

Course : Electronic Devices

Course Code : 18EC33

Syllabus

Module 1

Semi Conductors :

Bonding forces in solid, Energy bands, Metals, Semiconductors and Insulators, Direct and Indirect Semiconductors, Electrons and holes, Intrinsic and Extrinsic materials, Conductivity and mobility, Drift and Resistance, Effects of temperature and doping on mobility, Hall Effect.

(Text 1)

Module 2

PN Junctions :

Forward and Reverse biased Junctions - Qualitative description of current flow at a junction, reverse bias, Reverse bias breakdown - Zener Breakdown, avalanche breakdown, Rectifiers.

Optoelectronic Devices Photodiodes : Current and voltage in an illuminated Junction, Solar cells, Photo-detectors. Light Emitting Diode : Light Emitting materials.

(Text 1)

Module 3

Bipolar Junction Transistor

Fundamentals of BJT operation, Amplification with BJTs, BJT fabrication, The coupled diode model (Ebers-Moll model), Switching operation of a transistor, Cutoff, Saturation, Switching cycle, Specifications, drift in

the base region , Base narrowing , Avalanche breakdown , Base Resistance and Emitter Crowding .
(Text 1)

Module 4

Field Effect Transistors

Basic PN JFET operation , Equivalent Circuit and Frequency Limitations , MOSFET - Two terminal MOS Structure - Energy band diagram , Ideal Capacitance - Voltage Characteristics and Frequency Effects , Basic MOSFET operation - MOSFET Structure , Current - Voltage characteristics .
(Text 2)

Module 5

Fabrication of P-n junctions :

Thermal Oxidation , Diffusion , Rapid Thermal Processing
Ion implantation , chemical Vapour deposition ,
photolithography , Etching , metallization

Integrated Circuits :

Background , Evolution of ICs , CMOS process integration ,
Integration of other Circuit Elements .
(Text 1)

Text Books :

1. Ben-Gi Streetman , Sanjay Kumar Banerjee , "Solid State Electronic Devices" , 7th edition , Pearson Education , 2016 .
2. Donald A Neamen , Charles R. Bois , "Semiconductor Physics and Devices" , 4th edition , Mc Graw Hill Education 2012 .

Electronic Devices [18EC33]

Module 1

Semiconductors

Bonding forces in solids , Energy bands , Metals , Semiconductors and insulators , Direct and Indirect semiconductors , Electrons and Holes , Intrinsic and Extrinsic materials , Conductivity and Mobility , Drift and Resistance , Effects of temperature and doping on mobility , Hall Effect .

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Ben - Gi - Streetman , Sanjay Kumar Banerjee , "Solid State Electronic Devices" , 7th Edition , Pearson Education 2016.

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DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

SUBJECT: ELECTRONIC DEVICES	SUBJECT CODE: 18EC33
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QUESTION BANK

MODULE 1: SEMICONDUCTORS

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3rd Sem, 'C' sec

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Bonding Forces in Solids.

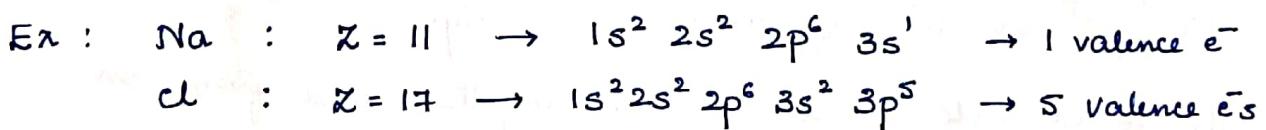
Solids can be classified according to the nature of the bonding between their atomic or molecular component. The interaction of electrons in neighboring atoms of solid serves the very important function of holding the crystal together.

There are 3 types of Bonding.

1. Ionic Bonding
2. Metallic Bonding
3. Covalent Bonding

① Ionic Bonding

It is a type of bonding where complete transfer of valence electrons takes place between the atoms resulting in positive ion and negative ion.



W.K.T, atom to become stable, there must be max 8 e^- in the outermost orbit.

\therefore If Na loses its outermost electron and Cl accepts one electron, then both Na and Cl becomes stable.

* ions have net electric charges after the electron exchange
The Na^+ ion has a net positive charge, having lost an electron, and the Cl^- ion has a net negative charge, having gained an electron.

* Thus NaCl structure is that all electrons are tightly bound to atoms. Once the electron exchange have been made between the Na and Cl atoms, it forms Na^+ and Cl^- ions.

the outer orbits are filled there are no loosely bound electrons to participate in current flow.

Thus NaCl is a good insulator.

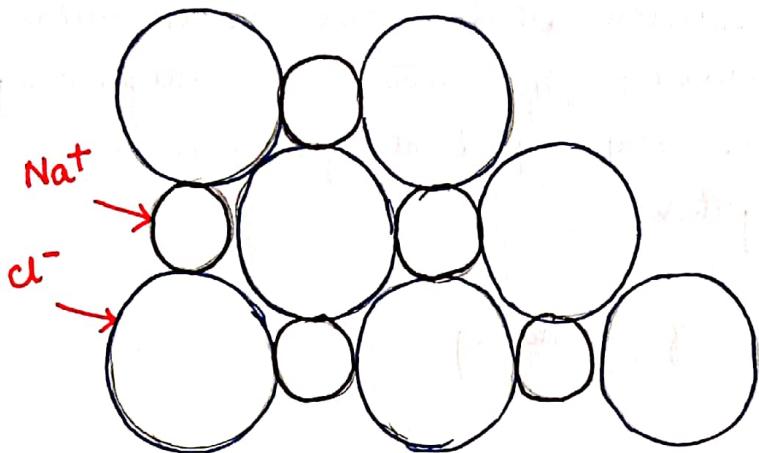


fig: Ionic Bonding
in NaCl .

(2) Metallic Bonding:

* In a metal atom, the outer electronic shell is only partially filled, usually by no more than three electrons.

* The alkali metals (Ex: Na) have only one electron in the outer orbit. This electron is loosely bound and is given up easily in ion formation. This accounts for the chemical activity and high electrical conductivity.

* The forces holding the lattice together arise from an interaction between the positive ion cores and the surrounding free electrons. This force of holding is known as metallic bonding.

(3) Covalent Bonding

* It is a chemical bonding in which pair of electrons are shared between two atoms.

* Bonding forces arise from interaction between the shared electrons. This is known as covalent bonding.

- * This type of bonding exists in 4th group element (there will be 4 valence electrons) i.e Ge, Si or C.
- * In these crystals each atom shares its valence electrons with its four neighbors.

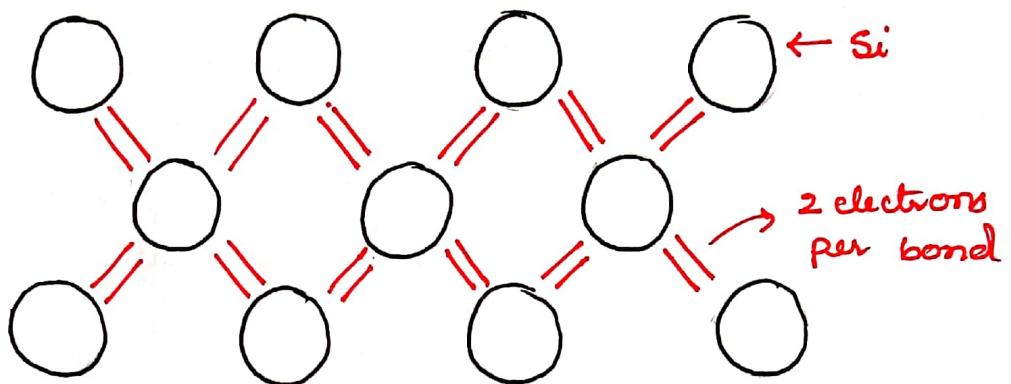


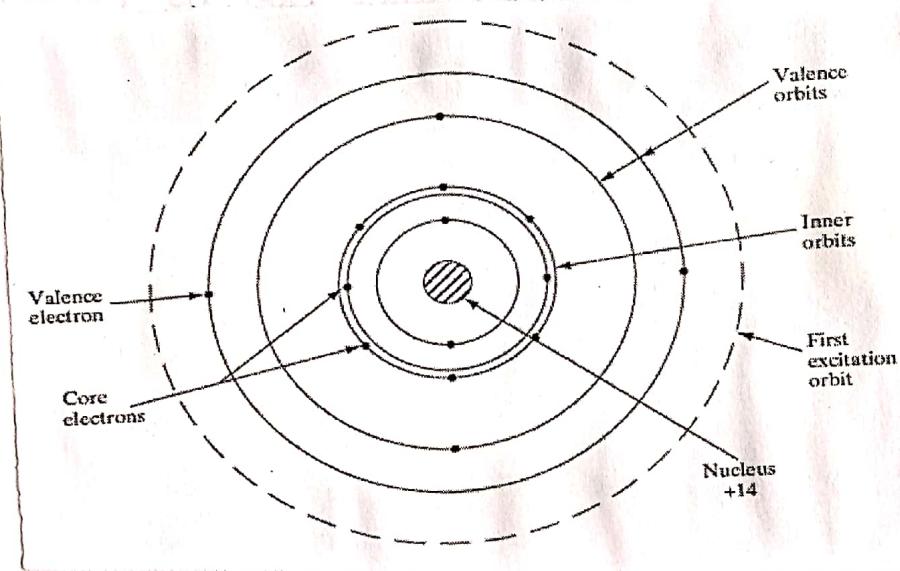
fig : Covalent Bonding in Si Crystal .

