LESSON -1

PHYSICS OF SEMICONDUCTOR

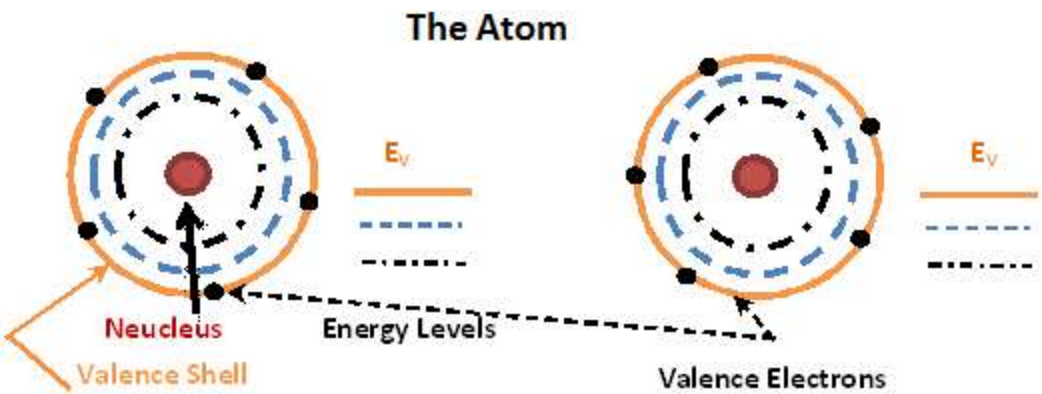


Fig. 1 – *Isolated Atoms (in a vapour state) and associated Energy Levels at Ground State .*

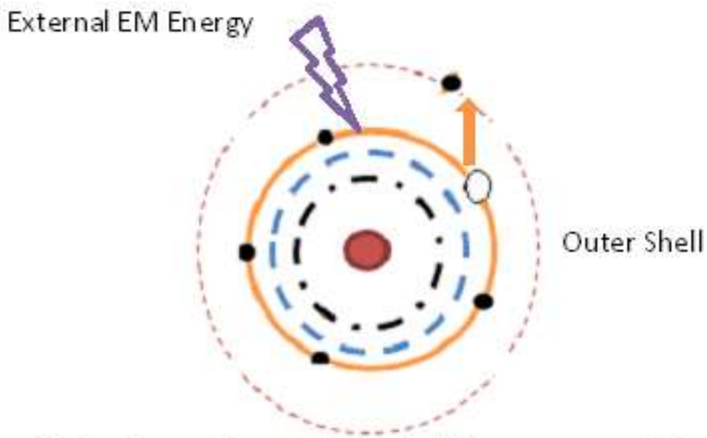


Fig. 2 – *Due to Externally Applied Electromagnetic Energy, Valence Shell Electron jumps to Higher Energy Outer Shell .*

