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DATE: 31/7/19. PAGE: 1

## INTRODUCTION

### Electronic System

Electronics is the branch of engineering which deals with the study of semiconductors whereas electrical engineering deals with study of devices made of conducting materials like Cu & Al.

### Semiconductor

They are the elements having  $\text{H}^+$  in the valence band. At  $0^\circ\text{K}$  they act as insulators.

- But by doping we can control the conductivity of semiconductor materials. Thus P & N type materials are formed.

Further P-N Junctions (diode) are formed.

Diodes can have many applications such as -

Rectifiers (switch), Photodiodes, LED's, switches etc.

- When more than 2-3 layers of P-N junctions are used we fabricate Bipolar Junction Transistors (PNP & NPN).

- They can be used as amplifiers & switches.

\* (continued)

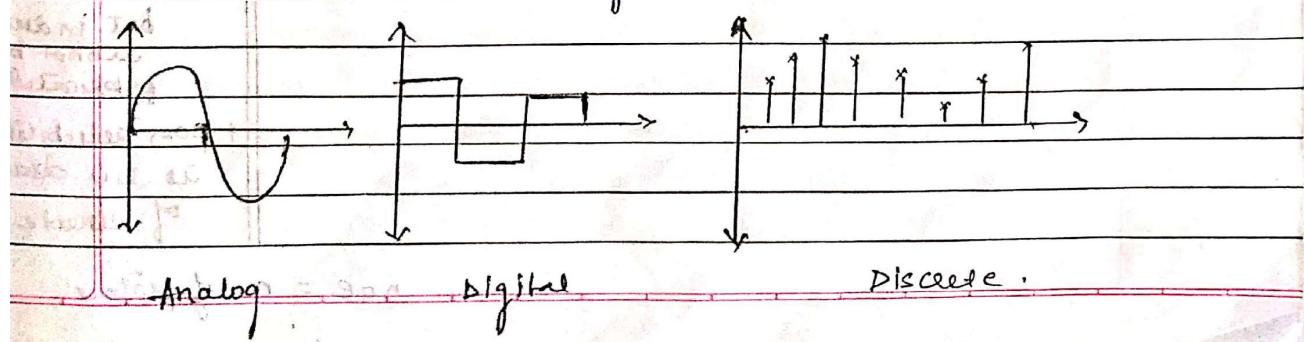
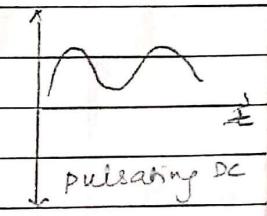
Parameters of Signals - Amp, freq & phase.

### Signals

- Analog - Varying varying signals

- Digital - amplitude remains the same

- Discrete - Discontinuous signals.



Pentagonal - N

- FET's are voltage controlled devices
  - FET's are smaller in size than BJT
  - If has better noise control efficiency
  - Amplifiers are used in active region i.e. E-B should be F.B.  
C.B. should be R.B.
  - (continued)
  - The 4<sup>th</sup> module deals with FET's which are voltage controlled devices. They have very high noise immunity compared to BJT's & less space required for fabrication compared to BJT. They also have similar applications as BJT
  - The 5<sup>th</sup> module deals with the fabrication of P-N junctions and integrated circuits
  - BJT has less noise immunity because it has lower input impedance even for small variations in I/P. There is a large variation in the o/p whereas FET has  $\text{Si}_3\text{N}_4$  layer which results in high impedance (I/P) in both ad no. BJT has high current capacity.
- \* 2 H transistors are present in 1 op-amp.
- \* Fabrication of diode, Ic, transistor, capacitor.
- but in depth cannot be fabricated.
- \* poor reliability in the draw of discrete
- noe = no. of protons
- $10.8 \text{ neutrons} = M - Z$

## MODULE 1 : SEMICONDUCTORS

Energy bands & charge carriers in semiconductors

### OBJECTIVES:

1. To study the mechanisms in which current flows in a solid.
2. How conductivity of a semiconductor can be varied.

### Orbital structure of Si atom

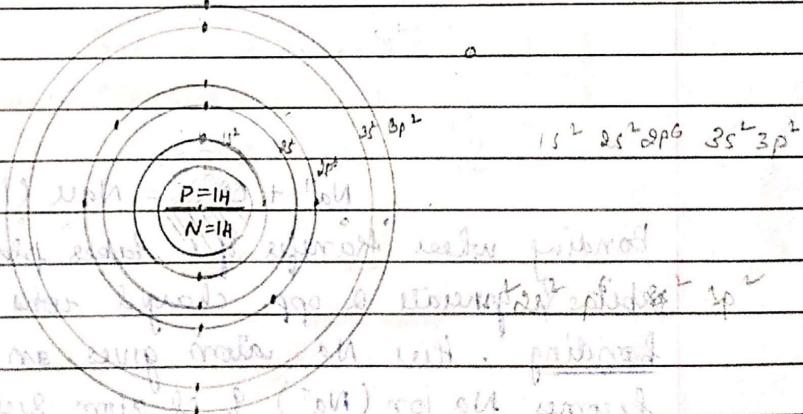
We know that atomic no. of Si is  $14$  & its atomic mass is  $28$ .

Therefore the no. of protons equals no. of electrons equals  $14$ .

The no. of neutrons = Atomic mass ( $M$ ) - Atomic no. ( $Z$ )

$$\begin{aligned} &= 28 - 14 \quad P = Z \\ &= 14 \quad N = M - Z \end{aligned}$$

The orbital structure of silicon atom can be drawn as below.



As shown in the diagram, the nucleus consists of protons & neutrons ( $14$  each). The nucleus is +vely charged (proton is +vely charged & neutrons are neutral).

The electronic configuration is  $1s^2, 2s^2, 2p^6, 3s^2, 3p^2$ .

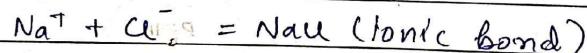
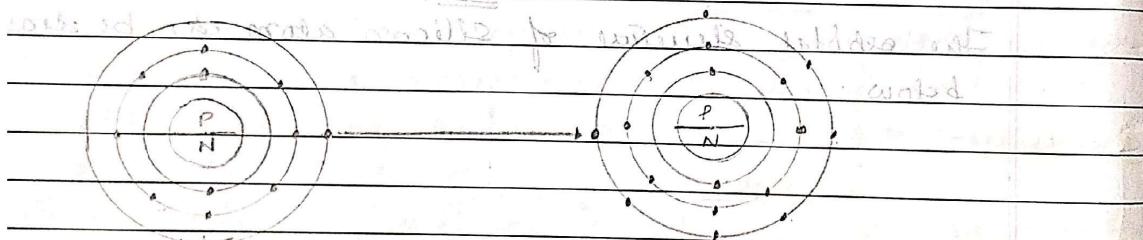
DATE: 5/8/19 PAGE: 4

## Energy levels within the system: BAND MODEL

In solid state  $e^-$  has a range or bands of energy. Electrons are restricted to a set of discrete energy levels within atoms.

Thus in solids, the wave function of  $e^-$  in outer orbit is influenced by neighbouring atoms & its overall wave function is altered which affects the potential energy  $E_g$  boundary conditions of the  $e^-$ .

Types of bonding: Consider a Na atom ( $Z=11$ ) coming closer to a Cl atom ( $Z=17$ ). The electronic configuration of Na is  $2, 8, 1$  & that of Cl is  $2, 8, 7$  & the bonding b/w the atoms can be shown as below:-



Bonding where transfer of  $e^-$  takes place in the outer most orbit & generates 2 opp. charged ions is known as ionic bonding. Here Na atom gives an  $e^-$  to the Cl atom & becomes  $Na^+$  ion, Cl atom receives an  $e^-$  & becomes  $Cl^-$  ion to form  $NaCl$  atom. Hence  $NaCl$  has ionic bonding.  $Na^+$  ions exert an electrostatic attractive force upon the neighbouring  $Cl^-$  ions which holds the crystal structure of  $NaCl$ . Thus the interactions of  $e^-$  in neighbouring atoms of a solid serves the function of holding the crystal structure of  $NaCl$ .