Note : Bonding between

- (1) metal and Non metal — Ionic Bonding
- (2) metal and metal — Metallic Bonding .
- (3) non metal and non metal — covalent Bonding .

Energy Bands

- * As isolated atoms are brought together to form a solid, various interactions occur between neighbouring atoms.
- * The forces of attraction and repulsion between atoms will find a balance at the proper interatomic spacing. In this process, important changes occur in the electron energy level configurations which results in the varied electrical properties of solids.
- * Consider the orbital model of a Si atom as shown



An the outermost shell or valence shell $n=3$, two $3s$ and two $3p$ electrons interact to form the four hybridized sp^3 electrons when atoms are brought close together.

- * figure (b) shows the coulombic potential wells of two atoms close to each other, along with wavefunctions of two electrons centred on the two nuclei.

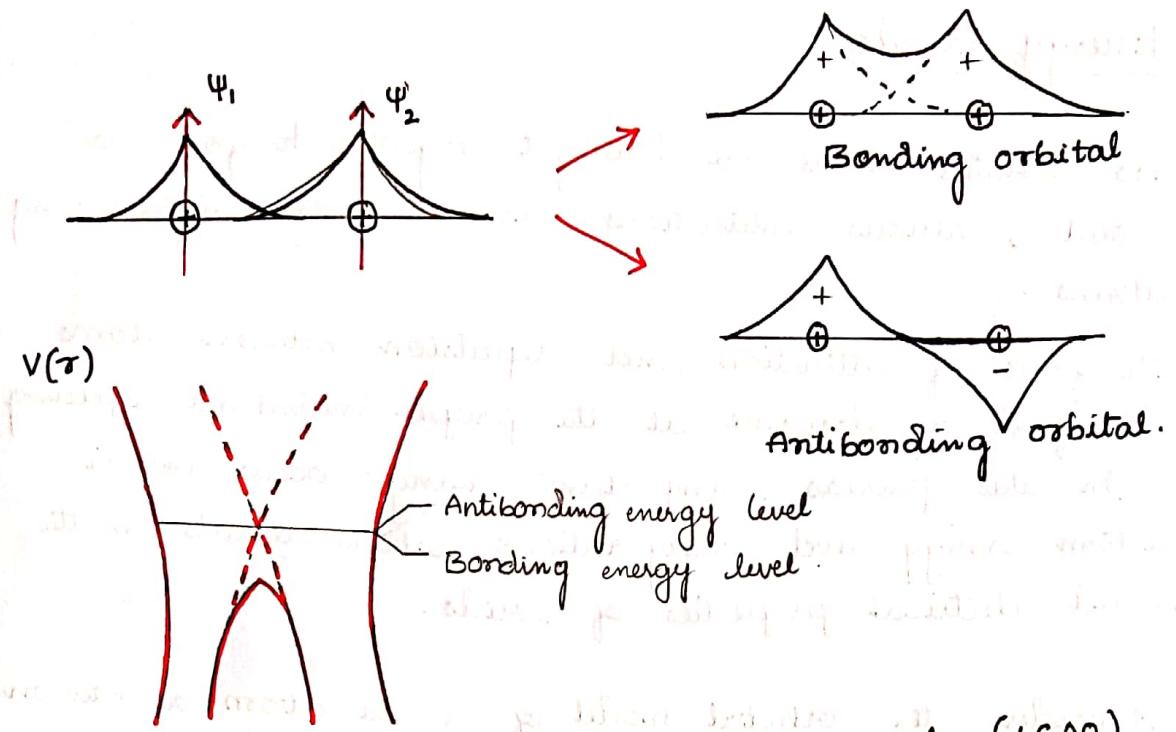


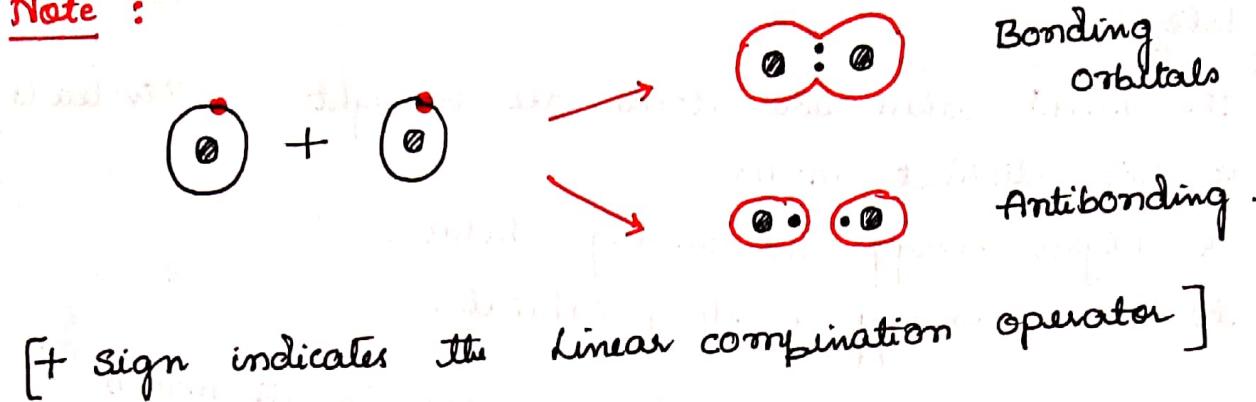
fig 6: Linear Combinations of atomic orbitals (LCAO)

- * By solving Schrodinger equation for such interacting system, we find that the composite two-electron wavefunctions are Linear Combinations of individual Atomic Orbitals (LCAO).
- * The odd or antisymmetric combination is called antibonding orbital, while the even or symmetric combination is the bonding orbital.
- * Hence the 2 electrons in the bonding orbital have opposite spins, while those in the anti-bonding state have parallel spins. (Pauli Exclusion Principle).

Note :

1. The LCAO when two atoms are brought together leads to two distinct modes
 - a) higher energy antibonding orbital .
 - b) lower energy bonding orbital .
 2. Electron probability density is high in the region b/w the ion cores (covalent bond) leading to lowering of the bonding energy level . Therefore
 - * Higher energy antibonding orbital has low electron probability density .
 - * Lower energy bonding orbital has high electron probability density .]
- * To determine the energy levels of the bonding and antibonding state , it is important to recognize that in the region between the two nuclei , the coulombic potential energy (V_r) is lowered (solid line) compared to isolated atoms (dashed line) in fig b .
- * V_r is lowered compared to isolated atom because an electron here would be attracted by two nuclei rather than just one .
- For bonding state the electron probability density is higher in this region of lowered potential energy than for anti bonding state .

