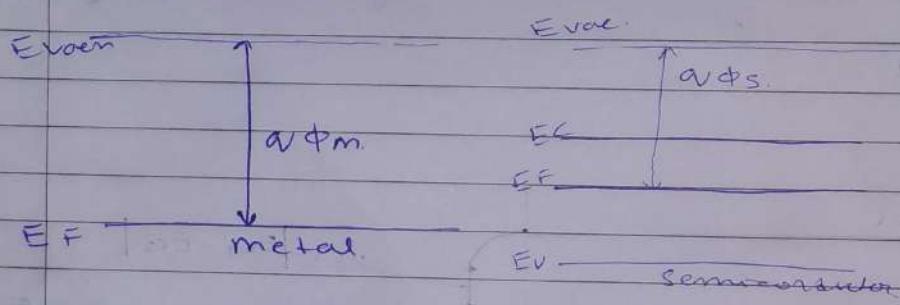
(6.3-6.3) = 0.0V

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Metal Semiconductor Junctions

- Metal - n type Semiconductor

(1) WORK Function of metal \rightarrow Work function of Semiconductor



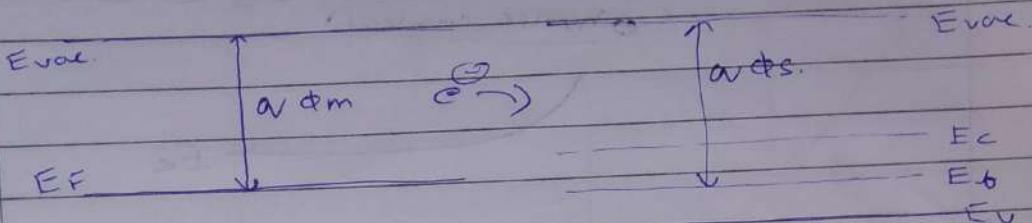
$$\alpha V_{bi} = \alpha\phi_B - (E_c - E_f)$$

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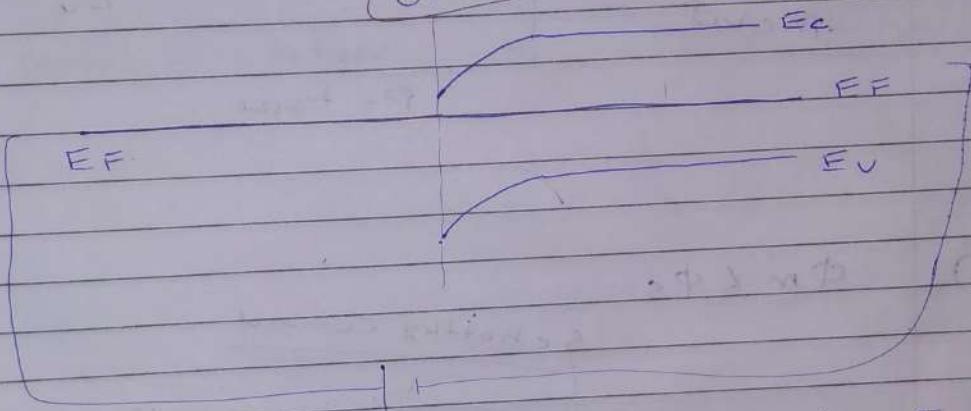
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② $\phi_m < \phi_s$



$\phi_m < \phi_s$

Ohmic contact



→ So when we connect in F.B.
then e^- is easily transfer via SC to M

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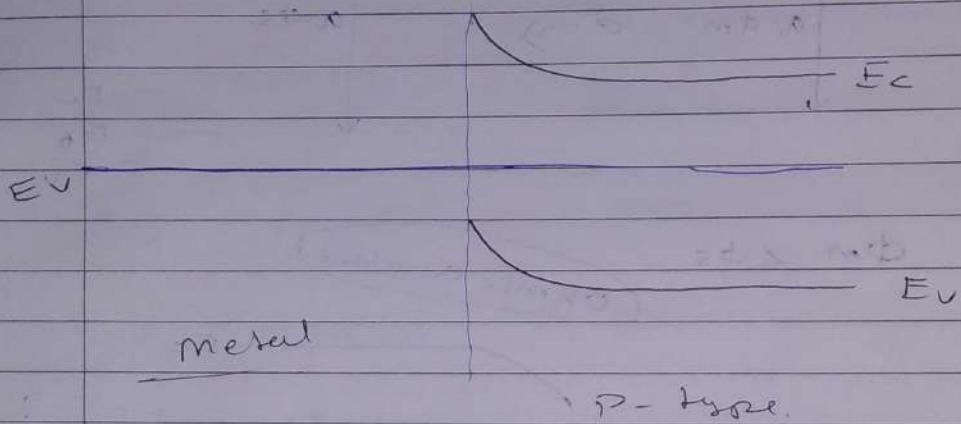
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(3)

$\phi_m > \phi_s$ \rightarrow metal - P-type

ohmic contact



(4)

$\phi_m < \phi_s$

Schottky contact

EF

metal

Ec

EF

P-type

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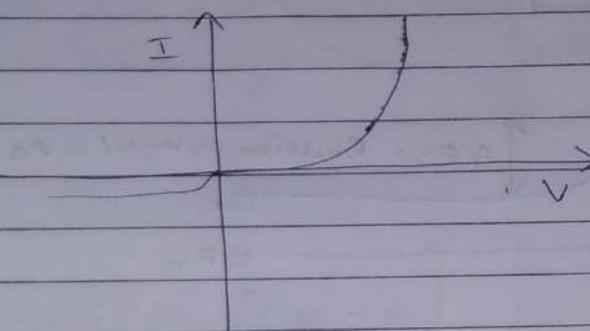
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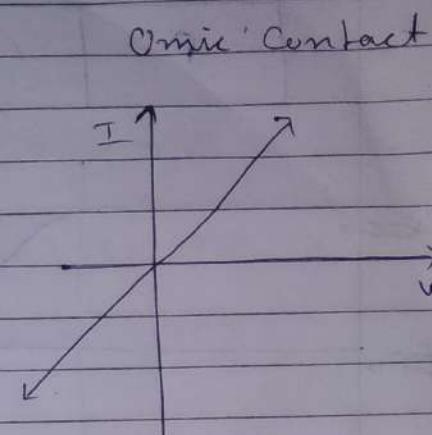
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In