Energy Band Theory of Crystals

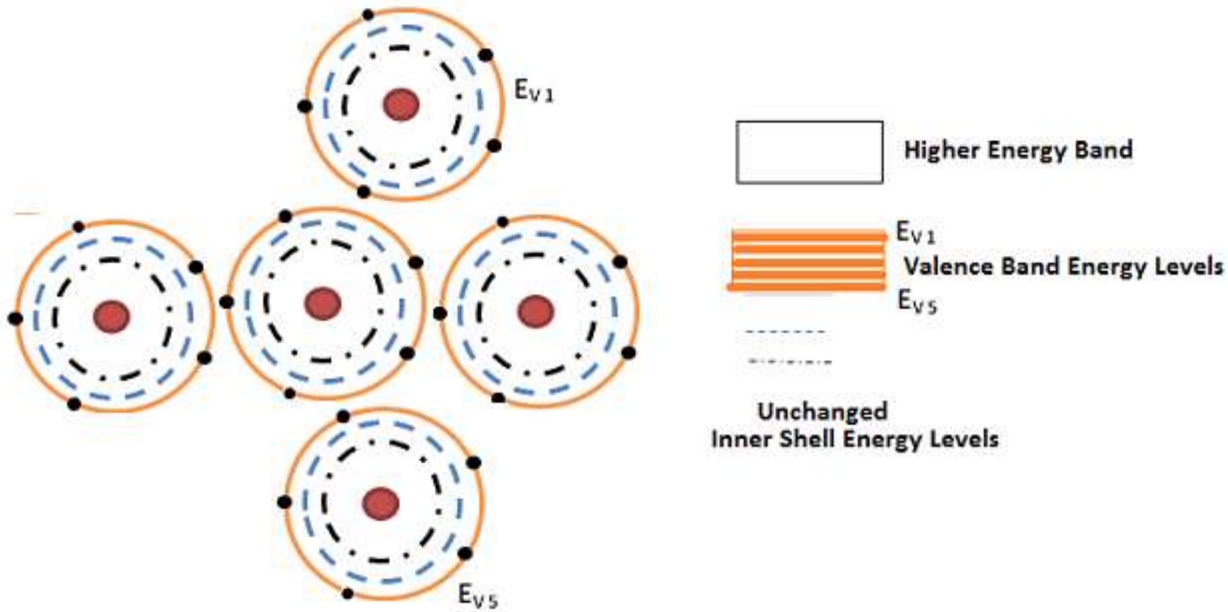


Fig. 3 – *Spreading out of the Valence Shell energy levels into a Band (Valence band)*

Conductors, Insulators & Semi-Conductors

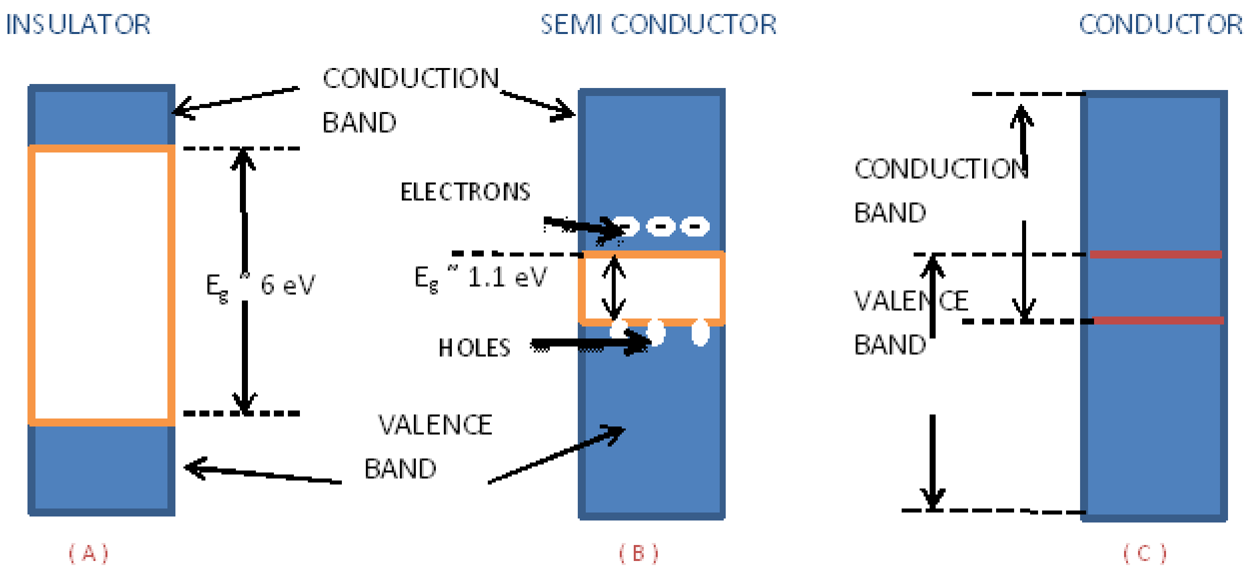
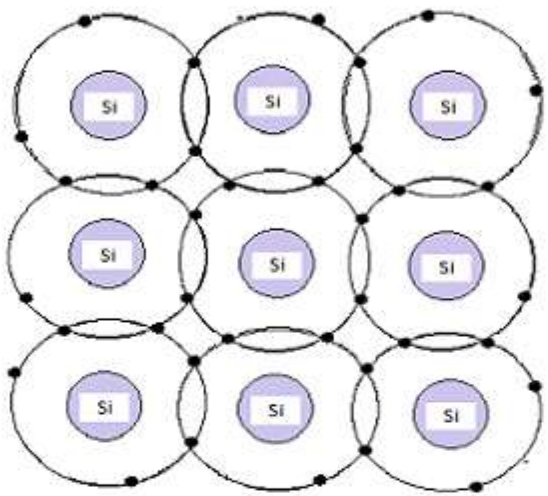