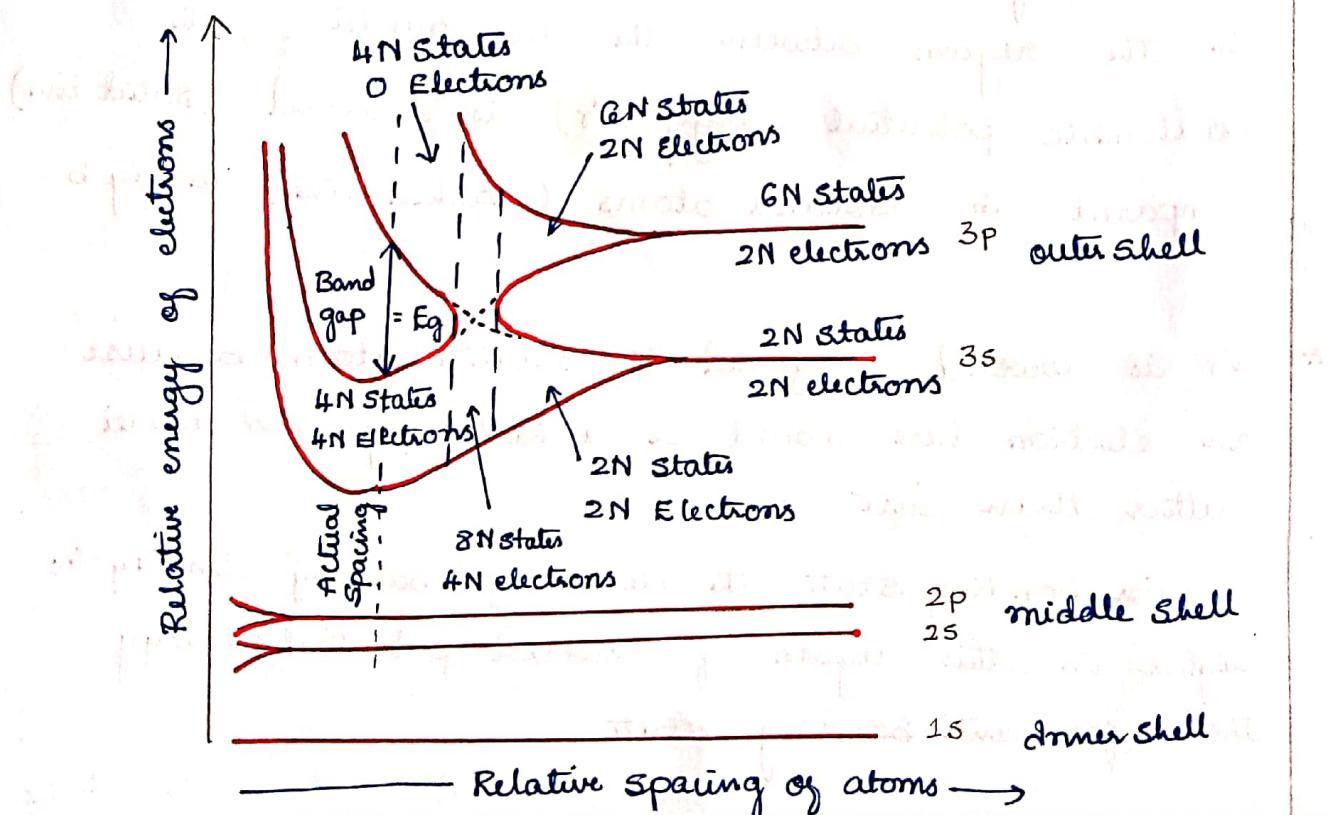
Note :



[+ sign indicates the linear combination operator]

Formation of Energy Bands (conduction & Valence band)

- * In solid, many atoms are brought together, so that split energy levels form [essentially] continuous bands of energies.



- * figure illustrates the imaginary formation of a silicon crystal from isolated silicon atoms.
- Each isolated Si atom has an electronic structure $1s^2 2s^2 2p^6 3s^2 3p^2$.
- here each atom has available two $1s$ states, two $2s$, six $2p$, two $3s$, & $3p$ states and higher states.
- If we consider N atoms, there will be $2N, 2N, 6N, 2N$ and $6N$ states of type $1s, 2s, 2p, 3s$ and $3p$ respectively.
- As interatomic Spacing decreases, these energy levels split into bands beginning with the outer ($n=3$) shell.
- As the $3s$ and $3p$ bands grows, they merge into a single band composed of a mixture of energy levels. This band of ' $3s-3p$ ' levels contains $8N$ available states.
- As the distance between atoms approaches the equilibrium interatomic spacing of silicon, this band splits into two bands separated by an energy gap ' E_g ' i.e upper band (conduction band) contains $4N$ states and lower band (valence band)
- Energy gap sometimes called a 'forbidden band',
- If electrons are counted, The lower $1s$ band is filled with $2N$ electrons, $2s$ band and $2p$ bands will have $2N$ and $6N$ electrons.

- * In $n=3$ shells, there are $4N$ electrons, $2N$ in $3s$ states and $2N$ in $3p$ states.

These $4N$ electrons must occupy states in the valence band or the conduction band in the crystal.

At OK, the electrons will occupy the lowest energy states available to them.

- * In Si crystal, there are exactly $4N$ states in the valence band available to the $4N$ electrons.

- * Thus at OK, every state in the valence band will be filled, while the conduction band will be completely empty of electrons.

Q. This system satisfies which of the following statements?

A. The Fermi level is at the top of the valence band.

B. The Fermi level is at the bottom of the conduction band.

C. The Fermi level is at the top of the conduction band.

D. The Fermi level is at the bottom of the valence band.

Ans: C. The Fermi level is at the top of the conduction band.

Q. Which of the following statements is/are correct?

Metals , Semiconductors , and Insulators .

- * Electrons to experience acceleration in an applied electric field , they must be able to move into new energy states. This implies there must be empty states available to the electrons.
- * As seen (3.1.2) Silicon band structure , valence band is completely filled with electrons at 0K and the conduction band is empty . There can be no charge transport within the valence band as no empty states are available . There are no electrons in the conduction band , so no charge transport can take place . Thus at 0K silicon has high resistivity typical of insulators .

Band structures at 0K

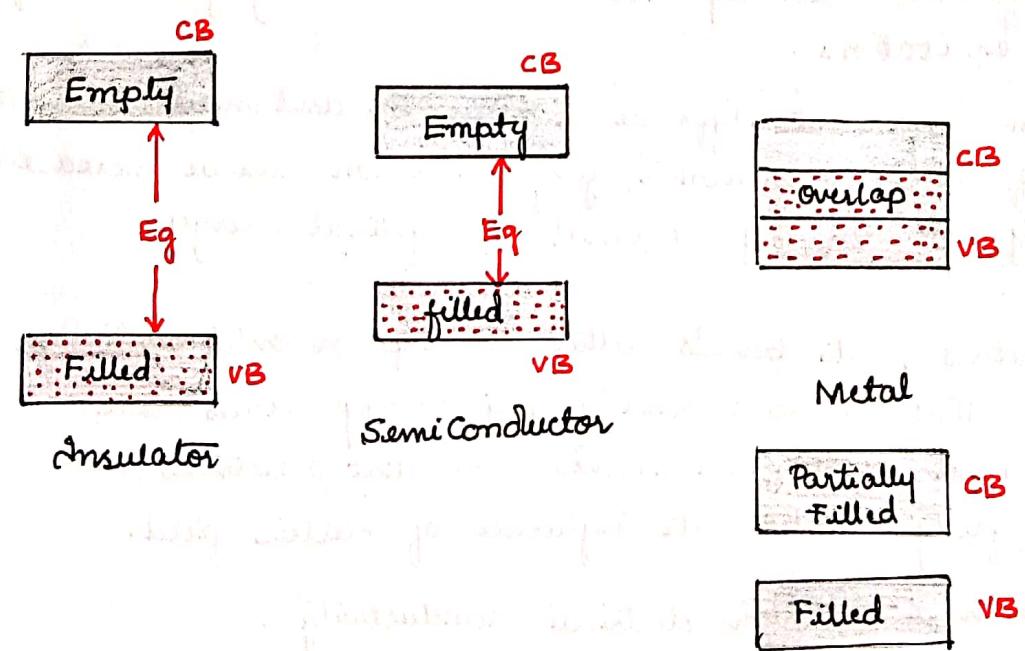


fig : Typical band structures at 0K .

- * at 0 K Semiconductor materials have basically the same structure as insulators. i.e a filled valence band separated from an empty conduction band by a band gap E_g .
- * Band gap ' E_g ' size is much smaller in semiconductors than in insulators.
for example, Semiconductor Si has $E_g = 1.1\text{ eV}$ compared with insulator diamond having $E_g = 5\text{ eV}$
- * The relatively small band gaps of semiconductors allow for excitation of electrons from the valence band to conduction band by reasonable amounts of thermal or optical energy.
for example, at room temperature, SC with 1 eV band gap will have a significant no. of electrons excited thermally across band gap into conduction band, whereas an insulator with $E_g = 10\text{ eV}$ will have a negligible no. of such excitations.
Thus an important difference between SC and insulator is that no. of electrons available for conduction can be increased greatly in SC by thermal or optical energy.
- * In metals, the bands either overlap or only partially filled - Thus electrons and empty energy states are intermixed within the bands so that electrons can move freely under the influence of electric field.
- * Metal have a high electrical conductivity.

Direct and Indirect Semiconductors.

when a single electron is assumed to travel through a perfectly periodic lattice, The wave function of the electron is assumed to be in the form of a plane wave moving in the x -direction with propagation constant k , also called a wavevector.

- * The space-dependent wave function for the electron is

$$\Psi_k(x) = U(k_x, x) e^{ik_x x} \quad (1)$$

where the function $U(k_x, x)$ modulates the wave function according to the periodicity of the lattice. Such wavefunctions are called Bloch functions.