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NaCl latticeNaCl latticeNaCl lattice

This closed shell configuration where Na atom & Cl atom get  $8^-$  in the outermost shell is similar to that of next gas atom i.e. there is no loosely bound  $e^-$  to cause current flow in NaCl material & hence it is a good insulator.

### (ii) Metallic bonding.

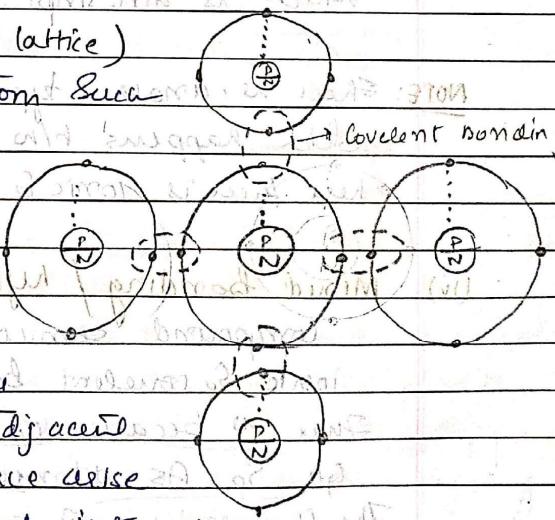
WKT in metals the outer electronic shell is partially filled usually with maximum of  $8^-$ . Consider Na atom having only  $3^-$  in the outermost shell which is loosely bound to the nucleus so the material will have high electrical conductivity. This condition can be considered as the ions with closed shell immersed in sea of free  $e^-$ . The force holding the lattice together arises from interactions b/w fully charged ion (positive) & fully charged free  $e^-$ . Thus bonding happening in metals in this way is known as metallic bonding.

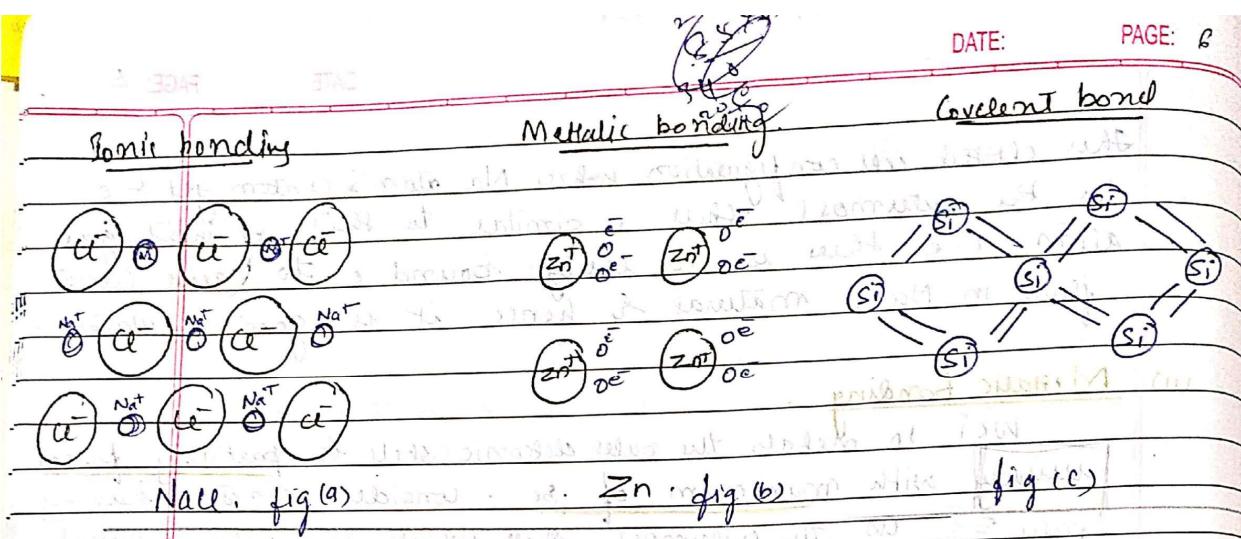
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### (iii) Covalent bonding (diamond lattice)

Consider a semiconductor atom such as  $P$ ,  $N$ ,  $C$ ,  $Si$  or  $Ge$  (diamond). It has  $4^-$  in the outermost shell which has  $4^-$  in the outermost shell by the adjacent atoms & the bonding force arise from quantum mechanical interaction b/w the shared  $e^-$ .

- The type of bonding occurring in such atoms is by mutual sharing of the  $e^-$  in the outermost shell by the adjacent atoms & the bonding force arise from quantum mechanical interaction b/w the shared  $e^-$ .
- Here both  $e^-$  belongs to the bond & thus  $e^-$ 's should





→ have opp. spin, thus each atom attains octant in the outermost shell. Thus free e<sup>-</sup> are not available in metal. So they behave like insulators.

An e<sup>-</sup> can be thermally or optically excited out of a covalent bond, thereby making it conductive.

And the method of inducing conduction is by doping, which is an imp. feature of semiconductor devices.

NOTE: There is another type of bonding known as hybrid bonding which happens b/w compound elements like GaAs.

→ here there is ionic & covalent bonding.

(iii) Mixed bonding / hybrid bonding  
Compound semiconductors such as GaAs has both ionic & covalent bond exist in the structures.

This is because of the difference in placement of Ga & As atoms in the periodic table.

The characteristics of such compounds differs from the other type. The crystal structure of diff. bonding can be shown schematically as above fig a, b, c



When isolated atoms are brought together to form a solid various interactions occur b/w the neighbouring atoms as discussed above.

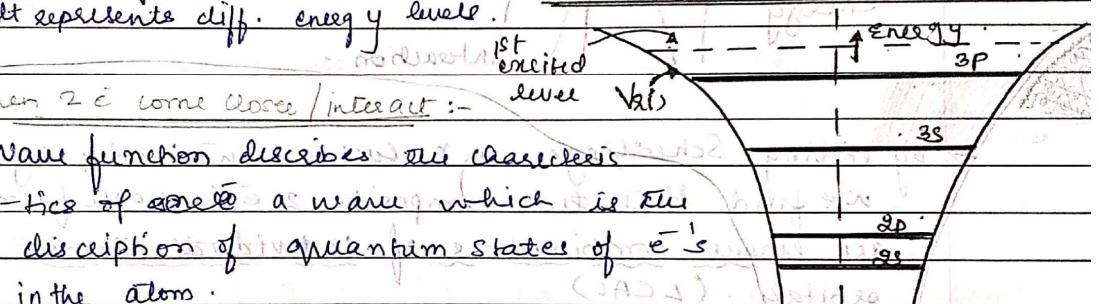
(\*) The force of attraction & repulsion b/w the atoms will find a balance at proper interatomic ~~force of attraction~~ spacing for a crystal. In this process, imp. changes occur in the energy levels which vary the electrical properties of a solid.

### Coulombic Potential Well of Nucleus of ~~separation~~

(single isolated atom)

Compressive well! (distance) ionization level → displacement

→ It represents diff. energy levels.



→ When 2 e<sup>-</sup> come close / interact :-

→ Wave function describes the characteristics

-like of atom as wave which is the description of quantum states of e<sup>-</sup>'s in the atoms.