Schottky Contact



metal - N^+ type



metal N^- type

Tungsten

↑ 9.8 ↑ 0.1

13 - 32

Wolfram

graphite

graphite = Wolfram

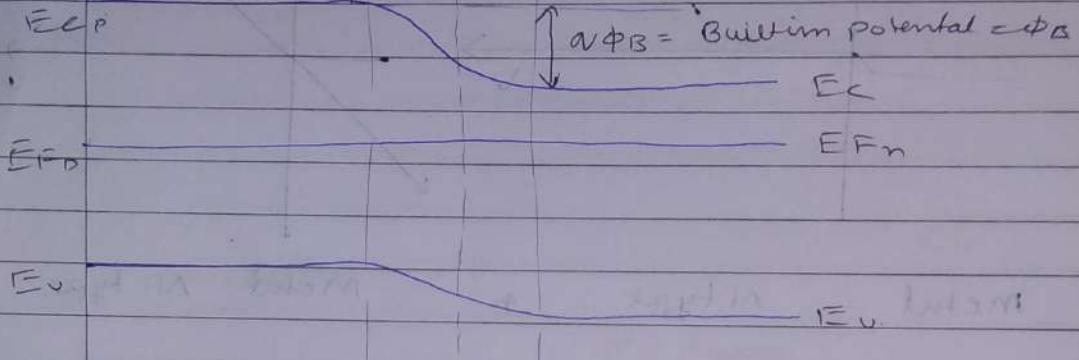
(graphite + Wolfram)

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Junction

P N

 $\Delta V_d \uparrow \quad B.P (\phi_B) \uparrow$ $\Delta N_A \uparrow \quad B.P \uparrow$ 

if $\Delta V_d > \Delta N_A$
 $\Delta C_P > \Delta C_N$

Dipole length $\propto \frac{1}{\Delta V_d}$ (constant) + $\Delta V_d < \Delta N_A$
 $\Delta C_N > \Delta C_P$

$$e\Delta V_d \times \Delta C_N \times A = e\Delta N_A \times \Delta C_P \times A$$

$$\Delta V_d \times \Delta C_N = \Delta N_A \times \Delta C_P$$

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$$\nabla E = \frac{f_v}{\epsilon}$$

$$\therefore \frac{dE}{dx} = \frac{f_v}{\epsilon}$$

$$\int dE = \left(\frac{f_v}{\epsilon} dx \right)$$

$$\left[E = \frac{f_v}{\epsilon} x + C \right]$$

P-Region

$$f_v = -eN_A$$

$$E = -\frac{eN_A}{\epsilon} x + C \quad \text{--- (1)}$$

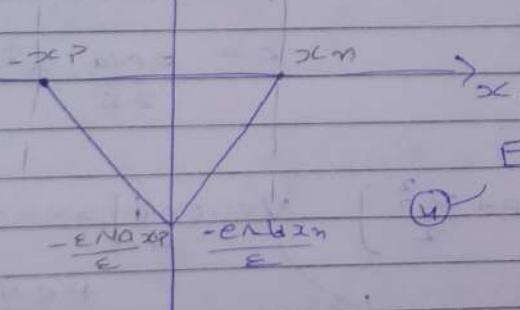
$$\text{at } x = -x_P \Rightarrow E = 0$$

$$C = -\frac{eN_A x_P}{\epsilon}$$

Now in (1)

$$E = -\frac{eN_A}{\epsilon} (x + x_P)$$

$$\text{--- (3)} \quad \hookrightarrow -x_P \leq x \leq 0$$



N-Region

$$E = -\frac{eN_A}{\epsilon} (x_n - x) \quad \text{--- (4)}$$

$$\hookrightarrow 0 \leq x \leq x_n$$

Also from Eq (3) & (4)

$$-\frac{eN_A x_P}{\epsilon} = -\frac{eN_A x_n}{\epsilon}$$

$$\left. \begin{aligned} N_A x_P &= N_A x_n \\ \end{aligned} \right\}$$

* E is max^{mm} at junction (always)

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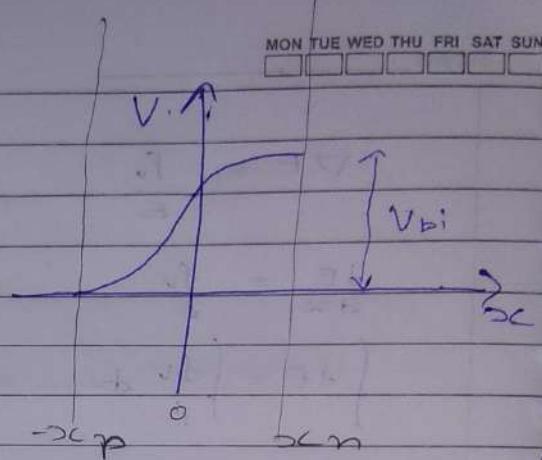
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Potential

$$E = - \frac{dV}{dx}$$

$$V = - \int E \cdot dx$$



for P-Region

$$E = - \frac{eN_{D}a}{\epsilon} (x + x_p)$$

$$V = \frac{eN_{D}a}{\epsilon} \left(\frac{x^2}{2} + x_p \cdot x \right) + C$$

$$x = -x_p, V = 0$$

$$C = \frac{eN_{D}a x_p^2}{\epsilon}$$

$$V = \frac{eN_{D}a}{\epsilon} \left[\frac{x^2}{2} + x \cdot x_p + \frac{x_p^2}{2} \right]$$

$$-x_p \leq x \leq 0$$

$$E = - \frac{eN_{A}a}{\epsilon} (x_n - x)$$

$$V = + \frac{eN_{A}a}{\epsilon} \left(x_n \cdot x - \frac{x^2}{2} \right) + C$$

$$x = x_n; V = 0$$

Both ends

$$C = \frac{eN_{A}a x_n^2}{\epsilon}$$

$$V = \frac{eN_{A}a}{\epsilon} \left[x_n x - \frac{x^2}{2} \right] + \frac{eN_{A}a x_n^2}{\epsilon}$$

$$0 \leq x \leq x_n$$

$$V_{bi} = \frac{eN_{D}a}{\epsilon} \frac{x_n^2}{2} + \frac{eN_{A}a x_n^2}{\epsilon}$$

$$* V_{bi} = \frac{e}{2\epsilon} (N_D x_n^2 + N_A x_p^2)$$

→ we know $\sigma_{cn} N_d = \sigma_{cp} N_a$

$$\text{dipolarion width. } \frac{1}{x_n} + \frac{\sigma_{cp}}{N_d} = \frac{N_d}{N_a} + \frac{1}{N_a}$$

$$\left(\sigma_{cd} \right) = \frac{N_a + N_d}{N_a N_d}$$

$$N_d \sigma_{cn} = \left(\frac{N_a N_d}{N_a + N_d} \right) \times \sigma_{cp}$$

$$\left. \begin{array}{l} \sigma_{cp} N_a = \sigma_{cn} N_d = \sigma_{cd} N_{ea} \\ \end{array} \right\} *$$

$$V_{bi} = \frac{e}{2\epsilon} \left(N_d \cdot \sigma_{cp} \frac{N_a^2}{N_a^2} + N_a \sigma_{cp}^2 \right)$$

$$V_{bi} = \frac{e}{2\epsilon} \left(\frac{N_a^2}{N_a^2} + \frac{N_a N_d}{N_a} \right) \sigma_{cp}^2$$

$$V_{bi} = \frac{e}{2\epsilon} \cdot \frac{N_a^2}{N_{ea}} \cdot \sigma_{cp}^2$$

$$\sigma_{cp} = \frac{1}{N_a} \sqrt{\frac{2\epsilon V_{bi} N_{ea}}{e}}$$

dipolarion width in P
origin.