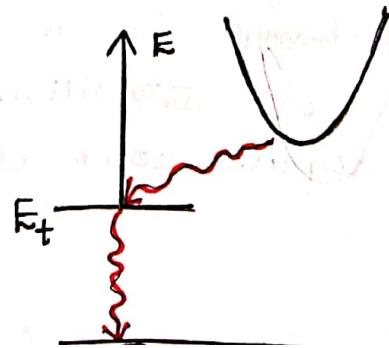
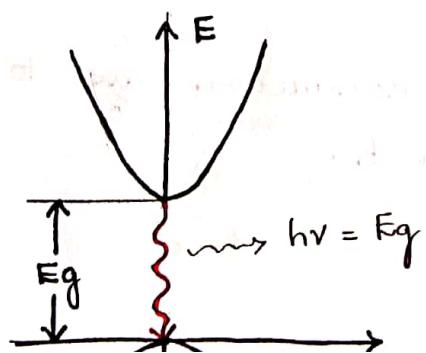
- * The band structure of GaAs has a minimum in the conduction band and maximum in the valence band for the same k value ($k=0$).

Si has its valence band maximum at a different value of k than its conduction band minimum.

- * Thus, in GaAs, the electron making a smallest energy transition from conduction band to valence band can do without change in k value.

But in Si, transition from conduction band to valence band requires some change in k .

- * There are two classes of semiconductor energy bands
 1. Direct Energy band Semiconductor.
 2. Indirect Energy band Semiconductor.
- * In a direct Semiconductor such as GaAs, an electron in the conduction band can fall into valence band, giving off the energy difference E_g as a photon of light.
- * In an Indirect Semiconductor such as Si, an electron in the minimum conduction band cannot fall directly to the valence band but must undergo a momentum change as well as changing its energy i.e. it goes through some defect state (E_t) within the band gap. here it involves a change in k, part of energy given up as heat rather than emitted photon.
- * This difference between direct and indirect band structures is very important for deciding which semiconductors can be used in devices requiring light output.



Elections and holes

(How electrons and hole pairs are formed)

- * As the temperature of a semiconductor is raised from 0 K, some electrons in the valence band receive enough thermal energy to be excited across the band gap to the conduction band leaving empty space in valence band.
- * This empty state in the valence band is referred to as a hole.
- * If the conduction band electron and hole are created by the excitation of a valence band electron to the conduction band, they are called 'Electron-hole pair (EHP)'.

Current-conduction in Valence Band >

- * After excitation to the conduction band, an electron is surrounded by a large number of unoccupied energy states.

For example, the equilibrium number of EHPs in pure Si at room temperature is only about 10^{10} EHP/cm³, compared to the Si atom density of 5×10^{22} atoms/cm³. Thus the few electrons in the conduction band are free to move about via the many available empty states.

- * In a filled band, all available energy states are occupied. For every electron moving with a given velocity, there is an equal and opposite electron motion in the band.

When an electric field is applied, the net current is zero because for every electron j moving with velocity v_j there is corresponding electron j' with velocity $-v_j$.

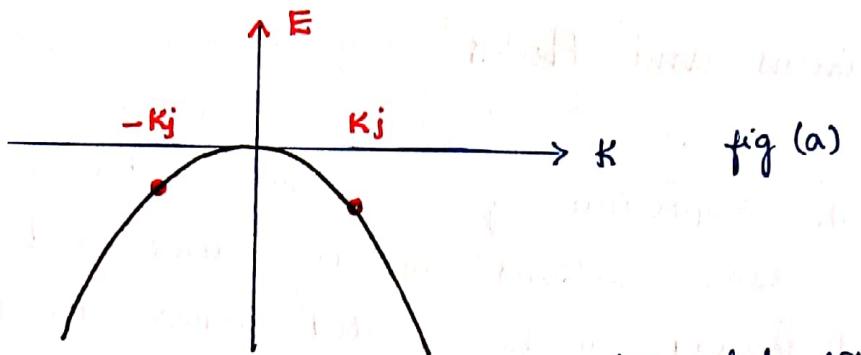


fig shows the electron energy v/s wavevector plot for the valence band.

Since K is proportional to electron momentum, it is clear the two electrons have oppositely directed velocities.

- * with N electrons/cm³ in the band, the current density using a sum over all of the electron velocities and including the charge $-q$ on each electron.

$$J = (-q) \sum_i^N v_i = 0 \quad (\text{filled band})$$

- * Now if hole is created ~~xxxxxx~~ by removing the j^{th} electron, the net current density is given by

$$J = (-q) \sum_i^N v_i - (-q) v_j \quad (j^{th} \text{ electron missing})$$

$$J = 0 - (-q) v_j$$

$$\therefore J = +q v_j \text{ is the net current. } \rightarrow \star$$

This equation indicates the current contribution of the hole is equivalent to that of a positively charged particle with velocity $+v_j$.

For simplicity, empty states in the valence band is treated as charge carriers with positive charge and positive mass.

- * The charge and mass of a hole have opposite signs from those of an electron <Illustrated

- * Electrons in the conduction band and holes in the valence band are considered for the current flow in a semiconductor by the motion of these two types of charge carriers.
- * Valence and conduction bands on an electron scale E as shown in figure. In the valence band, hole energy increases oppositely to electron energy, because the two carriers have opposite charge. Thus hole energy increases downward and holes seeking the lowest energy state available are generally found at the top of the valence band. In contrast, conduction band electrons are found at the bottom of the conduction band.

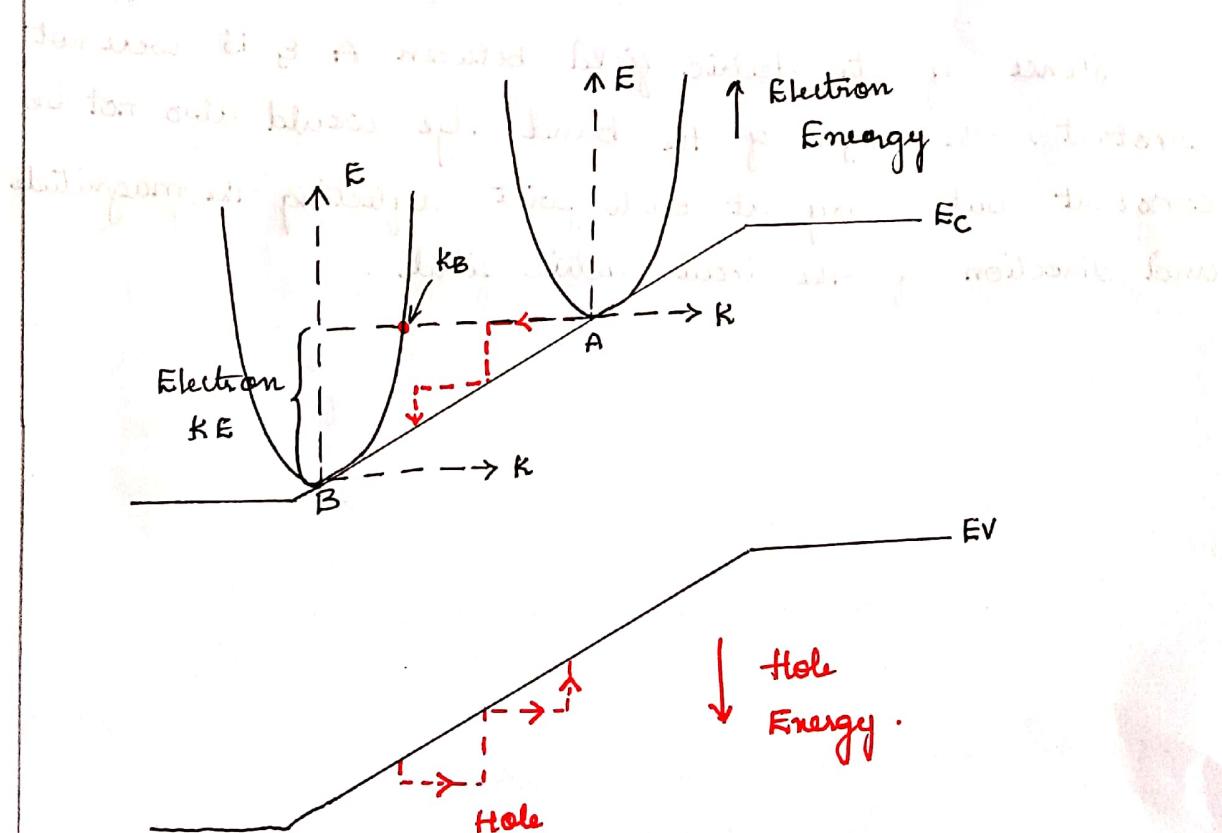


fig: Superimposition of the (E, k) band structure on the $E \times k$ position simplified band diagram for semiconductor in an electric field.