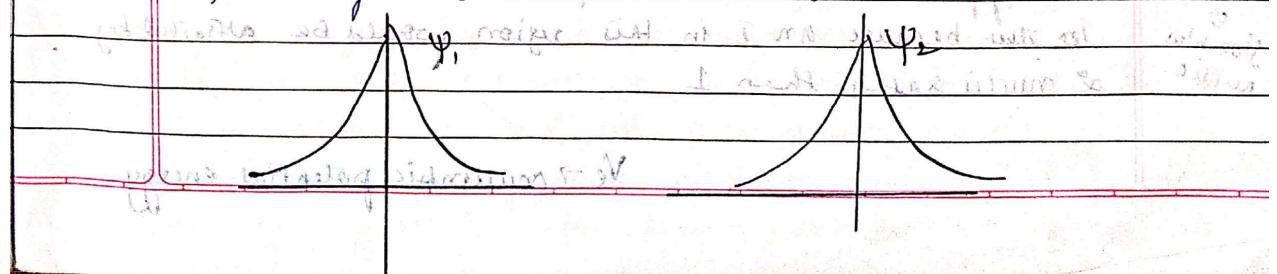
→ When 2 atoms come closer, there is in

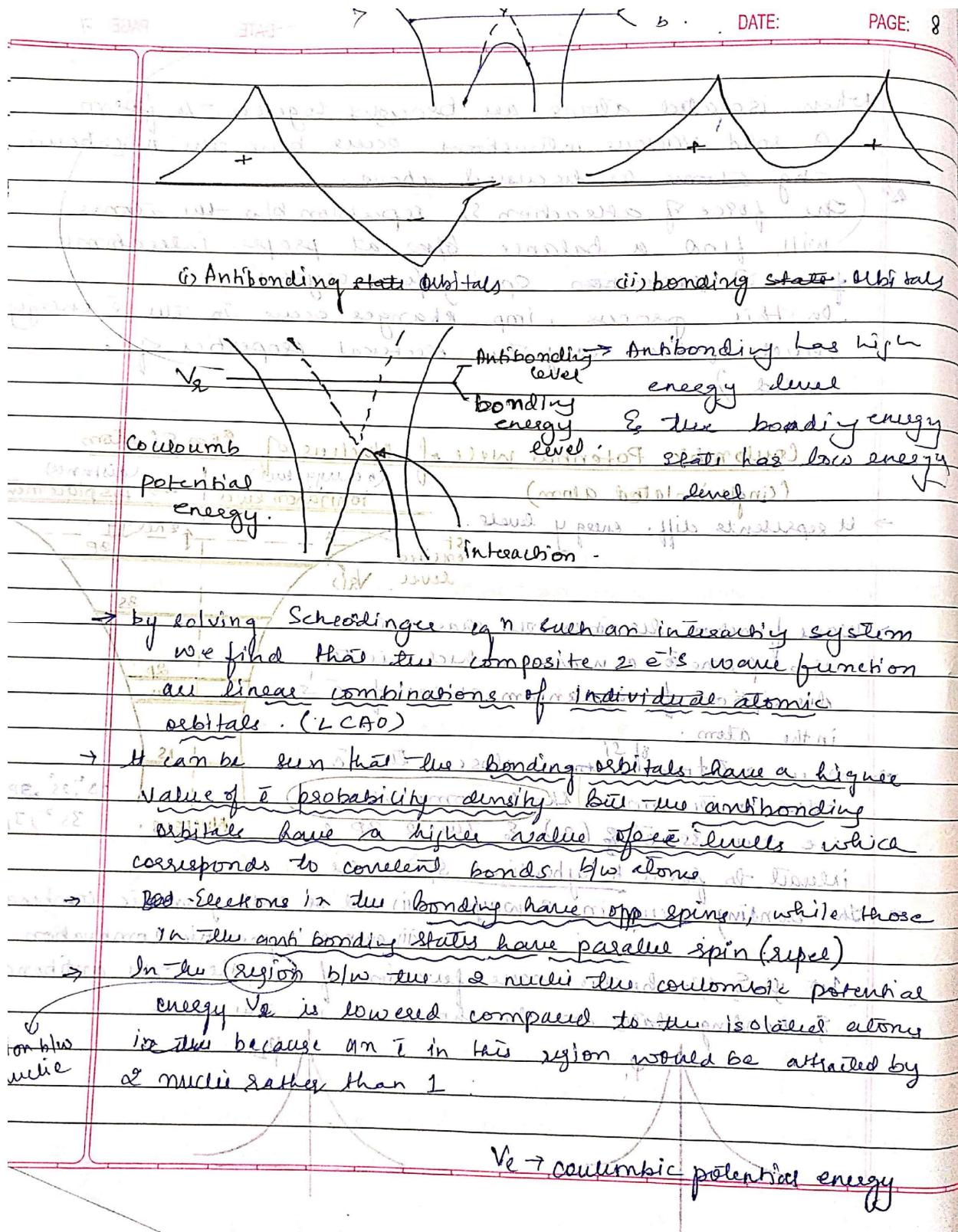
the outermost shell come closer i.e. the 3s e<sup>-</sup> (2) & the 2 p e<sup>-</sup>

interact to form hybridized sp<sup>3</sup> states.

→ The bonding occurs in 2 ways - (i) odd or Anti-symmetric combination (ungerade electrons) and (ii) even or symmetric combination.

Let  $\psi_1$  &  $\psi_2$  be the wave functions of  $2e^-$ , then the antibonding bonding states can be shown as in the sketch.





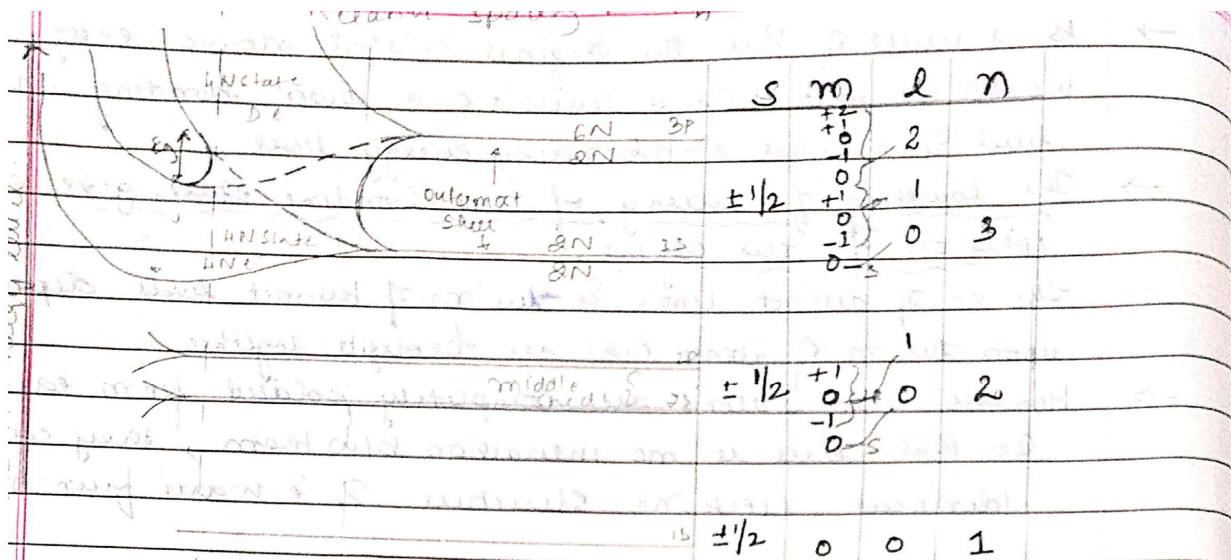
DATE \_\_\_\_\_ PAGE: 9

- As a result of this the original isolated atomic energy level would be split into 2 levels i.e. a lower bonding energy level & a higher antibonding energy level.
- The lowering of energy of the bonding state give rise to cohesion of the crystal.
- The no. of distinct levels  $E$  - the no. of distinct levels depends upon the no. of atoms that are brought together.
- However when  $n$  atoms are completely isolated from each other so that there is no interaction b/w them, they can have identical electronic structure &  $E$  wave function.