$$\sigma_{cn} = \frac{1}{N_d} \sqrt{\frac{2\epsilon V_{bi} N_{ea}}{e}}$$

$$\sigma_{cd} = \sqrt{\frac{2\epsilon V_{bi}}{e N_{ea}}}$$

total O. length.

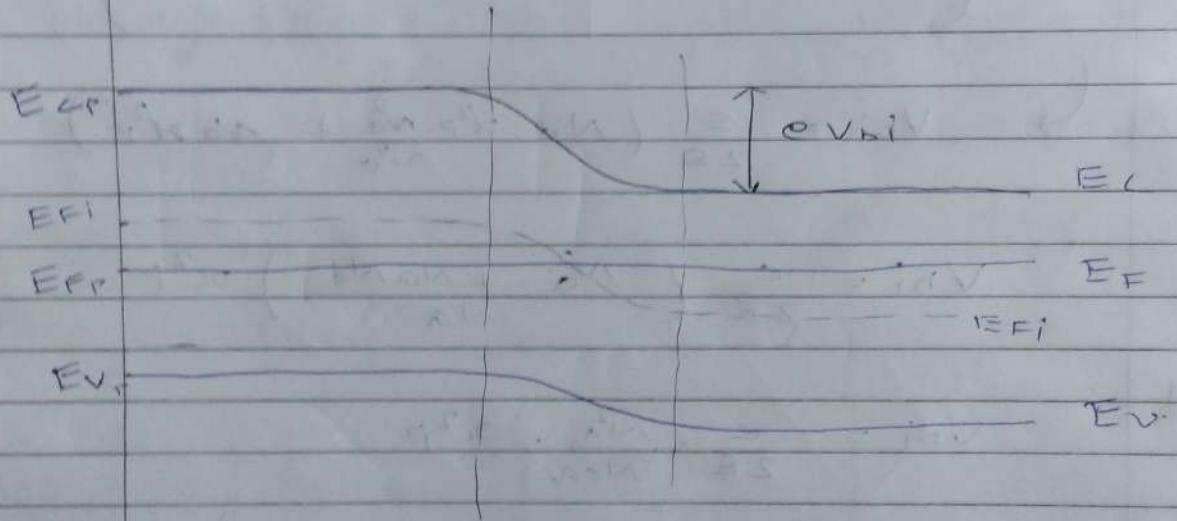
$$I_b \quad N_a >> N_d$$

$$\Delta E_n \approx \chi_d$$

$$I_b \quad N_d >> N_a$$

$$\Delta E_p \approx \chi_d$$

\hookrightarrow P-N JUNCTION



$$eV_{bi} = e\phi_1 + e\phi_2$$

$$e\phi_1 = E_{fi} - E_{fp} = kT \ln \left(\frac{P_p}{n_i} \right)$$

$$e\phi_2 = E_{fn} - E_{fi} = kT \ln \left(\frac{P_n}{n_i} \right)$$

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$$e\phi_1 + e\phi_2 = kT \ln \frac{p_p}{n_i} + kT \ln \left(\frac{n_n p_p}{n_i^2} \right)$$

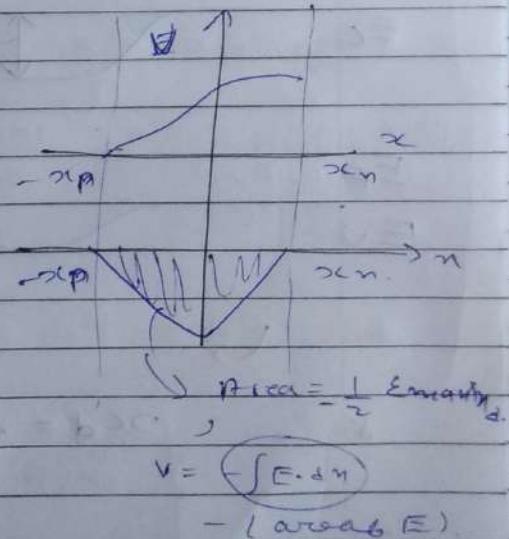
$$eV_{bi} = kT \ln \left(\frac{n_n p_p}{n_i^2} \right)$$

$$\star \left. \begin{array}{l} V_{bi} = \frac{kT}{e} \ln \left(\frac{n_i n_p}{n_i^2} \right) \end{array} \right\} \star$$

$$\left. \begin{array}{l} V_{bi} = V_T \ln \left(\frac{n_i n_d}{n_i^2} \right) \end{array} \right\} \rightarrow \text{Doping high.}$$

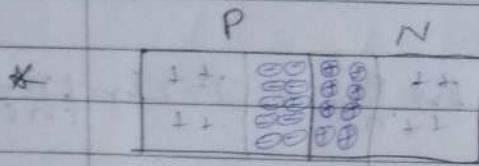
$$T \uparrow \rightarrow \left(V_{bi} \propto \frac{1}{T} \right) \quad \left. \begin{array}{l} n_i^2 \propto T^3 \\ \vdots \end{array} \right.$$

$$\left. \begin{array}{l} V_{bi} = \frac{1}{2} E_{max} \cdot \Delta d \end{array} \right\}$$