In the figure, the electron at location A sees an electric field given by the slope of the band edge, and gains kinetic energy by moving to point B. Correspondingly, in the (E - k) diagram, the electron starts at $k=0$, but moves to a non-zero wavevector k_B .

The electron then loses kinetic energy to heat by scattering mechanisms and returns to the bottoms of the band at B. The slopes of the (E , α) band edges at different points in space reflect the local electric fields at those points.

Hence if the electric field between A & B were not constant, the slope of the band edge would also not be constant but vary at each point reflecting the magnitude and direction of the local electric field.

Intrinsic Material

- * A perfect semiconductor crystal with no impurities or lattice defects is called an intrinsic semiconductor.
- * At higher temperatures Electron-Hole pairs [EHP] are generated and these EHPs are the only charge carriers in intrinsic material.
- * The generation of EHPs can be visualized in qualitative way by considering the breaking of covalent bonds in the crystal lattice as shown in fig.

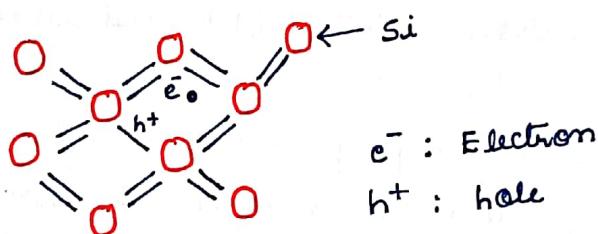


fig : Electron-hole pairs in the covalent bonding

- * If one of Si valence electrons is broken away from the bonding structure and free to move, conduction electron is created and a broken bond (hole) is left behind as shown in fig above. This model is referred to as 'Broken bond' model.
- * The energy required to break the bond is band gap Energy E_g .
- * Here, in intrinsic material, the concentration of electrons in the conduction band n (electrons per cm^{-3}) is equal to the concentration of holes in the valence band p (holes per cm^{-3}). Each of these intrinsic carrier concentrations is commonly referred to as ' n_i '.

$$\therefore n = p = n_i$$

- * If steady state carrier concentration is maintained, recombination of EHPs occurs at the same rate at which they are generated.

$$r_i = g_i$$

where g_i = generation rate, r_i = recombination rate.

- * Each of these rates is temperature dependent i.e. when $g_i(T)$ increases when the temperature is raised, a new carrier concentration n_i is established such that the higher recombination rate $r_i(T)$ just balances generation.
- * At any temp., r_i is proportional to the equilibrium concentration of electrons n_0 and the concentration of holes p_0

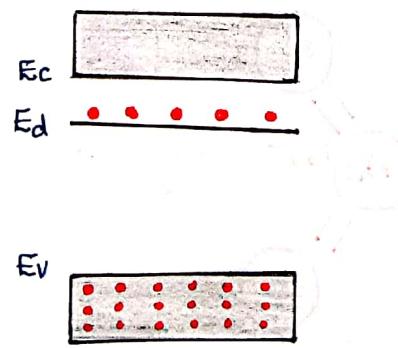
$$r_i = \alpha_r n_0 p_0 = \alpha_r n_i^2 = g_i$$

where α_r = proportionality constant.

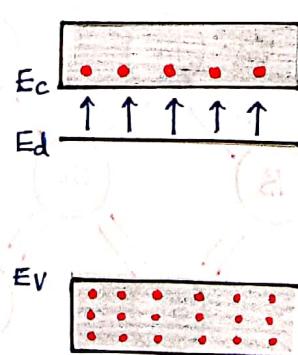
[Note : Recombination occurs when an electron in the conduction band makes a transition (direct or indirect) to an empty state (hole) in the Valence band.]

Extrinsic Material

- * When impurities are added to the pure semiconductors resulting materials are extrinsic material and the process is called as doping.
- * By doping, a crystal can be altered, so it has a predominance of either electrons or holes.
Thus there are two types of doped semiconductors
① n-type (mostly electrons) ② p-type (mostly holes)
- * When impurities are added to pure semiconductor, additional levels are created in the energy band structure usually within the bandgap.
- * When pentavalent impurities (column V elements - P, As, Sb) are added, it introduces an energy level close to conduction band in Ge or Si.
This level is filled with electrons at 0K and very little thermal energy is required to excite these electrons to conduction Band. At 50-100K, all electrons in the impurity level are donated to the conduction band.
Such impurity level are called donor level and impurities are called as donor impurities.



at $T = 0\text{ K}$



at $T = 50\text{ K}$

fig: donation of electrons from donor level to conduction Band.

- * Thus semiconductors doped with a significant number of donor atoms will have $n_o > (n_i, p_0)$ at room temp. This is n-type material.
- * when trivalent impurities are added (i.e column III - B, Al, Ga) it introduces impurity levels close to valence band in Ge or Si. These levels are empty of electrons at 0K. At low temp, enough thermal energy is available to excite e^- from VB to impurity level leaving behind the holes.

This type of impurity level accepts the electrons from valence band, it is called an acceptor level and impurities are called acceptor impurities.

As hole concentration p_0 is much greater than the CB electrons concentration n_o - This type is p-type material.

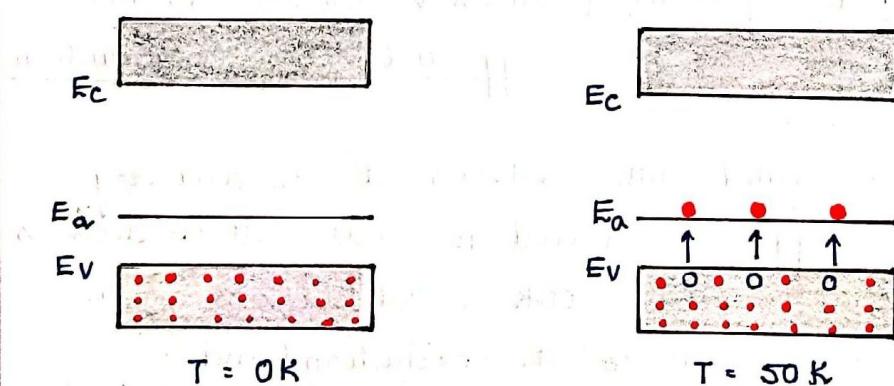


fig : acceptance of VB electrons by an acceptor level .

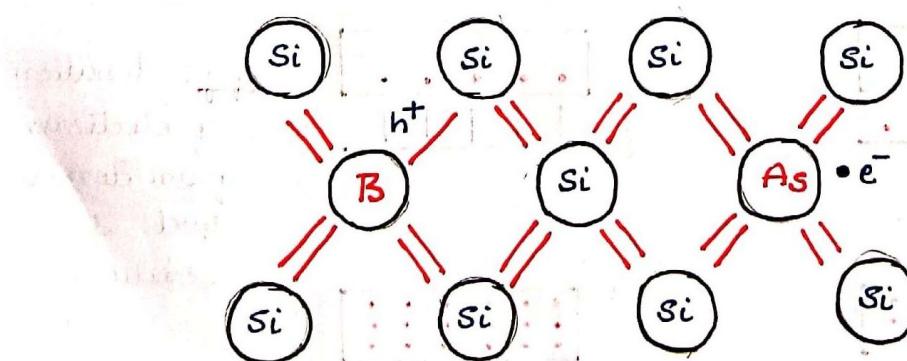


fig C: Donor and Acceptor atoms in Covalent Bonding model of Si crystal

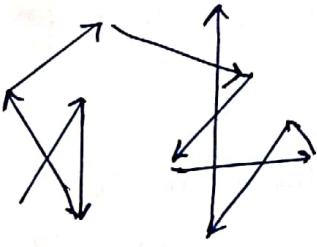
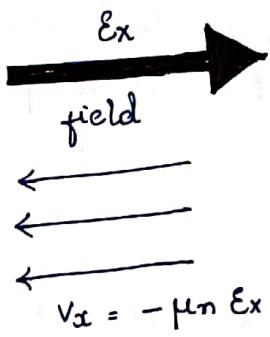
- * In the covalent bonding model, donor and acceptor atoms can be visualized as shown in fig (c)

As As has 5 valence electrons where 4 νe^- are shared with neighboring Si atoms and one valence electron is free to participate in current conduction and is donated to conduction Band.

Boron has 3 valence electrons to contribute to the covalent bonding, thereby leaving one bond incomplete. With a small thermal energy, this incomplete bond can be transferred to other atom as electrons exchange positions.

- * Column V donor levels lie approximately 0.01 eV below CB in Ge and column III acceptor levels lie about 0.01 eV above VB. In Si, donor and acceptor levels lie about 0.03 eV - 0.06 eV from the band edge.
- * When a semiconductor is doped n-type or p-type, one type of carrier dominates.
 - In n-type material - electrons are majority charge carriers and holes are minority charge carriers.
 - In p-type material - holes are majority charge carriers and electrons are minority charge carriers.