### Interaction of atoms & energy bands (Formation of Si crystal from isolated atoms)

- \* We know that each isolated atom of Si has  $1s^2 2s^2 2p^6 3s^2 3p^2$ . In its ground state, if we consider 'N' atoms there will be  $3N$ ,  $3N$ ,  $3N$ ,  $2N$  and  $6N$  states of type  $1s, 2s, 2p, 3s, 3p$  respectively (in which two many atoms interact).
- \* As the interaction spacing reduces, these energy levels split into bands beginning with the outer shell. As the  $3s, 3p$  bands grow they merge into single band composed of a mixture of energy levels.
- \* The  $3s, 3p$  bands contain  $8N$  available states. As the distance b/w atoms approaches an equilibrium interatomic spacing of silicon, this bands split into 2 bands separated by the energy gap  $E_g$ .
- \* The upper band is the conduction band containing  $4N$  states & also the lower band (valence band) containing  $4N$  states. The energy gap is called as the forbidden band because in a perfect crystal it contains no  $E$  states.
- \* At 0 K every state in the valence band will be filled w/ the conduction band will be completely empty. This arrangement of completely filled & empty  $E$  bands has an imp. effect on the electrical conductivity of the solid.

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metals, semiconductors & insulators

$n \rightarrow$  fundamental principle quantum no.

$l \rightarrow$  azimuthal quantum no.

$m \rightarrow$  magnetic quantum no.

Metals, Semiconductors & Insulators

Every solid has its own characteristic energy band structure.

This variation in band structure is responsible for the wide range of electrical characteristics observed in various materials.

We know that silicon has a diamond lattice & the band structure is explained in the previous section & it works as a good insulator at 0K.

The movement of e into new energy levels requires additional energy to overcome the forbidden gap. In the case of an applied electrical field the e's experience acceleration to move into new energy levels.

The forbidden gap Eg is smaller in Semiconductors than in Insulators.

In the case of Si atom the band gap energy is about

1.1 eV compared to 5 eV for diamond (Carbon)

The relatively smaller band gaps of semiconductors allow for excitation of  $e^-$  from the valence band to conduction band by lesser amounts of thermal or optical energy.

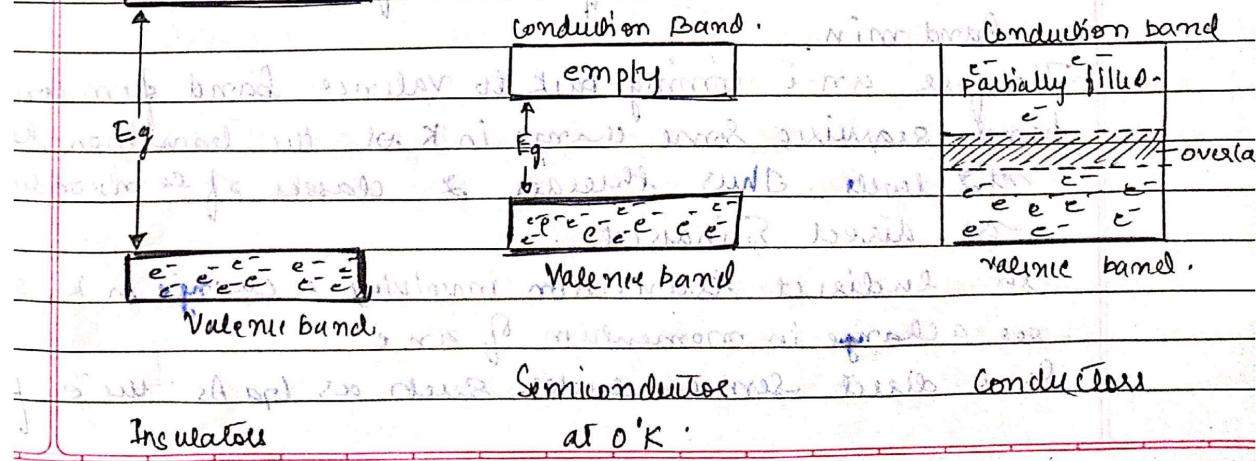
At room temp., a semiconductor with 1 eV band gap will have significant no. of  $e^-$ 's excited thermally across the energy gap into conduction band, whereas an insulator with  $E_g = 10 \text{ eV}$  will have negligible no. of excited  $e^-$ 's.

Thus an imp. diff. b/w semiconductors & insulators is that the no. of  $e^-$ 's available for conduction can be increased greatly in semiconductors by thermal or optical energy.

In metal bands either overlap or are partially filled. Thus,  $e^-$ 's are intermixed within the bands so that  $e^-$  can move freely under the influence of electric field. Thus in metallic band structures metals have high electrical conductivity.

Conduction Band: In insulation, there is no conduction band.

empty - In insulation there is no conduction band.



### Direct & indirect semiconductors

To understand the diff b/w direct & indirect Semiconductors we make use of ( $E, k$ ) diagram which is the plot of total energy ( $P.E + K.E$ ) as a function of crystal-direction-dependent wave vector which is prop. to the momentum of an  $e^-$ , i.e., in turn the velocity of the  $e^-$  at some point in space.

A single  $e^-$  is assumed to travel through a perfectly periodic lattice & the wave func. of the  $e^-$  is assumed to be in the form of a plane wave moving in the  $x$ -direction with propagation const.  $k$ .  $E_F$  is given by

$$\Psi(k) = U(k_x, x) e^{i(k_x x)}$$

where  $U(k_x, x)$  modulates the wave func.

Due to the periodicity of the lattice.

Using the above eqn, the values of energy can be plotted as a function of propagation constant  $k$ .

The band structure of GaAs has a min in conduction band & a max. in valence band for the same  $k$  value as shown in the sketch. Whereas silicon has its valence band max. at a diff. value of  $k$  than its conduction band min.

Therefore an  $e^-$  coming back to valence band from conduction band requires some change in  $k$  or the transition happens at 2 levels. Thus there are 2 classes of semiconductors as direct & indirect.

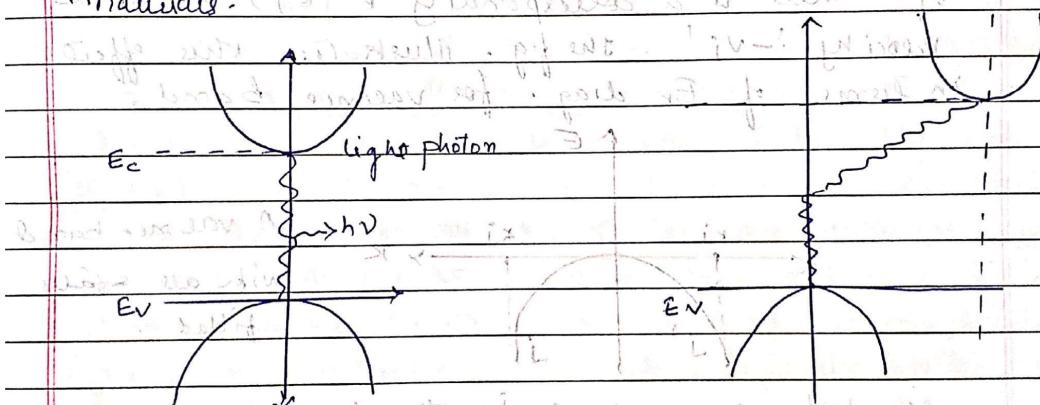
In indirect transition involving a change in  $k$ , requires a change in momentum of an  $e^-$ .

Direct semiconductor such as GaAs -  $e^-$  from

$$P = mv$$

DATE: PAGE: 13

conduction band can fall to an empty state in valence band by giving off the energy diff.  $E_g$  as a photon of light but am  $\epsilon$  in the conduction band min. of an indirect semiconductor (Si) cannot fall directly to the valence band as it has to undergo a momentum change to change its energy level. In this case part of energy is released as heat to the lattice. This diff. in semiconductors can be used in the app. of LED's & LASER's & should be made up of direct Semiconductor materials.



(GaAs) direct  $\rightarrow$  Indirect  $\rightarrow$  (Si)

As the temp. of Semiconductor (is) rises from 0K some  $e^-$ 's in the filled valence band receive enough thermal energy to be excited across the band gap to the empty conduction band as they depicted in the diagram.