Fig. 4 - A crystal having Energy Gap E_g nearly about 6 eV is an Insulator. Where the Valance Band and Conduction Band merge, the crystal is that of a Conductor. When Energy Gap E_g is nearly 1 eV, the crystal is that of a Semi-Conductor.

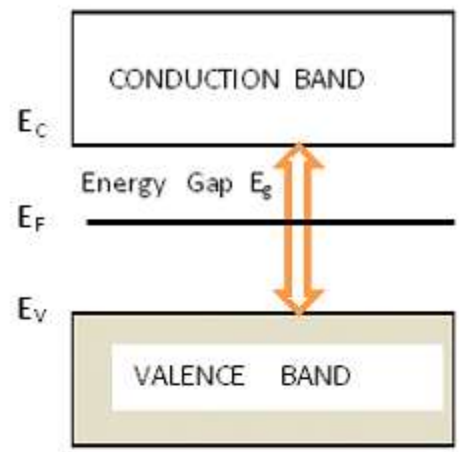
Silicon Crystal

Table 1 Electronic Configuration of Group-4(A) Elements

Element	Atomic Number	Electronic Configuration
C	6	$1s^2$; $2s^2$, $2p^2$
Si	14	$1s^2$; $2s^2$, $2p^6$; $3s^2$, $3p^2$
Ge	32	$1s^2$; $2s^2$, $2p^6$; $3s^2$, $3p^6$, $3d^{10}$; $4s^2$, $4p^2$
Sn	50	$1s^2$; $2s^2$, $2p^6$; $3s^2$, $3p^6$, $3d^{10}$; $4s^2$, $4p^6$, $4d^{10}$; $5s^2$, $5p^2$



Crystal Structure of Si



Energy Band Diagram

Fig. – 5. Crystal of Intrinsic Silicon and the Energy Band Diagram at near about Absolute Zero temperature. All valence electrons are bound to the valence band and conduction band is unocc