Conductivity and Mobility.

- * The charge carriers in a solid are in constant motion, even at thermal equilibrium.
- * At room temperature, the thermal motion of an individual electron may be visualized as random scattering due to lattice vibrations, impurities, other electrons and defects. Since the scattering is random, there is no net motion of the group of n electrons/cm³ over any period of time and no net current flow.
- * 
- (a) Random thermal motion of an electron in a solid
- 
- (b) well directed drift velocity with an applied electric field.
- * If an electric field E_x is applied in the x -direction each electron experiences a net force $-qE_x$ from the field. This force may be insufficient to alter appreciably the random path of an individual electron.
The effect when averaged over all the electrons, however, is a net motion of the group in the $-x$ -direction.
- * If P_x is the x -component of the total momentum of the group, the force of the field on the n electrons/cm³ is

$$-nqE_x = \frac{dP_x}{dt} \quad \text{field} \rightarrow \textcircled{1}$$

- eqⁿ (1) seems to indicate a continuous acceleration of the electrons in the $-x$ -direction.
- * The net acceleration of eqⁿ (1) is balanced in steady state by the deceleration of the collision processes. Thus while the steady field E_x does produce a net momentum P_x the net rate of change of momentum when collisions are included must be zero in the case of steady state current flow.
 - * To find the total rate of momentum change from collisions, if the collisions are truly random there will be a constant probability of collision at any time for each electron.
 - * Let us consider a group of N_0 electrons at time $t=0$ and define $N(t)$ as the number of electrons that have not undergone a collision by time t .

The rate of decrease in $N(t)$ at any time t is proportional to the number left unscattered at t ,

$$\boxed{-\frac{dN(t)}{dt} = \frac{1}{\bar{t}} N(t)} \quad \rightarrow (2)$$

where $\frac{1}{\bar{t}} = \bar{t}^{-1}$ is a constant of proportionality.

- * The solution to eqⁿ (2) is an exponential function

$$\boxed{N(t) = N_0 e^{-t/\bar{t}}} \quad \rightarrow (3)$$

and \bar{t} represents the mean time between scattering events, called mean free time (avg time b/w collisions)

- * The rate of change of P_{ex} due to the decelerating effect of collisions is

$$\left. \frac{dP_{ex}}{dt} \right|_{\text{collisions}} = - \frac{P_{ex}}{\bar{t}} \rightarrow (4)$$

- * The sum of acceleration and deceleration effects must be zero for steady state.

$$-\frac{P_{ex}}{\bar{t}} - nq E_x = 0 \rightarrow (5) \quad [\text{from eqn (1) \& (4)}]$$

- * The average momentum per electron is

$$\langle P_{ex} \rangle = \frac{P_{ex}}{n} = -q \bar{t} E_x \rightarrow (6)$$

where the angular brackets indicate an avg over the entire group of electrons.

- * net velocity of the electrons is given by

$$\langle v_{ex} \rangle = \frac{\langle P_{ex} \rangle}{m_n^*} = -\frac{q \bar{t}}{m_n^*} E_x \rightarrow (7)$$

eqn (7) represents the net drift of an avg electron in response to the electric field.

- * The current density density resulting from this net drift is,

$$\begin{aligned} J_x &= -q n \langle v_x \rangle \\ \frac{\text{ampere}}{\text{cm}^2} &= \frac{\text{coulomb}}{\text{electron}} \cdot \frac{\text{electrons}}{\text{cm}^3} \cdot \frac{\text{cm}}{\text{s}} \end{aligned} \rightarrow (8)$$

- * Substituting eqn (7) in eqn (8)

$$J_x = -q n \left[-\frac{q \bar{t}}{m_n^*} \right] E_x = \frac{n q^2 \bar{t}}{m_n^*} \cdot E_x \rightarrow (9)$$

- * from ohm's law, current density is proportional to the electric field.

$$J_{dx} = \sigma E_x \quad \rightarrow (10)$$

comparing eqn (9) and (10), conductivity is given by

$$\sigma = \frac{nq^2 \bar{t}}{m_n^*} \quad \rightarrow (11)$$

also $\sigma = q/n \mu_n$, where $\mu_n = \frac{\sigma}{q/n} = \frac{nq^2 \bar{t}}{m_n^* q/n}$

$$\therefore \mu_n = \frac{q \bar{t}}{m_n^*} \quad \rightarrow (12)$$

The quantity μ_n is called electron mobility that describes the ease with which electrons drift in the material.

here m_n^* is the conductivity effective mass for electrons.

- * Mobility is defined as the average particle drift velocity per unit electric field.

comparing eqn (12) and (7), $\mu_n = -\langle v_x \rangle / E_x$ [unit is $\frac{\text{cm}^2}{\text{V}\cdot\text{s}}$]

- * Current density in terms of mobility

$$J_{dx} = -q n \langle v_x \rangle = q n \mu_n E_x \quad \rightarrow (13)$$

- * for holes concentration changing $-q \rightarrow +q$, $\mu_n \rightarrow \mu_p$

- * if both electrons and holes participate,

$$J_{dx} = q (n \mu_n + p \mu_p) E_x = \sigma E_x \quad \rightarrow (14)$$

Drift and Resistance

- * If the semiconductor bar shown in the figure contains both types of carrier, the conductivity of the material is given by

$$\sigma = \frac{J_x}{E_x} \quad \text{where } J_x = \text{Current density}$$

$E_x = \text{Electric field.}$

- * The resistance of the material (bar) is given by

$$R = \frac{\rho L}{w t} = \frac{L \cdot \rho}{w t \sigma} \quad \text{where } \sigma = \text{conductivity}$$

$\rho = \text{resistivity } (\Omega \cdot \text{cm})$

- * Carrier drift requires that the holes in the bar move as a group in the direction of the electric field and electrons move as a group in the opposite direction.

- * Current due to holes and electrons are in the direction of the field, since conventional current is positive in the direction of hole flow and opposite to the direction of electron flow.

This drift current is constant throughout the bar.

- * The contacts to the bar are ohmic and have no special tendency to inject or collect either electrons or holes.

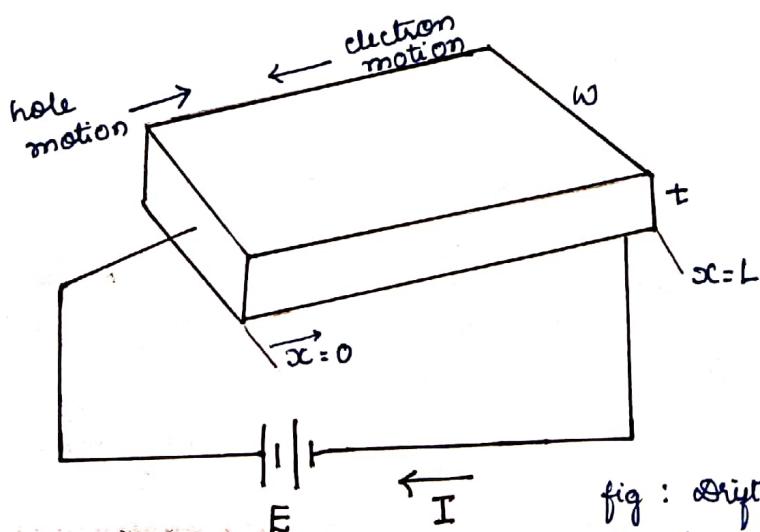


fig : Drift of e^- & holes in a semiconductor bar

- * If current due to electrons is carried around external circuit, electrons flowing into the bar at one end and out at the other (always opposite to I)
- * Every electron leaving the left end ($x=0$) of the bar, there is a corresponding electron entering at $x=L$, so that the electron concentration in the bar remains constant.
- * As a hole reaches the ohmic contact at $x=L$, it recombines with an electron and disappears, a corresponding hole must appear at $x=0$ to maintain charge neutrality.
- * At $x=0$, generation of EHP takes place and at $x=L$ recombination takes place.

Effects of Temperature and Doping on Mobility

- * Mobility can be defined as free movement of electrons or holes in a semiconductor bar from one end to the other. It is represented as ' μ '.

$$\mu = \frac{\text{drift velocity}}{\text{Electric field intensity}} = \frac{\text{cm}^2}{\text{V-S}} \text{ or } \frac{\text{m}^2}{\text{V-S}}$$

- * There are 2 types of scattering mechanisms that influence electron and hole mobility.

1. Impurity Scattering. (observed at low temperature)
2. Lattice Scattering. (observed at high temperature)

- * Impurity Scattering : Scattering from crystal defects such as ionized impurities becomes the dominating mechanism at lower temperature.