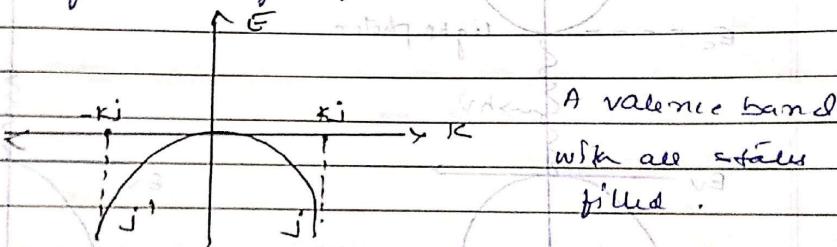
$\text{e}^-, \text{e}^-, \text{e}^-, \text{e}^-, \text{e}^-$  in empty states in valence band  
E.g.  $\text{! ! ! ! !}$  is represented as holes.

If the conduction band is full, holes are created by initiation of a valence band to the conduction band. Then they are known as e-hole pairs [EHP].

In a filled band all available states are occupied. For every  $e^-$  moving with a given velocity there is an equal  $e^+$  opp.  $e^+$  moving with else where in the band, if electric field is applied, the net current is zero unless one is removed.

Because for every  $e^-$  ( $v_j$ ) moving with a velocity ' $v_j$ ' there is a corresponding  $e^+$  ( $v_j'$ ) with the velocity ' $-v_j$ '. See fig. illustrating this effect.

In terms of E-k diag. for valence band.



With ' $N$ ' electrons/ $\text{cm}^3$  in the band the current density ' $j$ ' is expressed using a sum of overall  $e^-$  velocities including the charge of each  $e^- (-q)$  in a unit volume it is expressed as -

$$j = (-q) \sum_i v_i \rightarrow (1)$$

Now, when a hole is created by removing the  $j$  in the net current density in the valence band involves the sum of overall velocities minus the contribution of  $e^-$  which is removed can be written as -

$$j' = (-q) \sum_i v_i - (-q) v_j \rightarrow (2)$$

$$j' = 0 + q v_j$$

$$\boxed{j' = \pm q v_j}$$

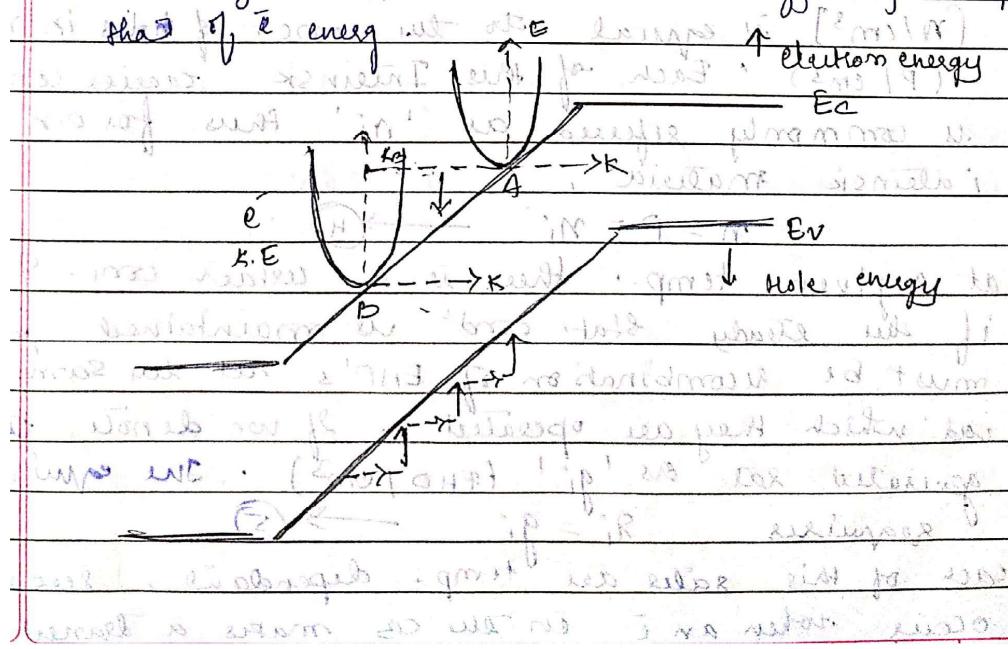
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i.e. the current contribution of the hole is equivalent to the charged particle with velocity  $v_j$ , that of the missing  $e^-$ .

In VB, the hole energy inc. oppositely to the  $e^-$  energy because the carriers have opp. charges. Thus hole energy inc. downwards as shown in fig. So holes seeking low lower energy state are available at the top of the V.B. C.B.  $e^-$  are found at the bottom of C.B.

The bottom of the CB corresponds to zero velocity ( $v=0$ ) & has potential energy as that of the point in space. For hole, the top of VB corresponds to zero K.E.

In the fig. an  $e^-$  at location A (seen) in electric field given by the slopes of the band edges (P.E.) & gains K.E. by moving to the point B (seen) in E.K. diag. If the  $e^-$  starts at  $k=0$  but moves to a non-zero wave vector  $\vec{k}$  in K.B. Then it then loses K.E. to heat by scattering mechanism by falling to the bottom of the band at B. In the  $e^-$  may lose the K.E. in stages by a series of scattering events as shown by the dotted lines. Hole energy is just opp. to that of  $e^-$  energy w.r.t. the Fermi level.



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## Intrinsic Semiconductors

A perfect semiconductor system with no impurities or lattice defects is called as intrinsic semiconductor. In such materials there are no charge carriers at 0K. Since the VB is completely filled with e<sup>-</sup>, CB is empty. At high temp., EHP's are generated in VB as are excited thermally across the band gap to the CB as shown in the fig. These e<sup>-</sup> hole pairs are the only carriers in the intrinsic material. In the fig if one of the Si valence e<sup>-</sup> is broken away from its bonding structure such that it becomes a free e<sup>-</sup> in the lattice.  $\rightarrow$  conduction e<sup>-</sup> is added & a broken bond is left behind (h<sup>+</sup>). The energy required to break the bond is the band gap energy (Eg). Since the e<sup>-</sup> & h<sup>+</sup> are created in pairs, the CB e<sup>-</sup> conc. ( $n/cm^3$ ) is equal to the conc. of holes in VB ( $P/cm^3$ ). Each of this Intrinsic carrier conc. is commonly referred as 'n<sub>i</sub>' thus for an intrinsic material,

$$n = P = n_i \rightarrow (4)$$

at a given temp. there is a certain conc. of EHP's ( $n_i$ ). If the steady state cond<sup>n</sup> is maintained, there must be recombination of EHP's at the same rate at which they are generated. If we denote the generated rate as ' $g_i$ ' ( $EHP/cm^3$ ). The equilibrium requires  $g_i = g_i \rightarrow (5)$

each of these rates are temp. dependant, recombination occurs when an e<sup>-</sup> in the CB makes a transition

DATE:

PAGE: 17

(Direct or Indirect) to an empty state (hole) in the valence band is at any temp. The rate of recombination is prop. to the equilibrium conc. of the sp. holes.