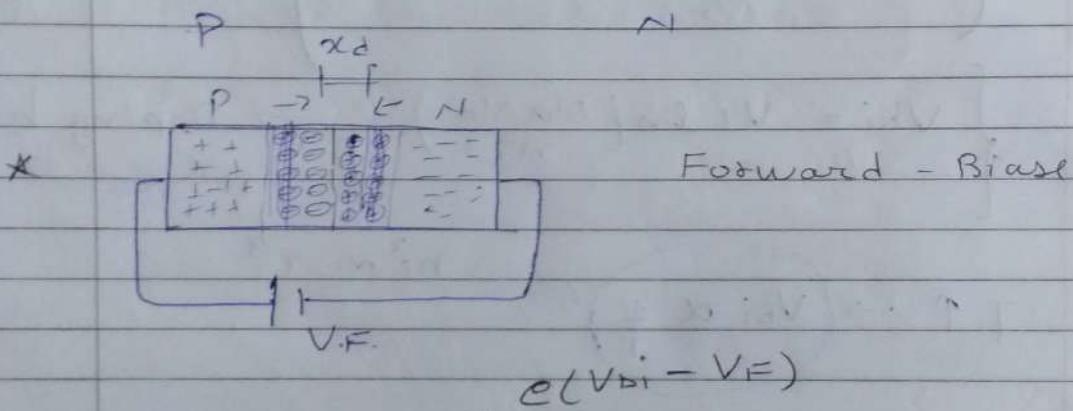
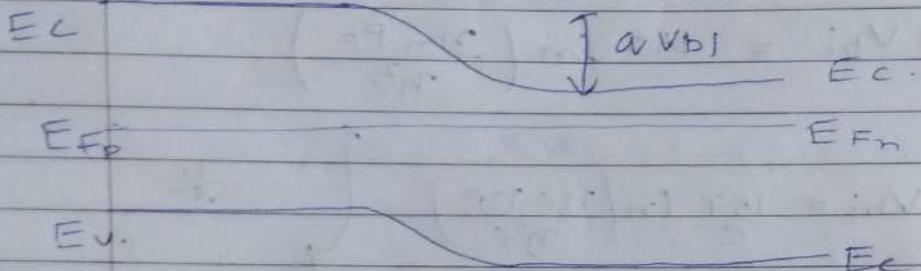
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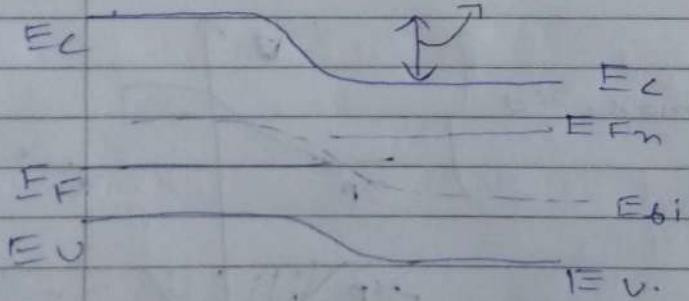
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No - Bias

$$x_d = \sqrt{\frac{2\epsilon V_{bi}}{e N_{ea}}}$$



Forward - Bias



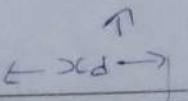
$$x_d = \sqrt{\frac{2\epsilon (V_{bi} - V_F)}{e N_{ea}}}$$

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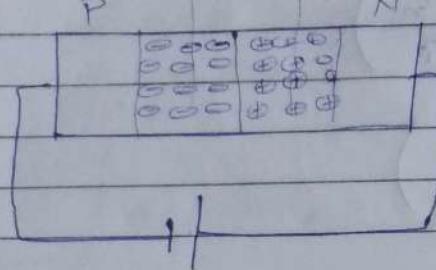
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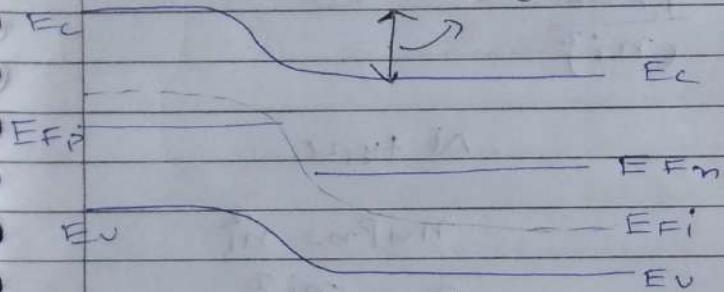


N

Reverse - Bias



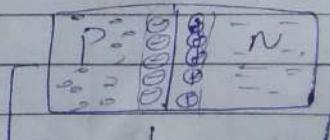
$$e(V_{bi} + V_{re})$$



$$\geq L_d = \sqrt{\frac{2e(V_{bi} + V_{re})}{\epsilon N_{ea}}}$$

Minority CARRIER AT THE edge of depletion region :

Forward Bias



n_p P_{no}

n_p P_{no}

at edge
increase

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$$V_{bi} = V_T \ln \left(\frac{P_p n_n}{n_i^2} \right)$$

$$\frac{V_{bi}}{V_T} = \ln \left(\frac{P_p n_n}{n_i^2} \right)$$

$$e^{\frac{V_{bi}}{V_T}} = \frac{P_p n_n}{(n_i)^2} \quad \text{--- (1)}$$

P-type

$$P_p n_p = n_i^2$$

$$n_p = \frac{n_i^2}{P_p}$$

() minority

N-type

$$n_n P_n = n_i^2$$

$$P_n = \frac{n_i^2}{n_n}$$

() minority

In (1)

$$- \frac{V_{bi}}{V_T}$$

$$- \frac{V_{bi}}{V_T}$$

$$n_p = n_{n0} e^{-\frac{V_{bi}}{V_T}} ; n_p = n_{d0} e^{-\frac{V_{bi}}{V_T}}$$

Minority carrier
at P-region

Majority carrier
at N-region

$$P_n = P_{p0} e^{-\frac{V_{bi}}{V_T}} ; P_n = N_{d0} e^{-\frac{V_{bi}}{V_T}}$$

$$\left. \begin{array}{l} \min = \text{Maj. } e^{-\frac{V_{bi}}{V_T}} \end{array} \right\}$$

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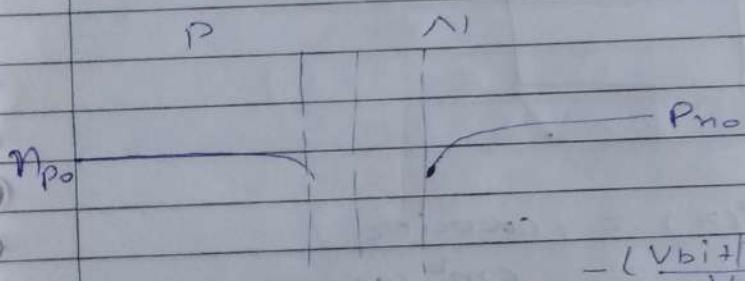
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when applied forward Biase

$$n_p(-\triangleright_P) = n_{n_0} e^{-\frac{(V_{bi} + V_F)}{V_T}}$$

$$\left. \begin{aligned} n_p(-\triangleright_P) &= n_{p_0} e^{\frac{+V_F}{V_T}} \\ p_n(+\triangleleft_N) &= p_{n_0} e^{\frac{+V_F}{V_T}} \end{aligned} \right\} *$$