INTRINSIC SEMICONDUCTOR AT ROOM TEMPERATURE

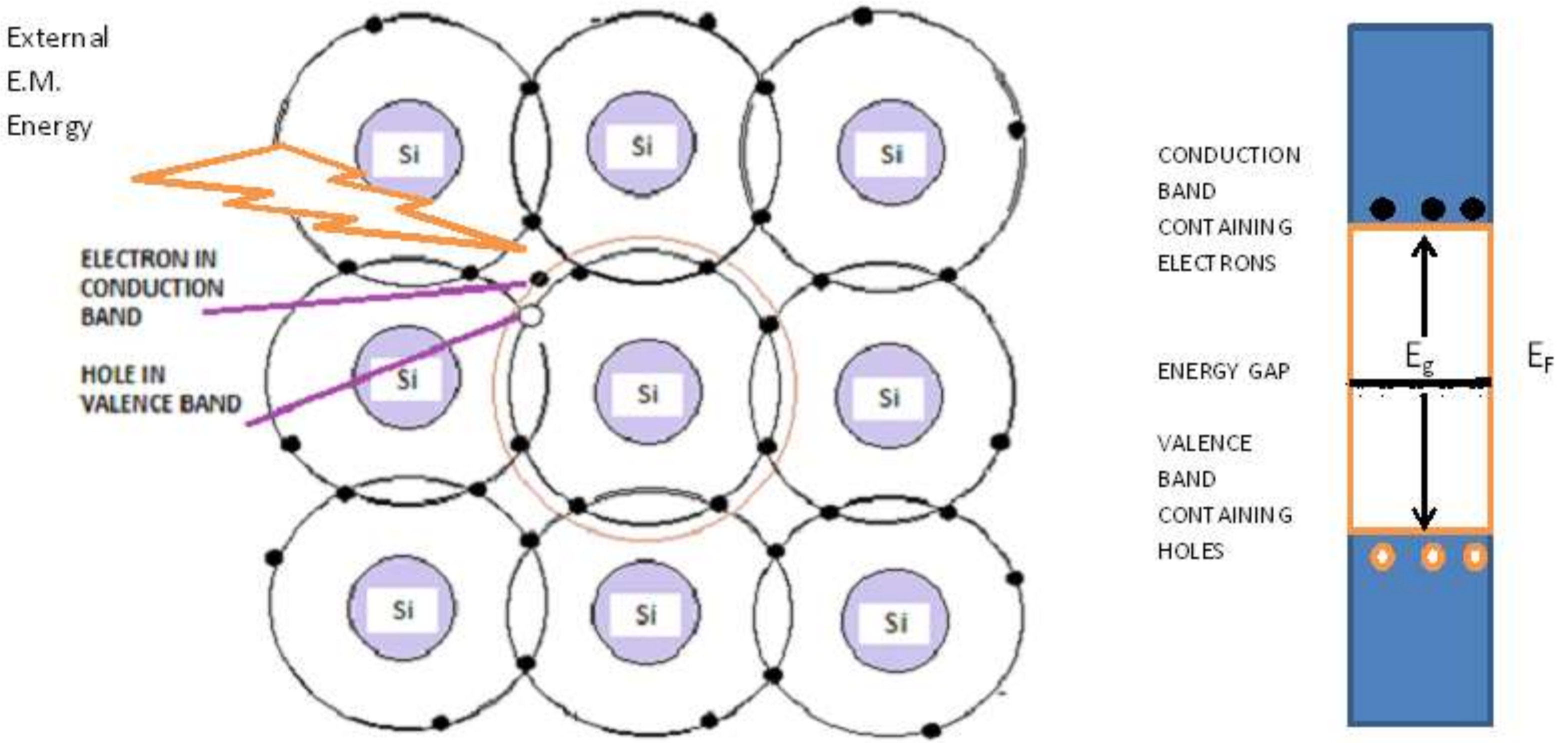


Fig. -6. *Energy Band diagram of intrinsic Si at normal room temperature and normal day light with free electrons in Conduction Band and holes in Valence Band. Both these entities namely the electrons in CB and holes in VB are carriers of current in intrinsic semiconductor.*

Intrinsic Concentration and Mass Action Law

The quantities concentration of free electrons in CB and concentration of holes in VB of an intrinsic semiconductor are called '*Intrinsic Concentration*'. These are denoted by n_i and h_i respectively, and given by the following equations.

$$n_i = 2\ \left(\frac{2\pi mqkT}{h^2}\right)^{3/2} e^{-(E - E_F)/kT} = N_C\ e^{-(E_C - E_F)/kT} \qquad .....(1)$$

$$h_i = N_V e^{-(E_F - E_V)/kT} \qquad .....(2)$$

Where, N_C and N_V are constants having dimensions of 'concentration', (i.e. number per cubic metre)

However in an intrinsic semiconductor n_i = hi. Thus we have

The Mass Action Law states that product of n_i and h_i is a constant given by

$$n_i . h_i = n_i^2 = h_i^2$$

Substituting from equations 1 and 2 and simplifying we have

$$n_i^2 = h_i^2 = N_C N_V e^{-(E_C - E_V)/kT} = N_C N_V e^{-E_g/kT}$$

(Since $(E_C - E_V)$ is nothing but the Energy Gap E_g)

$$E_g = E_{G0} - \beta T$$

Where E_{G0} is the energy gap at 0^0K, and this quantity is a property of the crystal, whose value is 1.21 eV in Si and 0.785 eV in Ge. The quantity β is a constant, whose value is 3.60 x 10^{-4} in Si and 2.23 x 10^{-4} in Ge.

The constants N_C and N_V contain the various physical constants, namely, mass of electron m, effective mass of hole m_h, charge of electron q, charge of hole, Boltzmann constant k and Planck's constant h. Substituting we get E_g, and n_i^2 in terms of a constant A_o.