$$g_i = \alpha n_i p_0 = g_i^* \rightarrow (6)$$

$$g_i^* = \alpha n_i^2 \text{ when } k_B T \gg E_g$$

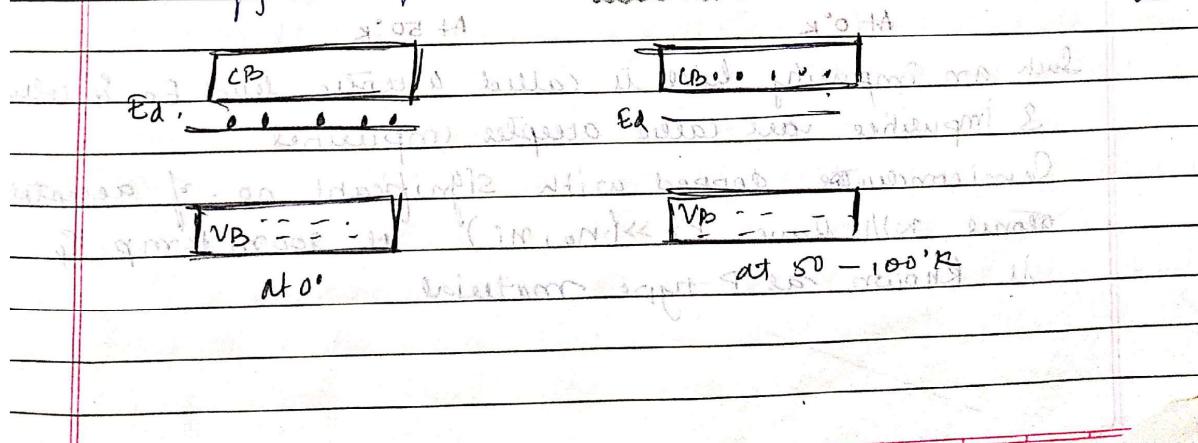
where  $\alpha$  is the prop. const which depends on the mechanism by which recombination takes place.

### Extrinsic Semiconductor

Doping is the process of purposefully introducing impurities into the crystal to create excesses to vary the conductivity of semiconductors. There are two types of materials such as n-type & p-type can be formed by introducing trivalent or pentavalent impurities to silicon crystal.

When a crystal is doped such that the equilibrium carrier conc.  $n_i$  &  $p_0$  are diff. from the intrinsic carrier conc.  $n_i^*$ . The material is called Extrinsic.

→ When impurities (or) lattice defects are introduced into a perfect crystal, additional energy levels are created in the energy band structure. For eg: Impurity from group V (As, Sb) introduces an energy level  $E_d$  very near to the CB in Ge or Si. This level is filled with  $e^-$  at  $0^\circ K$  & very little thermal energy is required to excite  $e^-$  to VB as shown in fig



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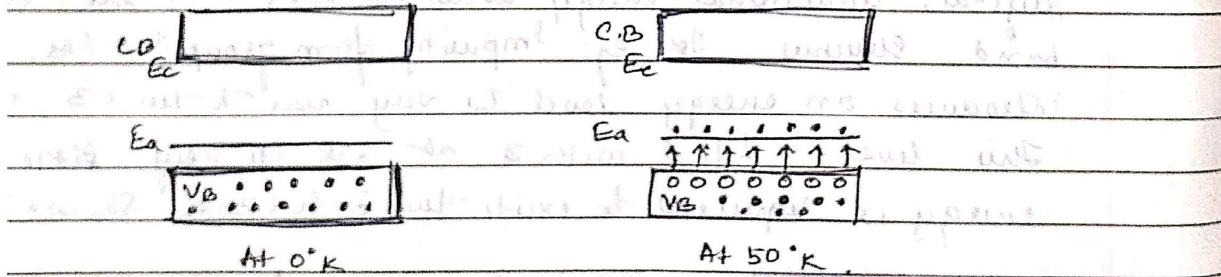
Thus along  $50-100^{\circ}\text{K}$ , virtually all the  $\text{e}^-$  in the impurity level are donated to the CB such an impurity level is called donor level ( $E_d$ ) Eg group -5 impurity are called donor impurities.

Semiconductors doped with significant no. of donor atoms will have,  $n \gg (P_n, n_i)$  at room temp & this material is known as n-type material. (Earlier approximately 0.01 eV below the conduction band.)

When atoms from 3rd group (B, Al, Ga, In) introduce impurity level in Germanium or Si near the valence band, these levels are empty of  $\text{e}^-$ 's at  $0^{\circ}\text{K}$  & represent as  $E_a$ . (at  $0^{\circ}\text{K}$  there is no electron in the  $E_a$  level)

$E_a$  is 0.01 eV above the valence band.

At low temp. enough thermal energy is available to excite  $\text{e}^-$ 's from valence band into the  $E_a$  level (impurity level) leaving behind holes in the Valence Band as shown in the fig.



Such an impurity level is called acceptor level  $E_a$  & column 3 impurities are called acceptor impurities.

Semiconductor doped with significant no. of acceptor atoms will have  $P_o \gg (n_o, n_i)$  at room temp & is known as P-type material.

DATE:

PAGE: 19

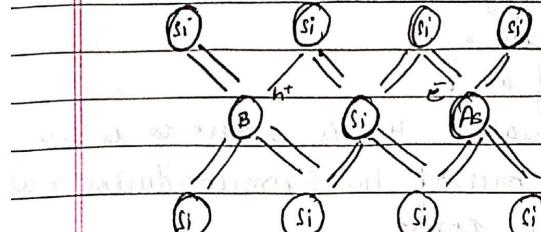


fig 3: donor & acceptor atoms in covalent

Amphoteric bonding model of Si system (crystal)

fig 3 shows donor & acceptor atoms in the covalent bonding model of Si crystal. As Atom (5<sup>th</sup> group) in the Si lattice has 4 necessary valence e<sup>-</sup>'s to complete the covalent bonds with neighbouring Si atoms plus 1 extra e<sup>-</sup> which doesn't fit into the bonding structure. Therefore it is closely bound to As atom. If thermal energy is sufficient to make this atom free, it participates in carrier conduction.

Similarly boron atom (group 3) in the silicon lattice has 3 valence e<sup>-</sup> which forms the covalent bond with neighbouring Si atoms thereby leaving one bond incomplete, with small amt of thermal energy this incomplete bond can be transferred to other atom as the bonding e<sup>-</sup>'s exchange position.

Amphoteric Si or Ge can serve as donor or acceptor atoms depending on whether they combine with group 3 or group 5 atoms in the crystal. In that case they are known as amphoteric materials. Thus doping controls the electrical properties of the semiconductor.

Example: When Si is doped with  $10^{15}$  As atoms/cm<sup>3</sup> the resistivity of Si changes from above 2x10<sup>10</sup> cm to 5 ohm cm.

using Bohr model results the appon. energy required to excite the 5<sup>th</sup> e<sup>-</sup> of Arsenic atom can be calculated. The mag. of the ground state energy (n=1) for such an e<sup>-</sup> is

$$E = \frac{m e^4}{8 \pi^2 \hbar^2} \quad \text{when } n=1$$

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Where  $E$  is the total energy of the  $e^-$ .

$m_e$  is the mass of the  $e^-$ .

$q$  is the charge of an  $e^-$ .

$K$  is the const. equal to  $4\pi\epsilon_0\epsilon_r$  where  $\epsilon_r$  is the relative dielectric const. of the Semiconductor material.

$\hbar$  is the Planck's const.