In Reverse Biase :



$$n_p(-\triangleright_P) = n_{n_0} e^{-\frac{(V_{bi} + |V_R|)}{V_T}}$$

$$\left. \begin{aligned} n_p(-\triangleright_P) &= n_{p_0} e^{-\frac{|V_R|}{V_T}} \\ " &= n_{n_0} e^{-\frac{|V_R|}{V_T}} \end{aligned} \right\} *$$

$$\left. \begin{aligned} p_n(+\triangleleft_N) &= p_{n_0} e^{-\frac{|V_R|}{V_T}} \end{aligned} \right\} *$$

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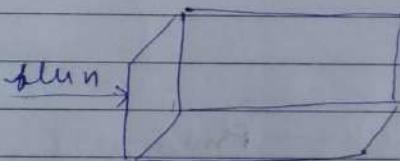
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_____In Forward Bias $\rightarrow D.C \gg$ drift current

- \hookrightarrow 1) drift current
- 2) Diffusion Current. \hookrightarrow (minority carrier conc gradient)
- 3) Recombination current

In Reverse Bias

- \hookrightarrow 1) drift Current \hookrightarrow (minority carrier conc)
- 2) Generation "

* Continuity Equation :-



$$F^-(x) = F^+(x) = \text{carrier } \frac{\text{cm}^2}{\text{sec}}$$

$$g = \text{carrier } \frac{\text{cm}^3}{\text{sec}}, R = \text{carrier } \frac{\text{cm}^3}{\text{sec}}$$

$$\frac{dP}{dt} = -\frac{dF^+(x)}{dx} + g - R$$

$$\frac{dP}{dt} = -\frac{df(n)}{dx} + g - \frac{\delta P}{t}$$

$$\frac{dn}{dt} = -\frac{dF^+(n)}{dx} + g - \frac{\delta n}{t}$$

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$$J_{\text{diff}} = -e \cdot P \cdot C \cdot D_p \frac{d(\delta P)}{dx} = \frac{K_c \pm e}{cm^2 \cdot \text{sec}}$$

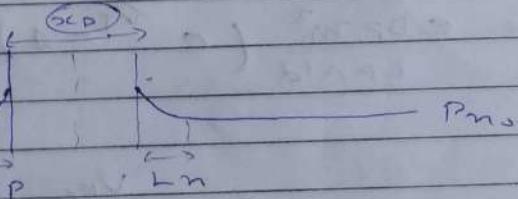
$$\frac{J_{\text{diff}}}{e} = f^+(x) ; \quad \frac{J_{\text{diff}}}{-e} = f^-(n).$$

$$\frac{d(\delta P)}{dt} = D_p \cdot \frac{d^2(\delta P)}{dx^2} + g - \frac{\delta P}{L}$$

→ steady state.
g = 0,

* $\frac{D_p \cdot d^2(\delta P)}{dx^2} - \frac{\delta P}{L} = 0$

* $D_p \frac{d^2(\delta n)}{dx^2} - \frac{\delta n}{L} = 0$



∴ $\frac{d^2(\delta P)}{dx^2} - \frac{\delta P}{(Lp)^2} = 0$

∴ $\frac{d^2(\delta n)}{dx^2} - \frac{\delta n}{(Ln)^2} = 0$

$$\delta P = A \cdot e^{-x/Lp} + B \cdot e^{-x/Lp}$$

$$\delta n = C \cdot e^{-x/Ln} + D \cdot e^{-x/Ln}$$

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$$\left\{ \begin{array}{l} SP = P_{no} \left(e^{\frac{V_F}{V_T} - 1} \right) e^{-\frac{(x_n - x)}{L_P}} \\ S_n = n_p \left(e^{\frac{V_F}{V_T} - 1} \right) e^{-\frac{(x_p + x)}{L_n}} \end{array} \right.$$

$$J_P = - e D_P \frac{dSP}{dx}$$

$$J_P = - e D_P \times \frac{d}{dx} \left[e^{\frac{x_n - x}{L_P}} \right]$$

$$J_P = e D_P \times \frac{1}{L_P} e^{\frac{x_n - x}{L_P}}$$

$$\left\{ \begin{array}{l} J_P = \frac{e D_P}{L_P} P_{no} \left(e^{\frac{V_F}{V_T} - 1} \right) \\ J_P = \frac{e D_P \cdot n_i^2}{L_P \cdot A_d} \left(e^{\frac{V_F}{V_T} - 1} \right) \end{array} \right.$$

$$\left\{ J_n = \frac{e D_n}{L_n} \cdot \frac{n_i^2}{A_d} \left(e^{\frac{V_F}{V_T} - 1} \right) \right\}$$

$$J_{total} = J_P + J_n$$

$$J = J_s \left(e^{\frac{V_F}{V_T} - 1} \right)$$

$$\left\{ I = I_s \left(e^{\frac{V_F}{V_T} - 1} \right) \right\}$$

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$$J_{sd} = \frac{e D_n n_i^2}{L_n N_A} + \frac{e D_p n_i^2}{L_p N_D}$$

* $I = I_s (e^{\frac{V_F}{2V_T}} - 1) *$ diffusion current

$$D_n \tau_n = L_n^2 ; L_n = \sqrt{D_n \tau_n}$$

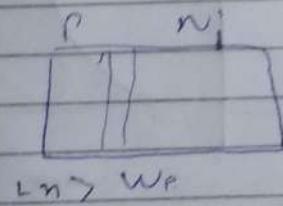
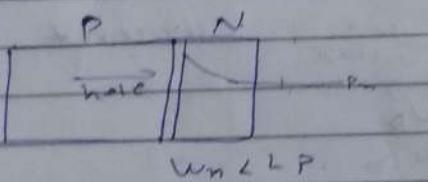
$$D_p \tau_p = L_p^2 ; L_p = \sqrt{D_p \tau_p}$$

$$I_s = e n_i^2 \left[\frac{1}{N_A} \sqrt{\frac{D_n}{\tau_n}} + \frac{1}{N_D} \sqrt{\frac{D_p}{\tau_p}} \right]$$

$$\Rightarrow \tau_n = \tau_p = \tau$$

$$I_s = \pi A \cdot e n_i^2 \cdot \left[\frac{1}{N_A} \sqrt{\frac{D_n}{\tau}} + \frac{1}{N_D} \sqrt{\frac{D_p}{\tau}} \right]$$