The thermal motion of the carriers is also slower. Since a slowly moving carrier is likely to be scattered more strongly by an interaction with a charged ion than is a carrier with greater momentum.

Impurity scattering events cause a decrease in mobility with decrease in temperature (i.e. mobility increases as temp increases).

[Note : $T = 0K$, Impurity Scattering will be more, μ is less.

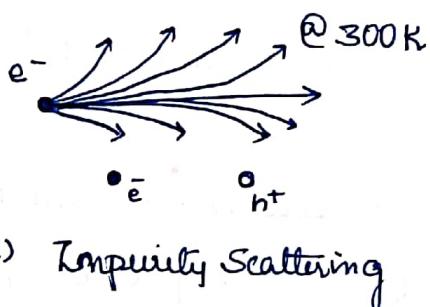
$T > 0K$, e^- gains Kinetic Energy (KE) = $\frac{1}{2}mv^2$ and moves with more velocity and IS decreases, mobility increases.

If Temp is further increased, $KE \uparrow$ $Ve \uparrow$ $IS \downarrow$ $\mu \uparrow^{es}$

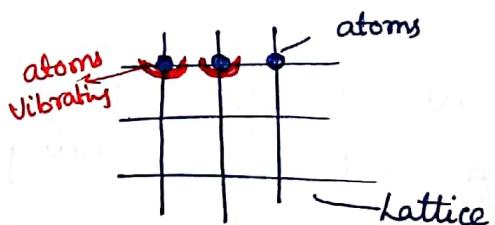
above $T = 300K$, e^- gains enough KE and Impurity scattering is no more observed, $\mu \uparrow^{ed}$.

- * Lattice Scattering : Here a carrier moving through the crystal is scattered by a vibration of the lattice, resulting from the temperature.
- The scattering increases as the temperature increases, as the thermal agitation of the lattice becomes greater, decrease in mobility is expected as the sample is heated.

[Note : Lattice Scattering \uparrow , RE \downarrow , $\mu \downarrow$ at $T > 300K$.]

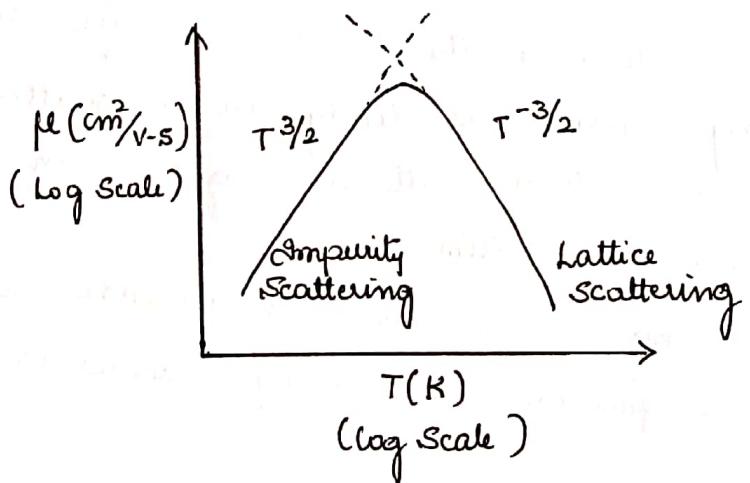


(a) Impurity Scattering



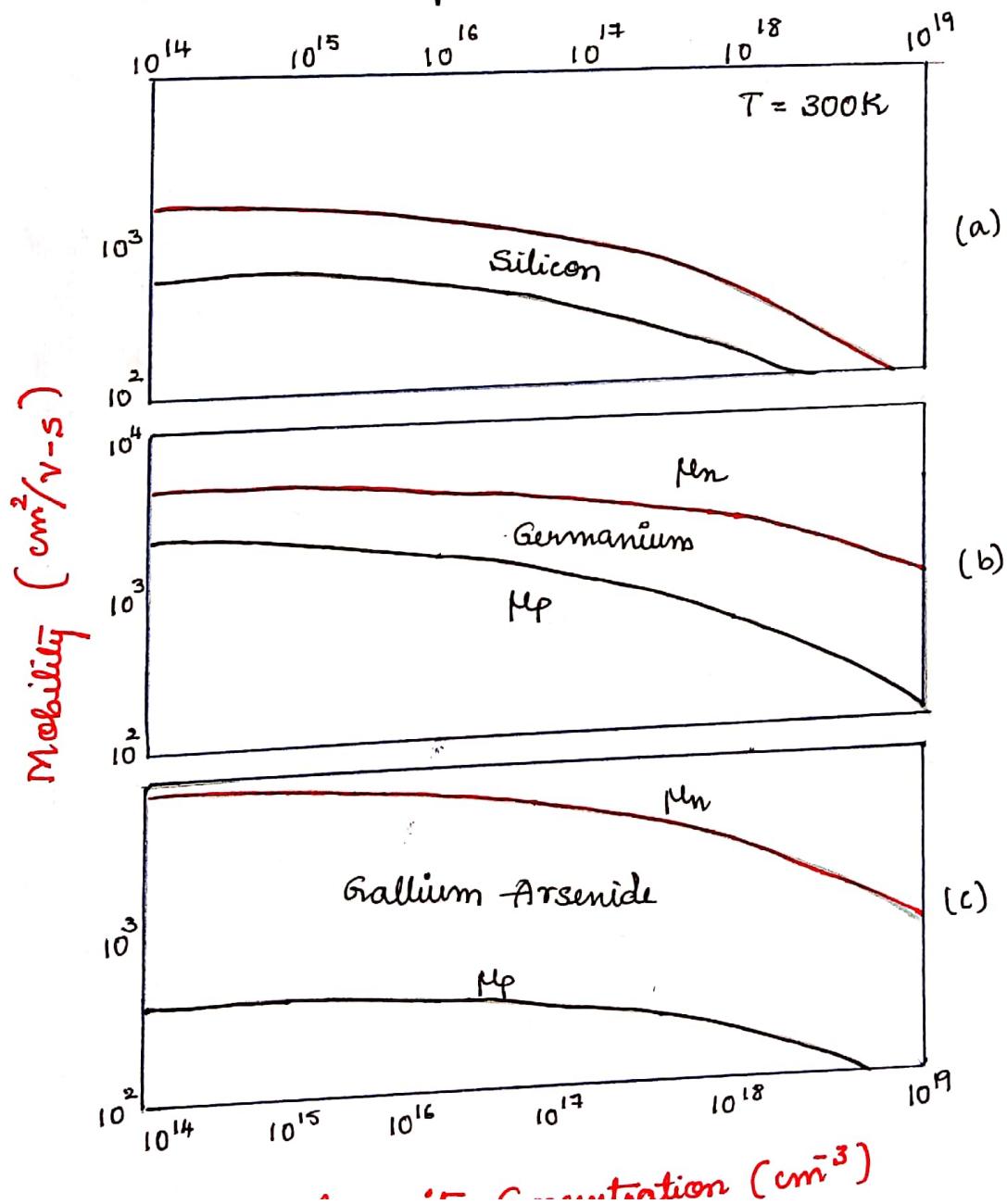
(b) Lattice Scattering.]

- * Below room temperature ($300K$) Impurity Scattering dominates Lattice Scattering and above room temp ($300K$) Lattice Scattering dominates impurity scattering.



- * As the concentration of impurities increases, the effects of impurity scattering are felt at higher temperatures.

Ex: The electron mobility μ_n of intrinsic silicon at 300K is $1350 \text{ cm}^2/\text{V}\cdot\text{s}$ with a donor doping concentration of 10^{17} cm^{-3} , however μ_n is $700 \text{ cm}^2/\text{V}\cdot\text{s}$. Thus the presence of the 10^{17} ionized donors/ cm^3 introduces a significant amount of impurity scattering. This effect is illustrated in fig below, which shows the variation of mobility with doping concentration at room temperature.