$k$  is the angular momentum =  $\frac{h}{2\pi}$

Drift Sp. resistance  $\propto \text{carrier mobility} \times \text{field}$

In papers  $\propto \text{carrier mobility} \times \text{field}^2$

so  $\propto \text{carrier mobility} \times \text{field}^2$

so  $\propto \text{carrier mobility} \times \text{field}^2$

Effects of temp. & mobility doping on mobility

Two type of scattering mechanisms in respect of  $\mu$  vs  $T$

that influence  $e^-$  hole mobility

are lattice scattering & impurity scattering

Lattice scattering  $\propto$  carrier velocity  $\propto T^{3/2}$  for  $T < T_c$

$\propto T^{-3/2}$  for  $T > T_c$

Impurity scattering  $\propto T^{-1/2}$

lattice scattering from temp.  $\propto \log T$

lattice scattering inc. as temp increases  $\propto \text{temperature} \rightarrow$

mobility of carriers & drift resistance in  $\log$

under this condition  $\propto \frac{1}{T} \propto \frac{1}{T} + \frac{C}{T^2}$

at low temp. scattering from impurities  $\propto T^{-1/2}$ ,  $M_1 \propto M_2$

Crystal defects such as ionised atoms increase  $\propto T$

Impurities (i.e. doping) becomes dominant

We know that a slowly moving carrier is scattered

more than a carrier with greater speed. Thus, impurity

DATE

PAGE: 21

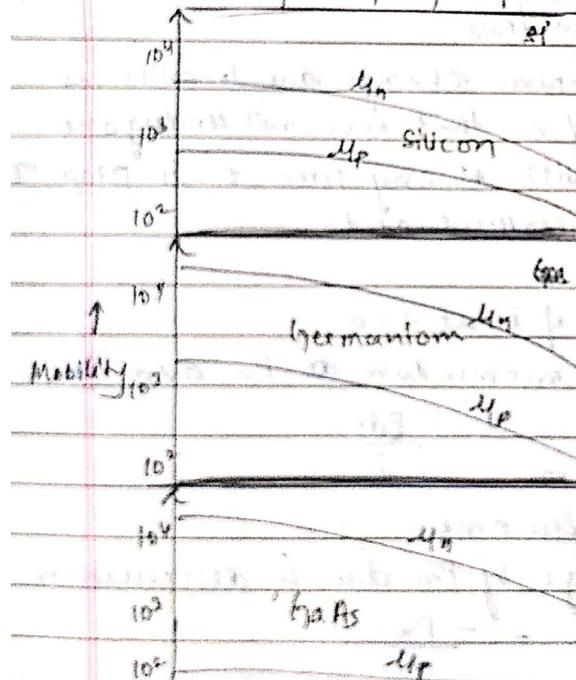
Scattering reduces mobility at lower temp. The Schottky model indicates that inc. in mobility is prop. to  $T^{3/2}$  at lower temp. & at higher temp. inc. in mobility is prop. to  $T^{-1/2}$ . Since the scattering probability is inversely proportional to the mean free time & therefore mobility, the mobility due to 2 or more scattering mechanisms is given by.

$$\frac{1}{M} = \frac{1}{M_1} + \frac{1}{M_2}$$

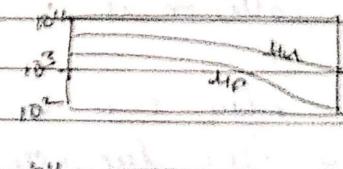
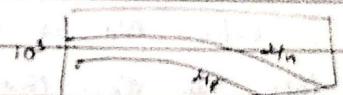
mean free time is the avg. time b/w two collisions.

Note: Mobility of e is more than holes because the energy band of e is more than that of holes.

$$10^{14}, 10^{15}, 10^{16}, 10^{17}, 10^{18}, 10^{19}$$



As the conc. of impurity inc.  
the effects of impurity  
scattering are felt even at  
higher temp.



Cause conc.

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### Conductivity & Mobility

Let an electric field  $E_x$  be applied in the  $x$ -direction & each  $e^-$  experience a net force where  $F = -\sigma q E_x$ .  
If there are  $n$   $e^-$  per  $\text{cm}^3$  then total force

$$F = -nq E_x \quad \rightarrow (1)$$

We know that force is also equal to  $m\alpha$ , or it's equal to  $m \frac{dv}{dt}$  (rate of change of momentum)  $\Rightarrow F = m \frac{dv}{dt} = \frac{P_x}{dt}$  over the field

$$\text{where } P_x = \frac{d}{dt} \text{ [momentum over the field]}$$

where  $P_x$  is the  $x$  component of the total momentum of  $e^-$ .

$$\text{from (1) & (2)} \quad -nq E_x = \frac{P_x}{dt}$$

$$-nq E_x = \frac{d}{dt} \left[ \frac{P_x}{dt} \right]$$

But the total  $x$  momentum change due to collisions

Let  $N(t)$  be the no. of  $e^-$  that have not undergone collision. The dec. in  $N(t)$  at any time  $t$  is prop. to the no. of  $e^-$  left unscattered at  $t$ .

$$\text{Then } N(t) = N_0 e^{-\frac{t}{\tau}}$$

where  $N_0$  is the no. of  $e^-$  at  $t=0$

then the diff. change in momentum due  $P_x$  due to collision is  $\frac{dP_x}{dt}$ .

$$= -\frac{P_x}{\tau}$$

where  $\tau$  is the mean free time.

Therefore the rate of change of  $P_x$  due to deceleration

$$\text{effect of collision is } \frac{dP_x}{dt} = -\frac{P_x}{\tau}$$

But we know that the sum of acceleration & deceleration effect must be 0 at steady state.

$$\therefore -\frac{P_x}{\tau} - nq E_x = 0$$

$$\text{Therefore, } -\frac{p_n}{t} = nq\bar{v}_n E_x$$

$$p_n = -nq\bar{v}_n t E_x$$

Avg. momentum per e is  $(p_n) = \frac{-nq\bar{v}_n t E_x}{n}$

$$(p_n) = -q\bar{v}_n E_x$$

$$\therefore \text{the net velocity } v_n = \frac{(p_n)}{m^*} = -\frac{q\bar{v}_n E_x}{m^*}$$

where  $m^*$  is the effective mass of the e.

$$\text{where } \frac{1}{m^*} = \frac{1}{m_l} + \frac{1}{m_t}$$

where  $m_l$  = longitudinal mass

$m_t$  = transversal mass

We know that current density  $J_n = -q n v_n$

$$\left\{ J_n = \frac{\text{coulomb}}{\text{coulomb}} \times \frac{\text{electron}}{\text{cm}^2} \times \frac{\text{cm}^2}{\text{sec}}$$

$$J_n = \frac{\text{Ampere}}{\text{cm}^2} = \frac{I}{A}$$

$$\therefore J_n = -q n \left[ -\frac{q\bar{v}_n E_x}{m^*} \right]$$

$$J_n = \frac{nq^2\bar{v}_n E_x}{m^*}$$

We also know that  $J_n = \sigma E_x + T E_x$

$$\left. \begin{aligned} \therefore \sigma &= \frac{J_n}{E_x} = \frac{nq^2\bar{v}_n}{m^*} \end{aligned} \right\} \rightarrow \text{conductivity}$$

We also know that  $\sigma = q n \mu_n$

$$\left. \begin{aligned} \mu_n &= \frac{\sigma}{q n} = \frac{q^2\bar{v}_n}{m^*} \end{aligned} \right\}$$

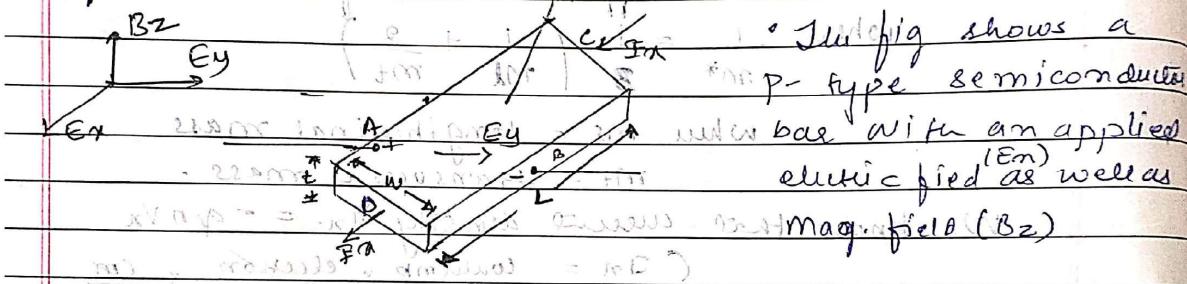
where  $\mu_n$  is mobility

The derivation has been done on the assumption that the current flow is primarily due to e flow. If we consider the hole

Conduction also  $J_m$  can be written by changing  
 $n$  to  $p$  &  $-q$  to  $+q$  &  $N_n$  to  $N_p$ .  
 Then  $J_m = (nqN_n + pN_p) E_{ext} = n^2 E_a$ .