→ SHORT DIODE



$$\hookrightarrow L_p = W_n$$

$$\hookrightarrow L_n = W_p$$

② Recombination Current

$$J = \frac{2 n_i \tau_d}{2 \epsilon_0} \left(e^{\frac{V_F}{2V_T}} - 1 \right)$$

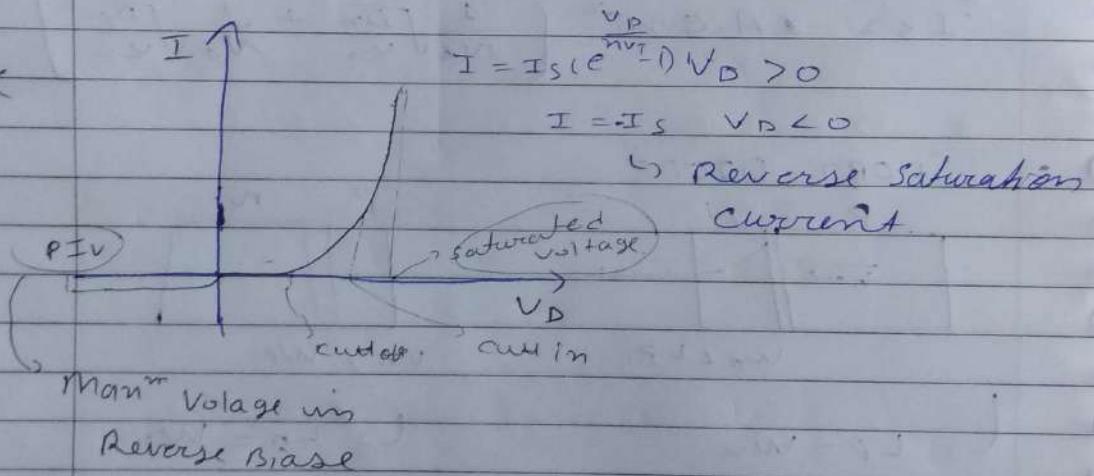
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$$J = J_s + J_d$$

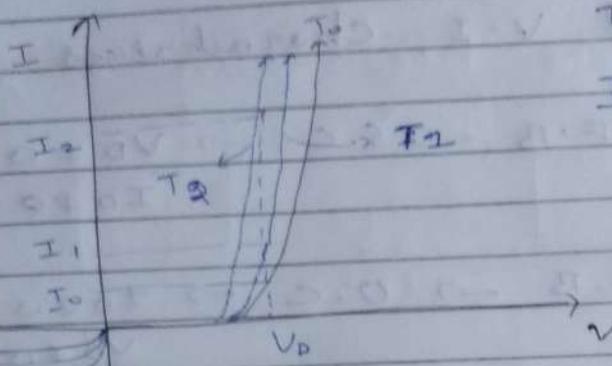
$$J = J_s \left(e^{\frac{V_D}{nV_T}} - 1 \right)$$

$$\left. \begin{aligned} I &= I_s \left(e^{\frac{V_D}{nV_T}} - 1 \right) \\ \end{aligned} \right\}$$

$$n < \rightarrow n = 1 \quad S_i \rightarrow n = 2$$



Subject _____



$$T_2 > T_1 > T_0$$

$$I_0 < I_1 < I_2$$

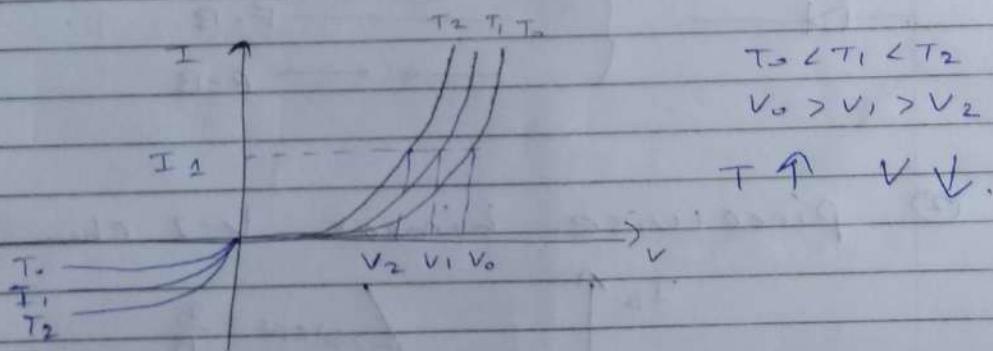
$$T \uparrow, I \uparrow$$

F.B.

Current Becomes Double for increment in temp by 5°C . ($\text{Voltage} = \text{Constt}$)

$$T + 5^{\circ}\text{C} \uparrow \rightarrow 2 \times I$$

R.B. current becomes Double for inc. in temp by 10°C .



$$T_0 < T_1 < T_2$$

$$V_0 > V_1 > V_2$$

$$T \uparrow V \downarrow$$

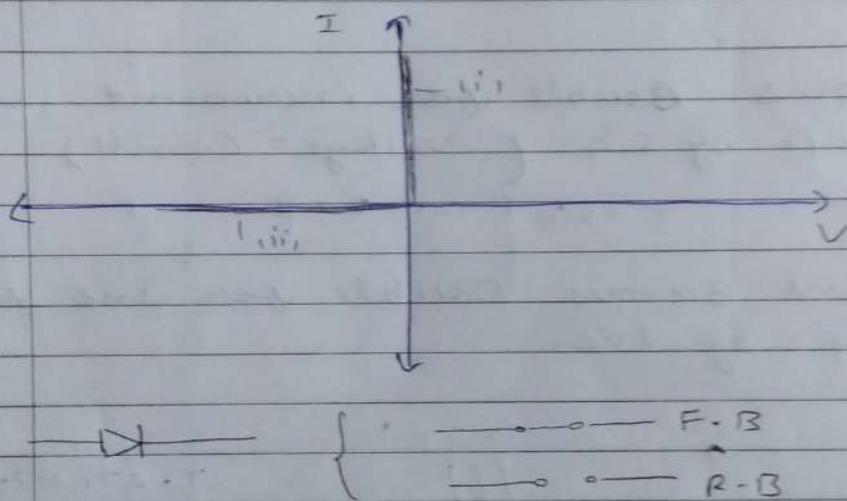
* $\rightarrow 1^{\circ}\text{C} T \uparrow$ - then $V = 2 \cdot 3 \text{ mV} \downarrow$ Si
 $(I = \text{constt})$ $V = 2 \cdot 12 \text{ mV} \downarrow$ Ge.