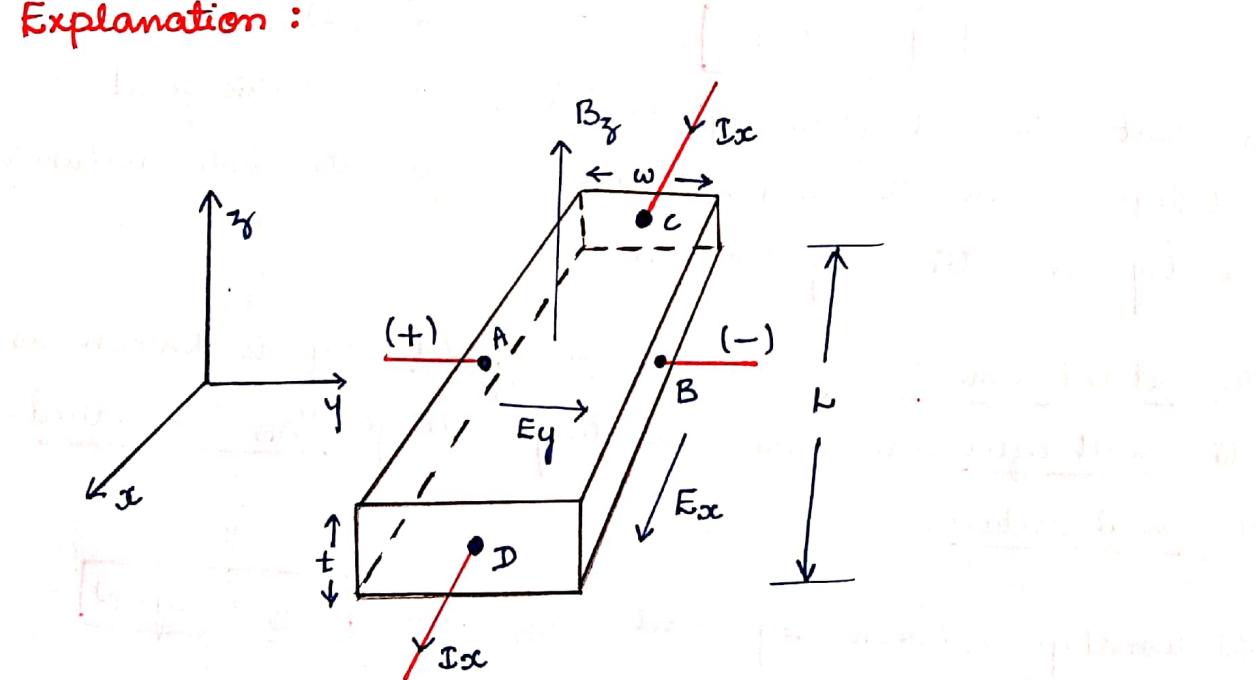
Hall Effect :

When a magnetic field is applied to a current carrying conductor in a direction perpendicular to that of the flow of current, a potential difference or electric field is created across a conductor. This phenomenon is known as Hall effect.

Application :

1. It is used to find type of semiconductor.
2. It is used to find carrier concentration (n, p_0), to calculate mobility of charge carriers, measure conductivity ...

Explanation :



- * If a magnetic field is applied perpendicular to the direction in which holes drift in a p-type bar, the path of the holes tends to be deflected.

- * The total force on a single hole due to the electric and magnetic field is

$$F = q(E + v \times B)$$

- * In the $-y$ -direction, the force is given by

$$F_y = q(E_y - v_x B_z) \rightarrow (1)$$

unless an electric field E_y is established along the width of the bar, each hole will experience a net force in $-y$ direction due to $q v_x B_z$ product.

- * To maintain a steady state flow of holes down the length of the bar, E_y must balance the product $v_x B_z$.

$$E_y = v_x B_z \rightarrow (2)$$

so that the net force F_y is zero. This electric field is set up when the magnetic field shifts the hole distribution slightly in the $-y$ -direction.

- * The establishment of the electric field E_y is known as the Hall effect and the resulting voltage V_{AB} is called the Hall voltage.

- * Relationship between E_y and V_{AB} is $V_{AB} = E_y \cdot W$ - (3)

- * W.K.T current density of hole is $J_x = q_p v_x$

$$(from 2) \therefore E_y = \frac{J_x \cdot B_z}{q_p} = J_x R_H B_z \rightarrow (4)$$

where $R_H = \frac{1}{q_p p_0}$ $\rightarrow (5)$ is Hall co-efficient.

* To determine carrier concentration P_0 .

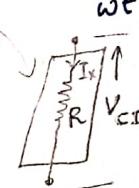
$$P_0 = \frac{1}{qR_H} = \frac{1}{q \left(\frac{E_y}{I_x B_z} \right)} = \frac{I_x B_z}{q E_y} = \frac{\left(\frac{I_x}{wt} \right) B_z}{q \left(\frac{V_{AB}}{w} \right)} = \frac{I_x B_z}{q t V_{AB}} \rightarrow ⑥$$

$$\therefore P_0 = \frac{I_x B_z}{q t V_{AB}} \quad (\text{from 3})$$

* If a measurement of resistance R is made, resistivity σ can be calculated as

$$\sigma (\Omega \cdot \text{cm}) = \frac{R \cdot wt}{L} = \frac{R}{\frac{L}{wt}} = \frac{V_{CD}}{I_x} \quad \therefore R = \frac{\sigma L}{wt}$$

$$\sigma (\Omega \cdot \text{cm}) = \frac{V_{CD}/I_x}{L/wt} \rightarrow ⑦$$



* Conductivity is given by $\sigma = \frac{1}{\rho} = q \mu_p P_0 \rightarrow ⑧$

$$\therefore \text{mobility is given by } \mu_p = \frac{1}{\sigma q P_0} = \frac{1}{\sigma \left(\frac{1}{R_H} \right)} = \frac{R_H}{\sigma}$$

$$\mu_p = \frac{R_H}{\sigma} \rightarrow ⑨$$

Note : 1: Above discussions are related to P-type material.

for n-type material

V_{AB} — negative

q → $-q$

R_H → $-R_H$

2. Measurement of sign of Hall voltage V_{AB} is common technique for determining the unknown sample as p-type or n-type.

Problem

1. Semiconductor bar has $w = 0.1 \text{ mm}$, $t = 10 \mu\text{m}$ and $L = 5 \text{ mm}$
 For $B = 10 \text{ kG}$ in z -direction ($1 \text{ kG} = 10^{-5} \text{ wb/cm}^2$) and
 a current of 1 mA , $V_{AB} = -2 \text{ mV}$ and $V_{CD} = 100 \text{ mV}$
 Find the type, concentration and mobility of the
 majority carrier.

Solution : $w = 0.1 \text{ mm} \quad (10 \mu\text{m} = 0.01 \text{ cm}) \quad t = 10 \mu\text{m} \quad (0.5 \text{ cm}) \quad L = 5 \text{ mm} \quad I = 1 \text{ mA}$
 $B = 10 \text{ kG} = 10^{-4} \text{ wb/cm}^2 \quad V_{AB} = -2 \text{ mV}$
 $V_{CD} = 100 \text{ mV}$.

As $V_{AB} = -2 \text{ mV}$, majority carriers are electrons.

(*) \therefore it is n-type material

(*) concentration $n_0 = \frac{I_x B_z}{q + (-V_{AB})} = \frac{(10^{-3})(10^{-4})}{(1.6 \times 10^{19})(2 \times 10^{-3})(10 \mu\text{m})} = 3.125 \times 10^{17} \text{ cm}^{-3}$

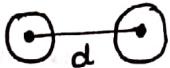
$$\rho = \frac{R}{L/wt} = \frac{V_{CD}/I_x}{L/wt} = \frac{0.1/10^{-3}}{0.5/0.01 \times 10^{-3}} = 0.002 \Omega \cdot \text{cm}$$

(*) $\mu_n = \frac{1}{\rho q n_0} = \frac{1}{(0.002)(1.6 \times 10^{19})(3.125 \times 10^{17})} = 10,000 \text{ cm}^2 (\text{v} \cdot \text{s})^{-1}$

Definitions to be Recalled:

Intratomic Spacing :

It is the distance between the nuclei of atoms in a material.



Lattice :

It is a 3-dimensional arrangement of constituent particles (atoms, molecules, ions) of crystalline solids.

Hybridization :

It is the mixing of standard atomic orbitals to form new orbitals which can be used to describe bonding in molecules. we have sp , sp^2 , sp^3 hybridization.

Propagation Constant :

The propagation constant of a sinusoidal electromagnetic wave is a measure of the change undergone by the amplitude and phase of the wave as it propagates in a given direction.

Momentum :

- * It refers to the quantity of motion that an object has.
- * If an object is in motion (on the move) then it has momentum.
- * It is defined as "mass in motion"

Electron Probability Density :

It is the measure of the probability of an electron being present at a specific location.

Velocity :

It is defined as the rate of change of position with respect to time. Unit : m/s

Acceleration : the rate of change of velocity per unit of time.

Unit : m/s^2 (increase in speed or rate)

Deceleration : It is the rate at which an object slows down (decrease in speed) (opposite of acceleration)

Drift : to become driven or carried along

Magnetic field and Electric field :

Magnetic field is an exerted area around the magnetic force while Electric fields are generated around the particles which obtains electric charge.

What is the effect of electric field on charged particle?

Electric field (force of net motion) acts on charged particles.

Electric field seems to act towards the negative charge.