### Hall Effect

- If a current carrying conductor or semiconductor is placed in a transverse mag. field ( $B_z$ ) an E.F.C. is induced inside the conductor in the direction  $\perp$  to both electric & mag. field.



- Because of the Hall effect the hole  $\rightarrow$  is deflected on both the sides instead of linear drifting in the bar. This creates accumulation of holes in one side & in the other side of the bar (width wise). Hence an EMF is induced.
- This induced EMF is  $\perp$  to both the applied E.F & m.F.
- This effect is known as Hall effect & the Vtg. V<sub>AB</sub> is known as Hall voltage.

We know that the force acting on charge in an electric field  $F = -qE$  (for hole)

$$F = qvB \quad (\text{for } e^-)$$

The force acting on the hole due to the applied m.F.,  $F = qv(B \times B)$

where  $v$  is the velocity &  $B$  is the flux density

On doing integration we get  $V = \frac{q}{2m} B^2 L^2 / (V \times B)$ . Now it's clear that  $V \propto B$ .

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DATE: \_\_\_\_\_ PAGE: 25

$\therefore$  total force acting on a hole,  $F = q_f(E + v \times B)$

Now consider the P-type bar in the sketch & the force acting on a hole in the y direction can be written as  $q_f y$

$$F = q_f(E_y - v_n B_z)$$

At steady state the net force acting on the holes becomes zero i.e.  $F_y = 0$ .  $\therefore$  Therefore  $E_y = v_n B_z \rightarrow 0$

Under this condn we get a steady state current flow from C to D in the n-direction.

But w.r.t current density  $J_n = -q v_n n_a$  (for an e)

$\therefore J_n = q p_o v_n$  (for a hole)

$$\therefore V_m = J_n \frac{d\phi}{dx} = q p_o v_n \frac{d\phi}{dx} \quad V_m = J_n \cdot \frac{d\phi}{dx}$$

$$q p_o \cdot$$

Subs in eqn ①.

$$E_y = \frac{J_n \cdot B_z}{q p_o}$$

$$E_y = \frac{q p_o}{q p_o} \cdot \frac{B_z}{B_z}$$

As we know that,  $q$  &  $p_o$  are const. we can write that  $E_y \propto J_n \cdot B_z$

i.e. Hall induced electric field because of hall effect is directly proportional to the current density & flux density of the mag. field.

$$\therefore E_y = R_H J_n B_z$$

where  $R_H = \frac{1}{q p_o}$   $E_y$  is known as hall effect coefficient.

$$\text{also } \left\{ \begin{array}{l} R_H = \frac{E_y}{J_n B_z} \\ p_o = \frac{1}{q R_H B_z} \end{array} \right.$$

$$p_o = \frac{1}{q R_H B_z} \quad \text{Subs for } R_H \text{ as } \frac{E_y}{J_n B_z}$$

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$$P_0 = I_m B_z$$

E.g.

$$P_0 = \frac{I_m B_z}{(Wt)} \cdot \frac{(V_{AB})}{V_{AB} + V_g}$$

$$\boxed{P_0 = \frac{I_m B_z}{V_{AB} + V_g}} \quad \rightarrow \textcircled{2}$$

from eqn ② it is clear that with using Hall effect the carrier cone can be found out in a bar.

$$\text{WKS, Resistance, } R = \frac{P_0}{I_m} \text{ with } I_m \text{ & } P_0 \text{ are known}$$

hence by measuring the resistance of the bar we get the resistivity of the material.

$$\therefore \rho = \frac{R a}{l} = \frac{R \times W t}{l} = \text{③}$$

$$R = \frac{V_{CD}}{I_m} \quad \text{for } \bar{n} = N_{Dz}$$

$$\boxed{\text{Resistivity, } \rho = \frac{V_{CD} W t}{I_m l}}$$

also WKS conductivity,  $\sigma_{WS} = q n / \rho$  for an e

$\therefore \sigma_{WS} = q V_{AB} / P_0 \cdot \rho$  for a hole.

$$\therefore \mu_p = \frac{q V_{AB}}{P_0 \cdot \rho} = 1 / \rho$$

$$\boxed{\mu_p = \frac{R_H}{\rho}} \quad \frac{1}{\rho} = \frac{R_H}{V_{AB}}$$

$\therefore \mu_p$  mobility is the ratio of hall effect coefficient to resistivity of the bar.

NOTE: Thus by measuring  $V_{AB}$  we can know whether the material belongs to n-type or p-type i.e if  $V_{AB}$  is +ve the material is p-type &

if  $V_{AB} = -ve$  then n-type. To derive the carrier cone of n-type bar we go with  $-V_g$ ,  $P_0$  will be  $\frac{1}{2} V_{AB}$  &  $R_H$  will be -ve in that case.

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PAGE:

Drift & resistance .

- Consider a semiconductor bar having length  $l$  width  $w$  & thickness  $t$ .

We know that drifting is the process of  $\bar{e}$  movement due to the application of an external electric field.

- Consider an external electric field  $E_x$  is applied across the bar of Semiconductor across the length  $l$ .

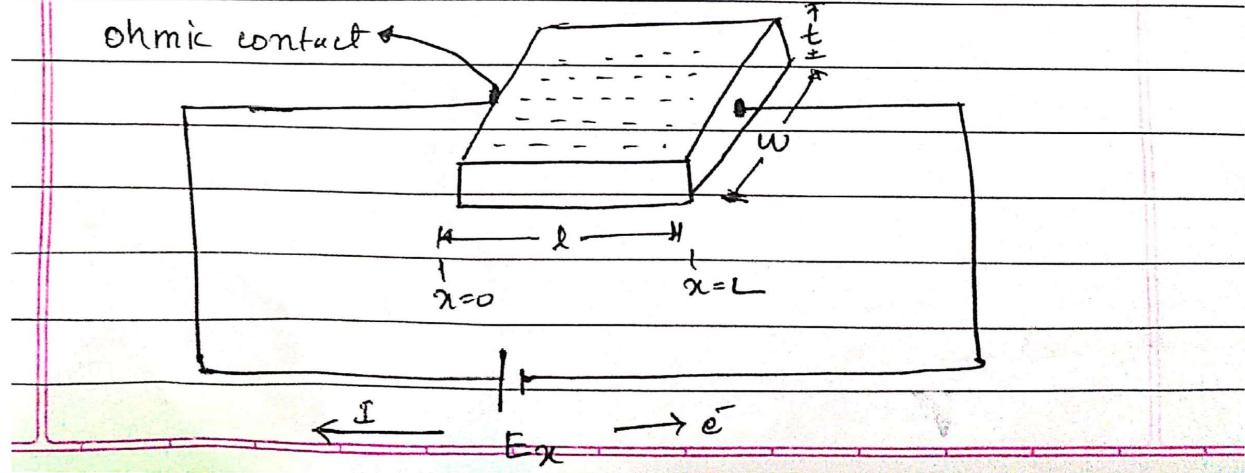
- Then the resistance of the bar can be written as -  $R = \frac{\rho l}{wt}$

$$\text{or } R = \frac{l}{\sigma wt} \quad \text{where } \rho \text{ is the resistivity in } \Omega \cdot \text{cm.}$$

$\sigma$  is the conductivity.

- Consider the external circuit completed through ohmic contacts as shown in the sketch.

hole motion  $\rightarrow$   $\leftarrow \bar{e}$  motion



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ohmic contact refers to perfect source & sinks of both carrier types, and has no sp. tendency to inject or collect either e or hole.

When we apply the external field  $E_x$  on a group of e, a group of holes move in the opp. direction as shown in the sketch. The drift area is const. throughout the Bar thus for every e leaving the left end where  $n=0$  of the bar there is a corresponding e entering at  $n=L$ . Similarly as the hole reaches at  $n=L$  a compensating hole must appear at  $n=0$  thus maintaining the e const. & space charge neutrality const in the Bar.