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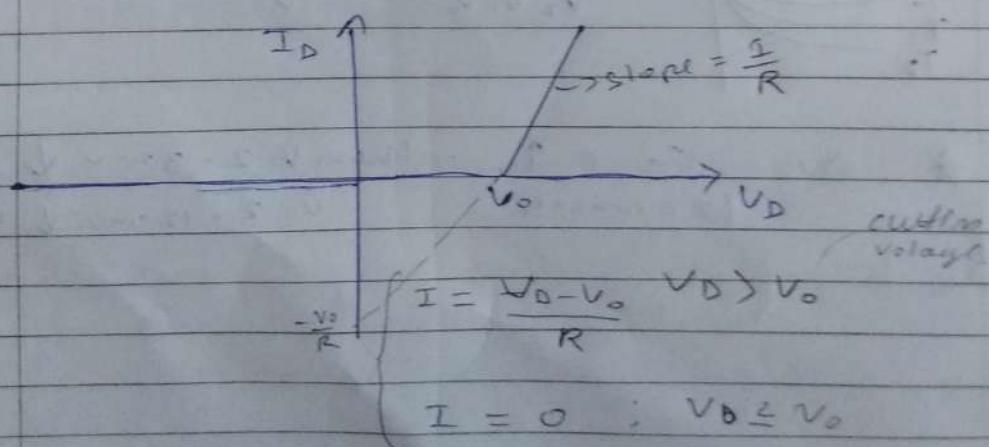
① Ideal V-I characteristics

iii) In F.B \rightarrow S.C $\rightarrow V_D = 0$
 $I_D \neq 0$

iv) In R.B \rightarrow O.C $\rightarrow I_D = 0$
 $V_D \neq 0$



② Piecewise linear V-I char

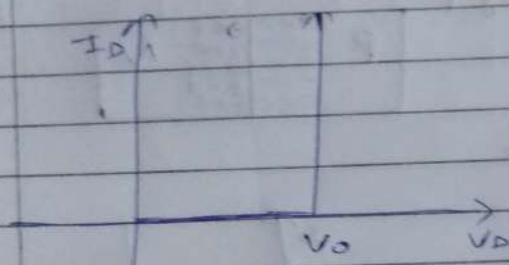


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③ Constant Battery.



I_D

V_D

↳ simple
diode

↳ constant battery.

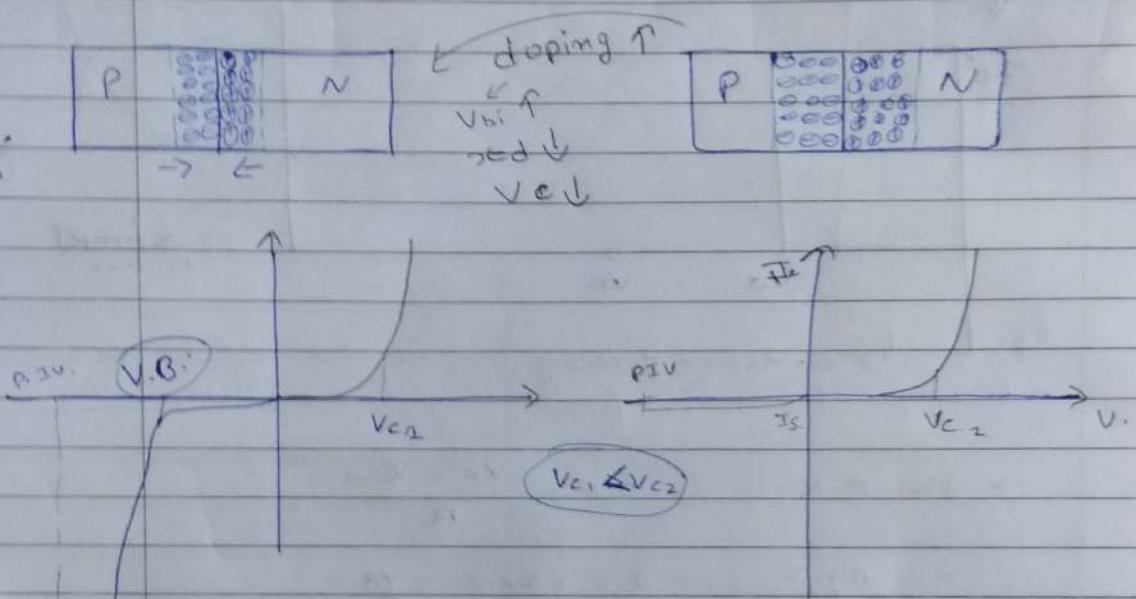
↳ In F-B

$$I_F = \frac{V_F - V_{cut}}{R}$$

$$\therefore R + B = I = +IR = -\frac{VR}{R}$$

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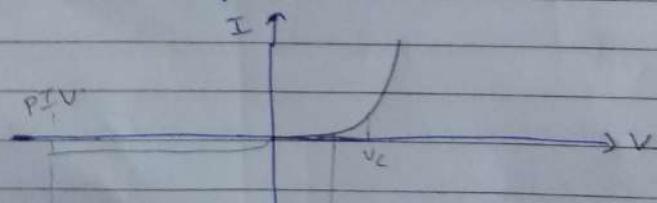
Avalanche Breakdown :



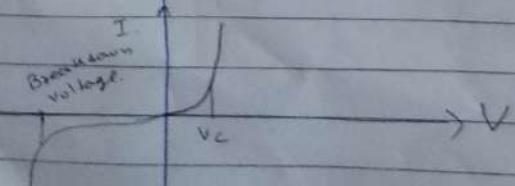
V_b battery $\rightarrow \uparrow \rightarrow$ $\text{I} = \uparrow$

when $T \uparrow \rightarrow V_c \uparrow$
 along PTV $\rightarrow V_b \uparrow$

Common Graph

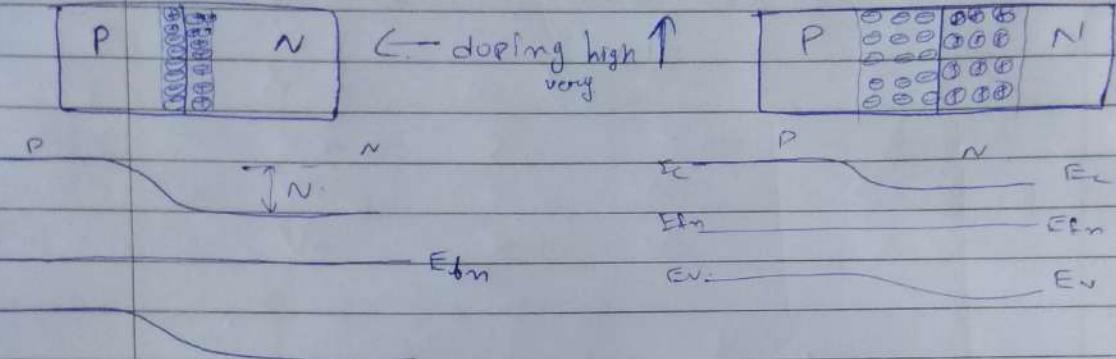


Breakdown voltage

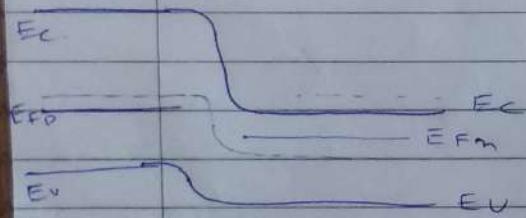


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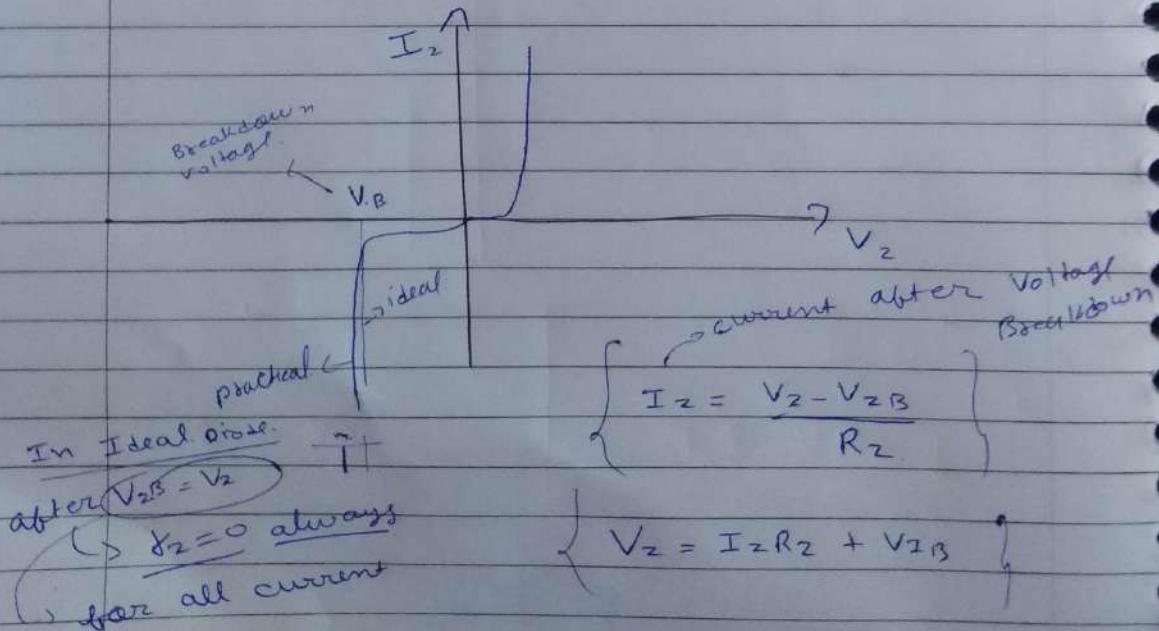
Zener Breakdown of Zener Diode :



when R.B.



V-I char for Zener Diode :-



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Normal diode

Avalanche Diode

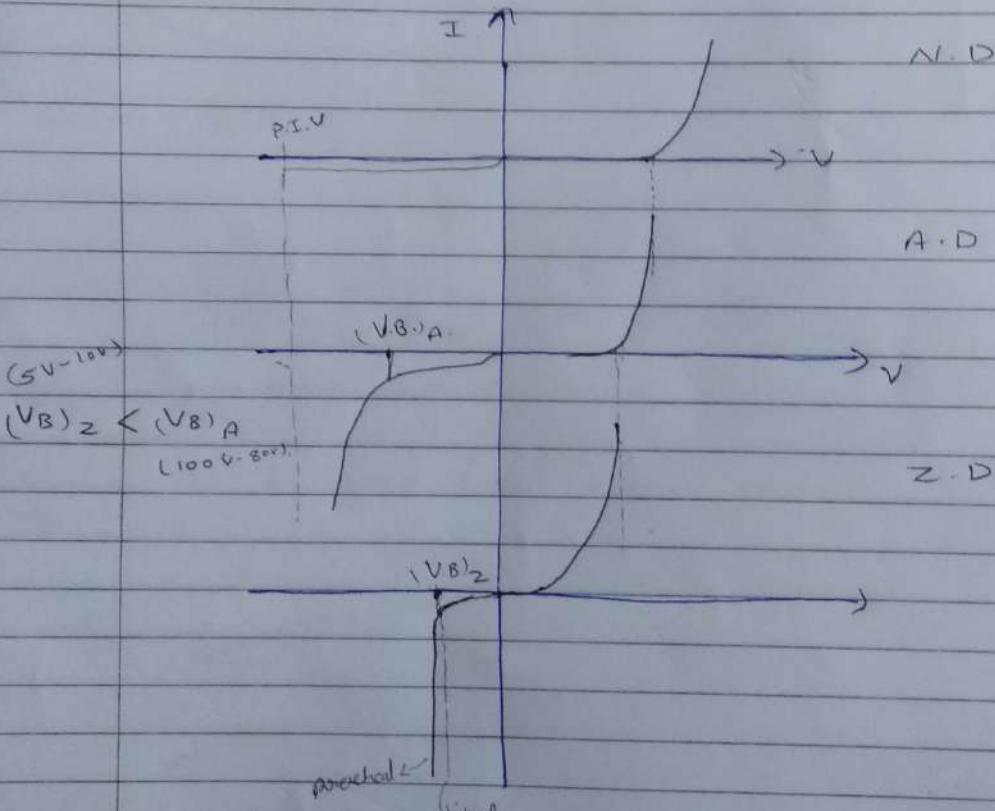
Zener diode

Doping	N_n	<	N_A	<	N_Z
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Diffusion width	x_n	>	x_A	>	x_Z
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Built-in potential	$(V_{bi})_n$	<	$(V_{bi})_A$	<	$(V_{bi})_Z$
--------------------	--------------	---	--------------	---	--------------

Cut-off voltage	$(V_c)_n$	>	$(V_c)_A$	>	$(V_c)_Z$
-----------------	-----------	---	-----------	---	-----------



Avalanche Diode

Zener diode

$$T \uparrow (V_{B.V})_A \uparrow$$

$$T \uparrow (V_{B.V})_Z \downarrow$$

Due to \square
lattice vibrations