Value of A_o for various semiconductor materials is tabulated in Table : 1.2 below.

$$n_i^2 = A_o T^3\ e^{-E_g/kT} \qquad .....(3)$$

Tab :– 2 Semiconductor Constants

Semiconductor Material	Value of E_g (eV)	Value of A_o $cm^{-6}\,{}^oK^{-3}$
Si	1.1	2.735×10^{31}
Ga As	1.5	4.41×10^{28}
Ge	0.72	2.756×10^{31}

Fermi Level in Intrinsic Semiconductor

$$E_F = \frac{E_C - E_V}{2} \quad \text{.....(4)}$$

This shows that Fermi Level in an Intrinsic Semiconductor lies in the middle of the energy levels E_C and E_V

INTRINSIC EFFECT

Example 1.1 : – Calculate Intrinsic Concentration in (a) silicon (b) GaAs and (c) Germanium crystals at a room temperature of (i) 300^0K , (ii) 310^0K and (iii) 290^0K.

Solution :- Substituting the numerical values of the quantities from the Table 1.2, using the value of Boltzmann Constant k = 86x 10^{-6} $eV/^0K$ and taking appropriate room temperatures of (i) 300^0K and (ii) 310^0K and (iii) 290^0K

(a) For Si (i) at 300^0K $n_i^2 = 2.735 \text{ x } 10^{31} \text{x } 300^3 \text{ x } e^{(-1.1/86x10^{-6}x300)}$

$= 2.25x10^{20}$

$n_i = 1.5 \text{ x}10^{10}$ intrinsic electrons/cm^3 (at 300^0K)

(ii) at 310^0K$n_i^2 = 2.735 \text{ x } 10^{31} \text{x } 310^3 \text{ x } e^{(-1.1/86x10^{-6}x310)}$

$= 9.81x10^{20}$

$n_i = 3.1 \text{ x}10^{10}$ intrinsic electrons/cm^3 (at 310^0K)

$= 6.7x10^{10}$

(b) For GaAs (i) at 300^0K $n_i^2 = 4.41\text{x } 10^{28} \text{x } 300^3 \text{ x } e^{(-1.5/86x10^{-6}x300)}$

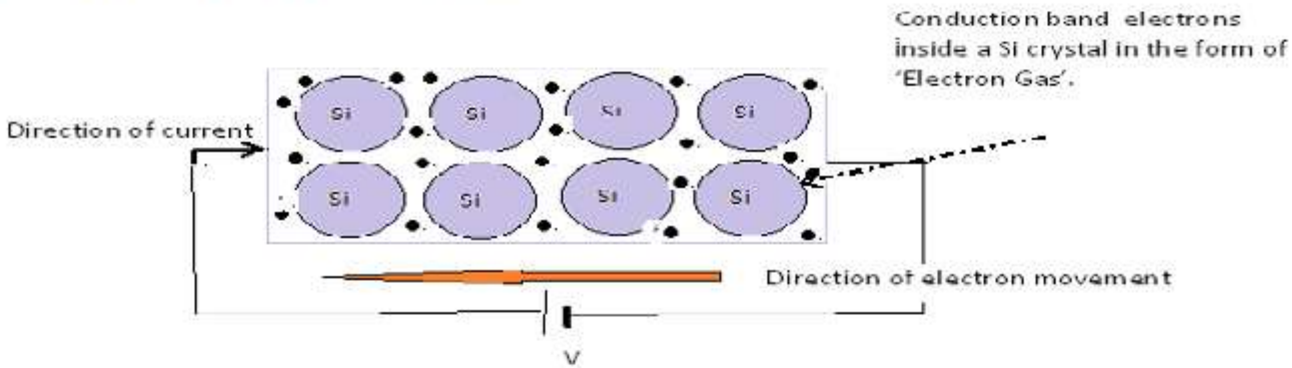
$n_i = 2.6 \text{ x}10^5$ intrinsic electrons/cm^3 (at 300^0K)

(ii) at 310^0K $n_i^2 = 4.41\text{x } 10^{28} \text{x } 310^3 \text{ x } e^{(-1.5/86x10^{-6}x310)}$

$= 48x10^{10}$

CURRENT FLOW IN ITRINSIC SEMICONDUCTOR

Electron Current in Intrinsic Semiconductor



Hole Current in Intrinsic Semiconductor

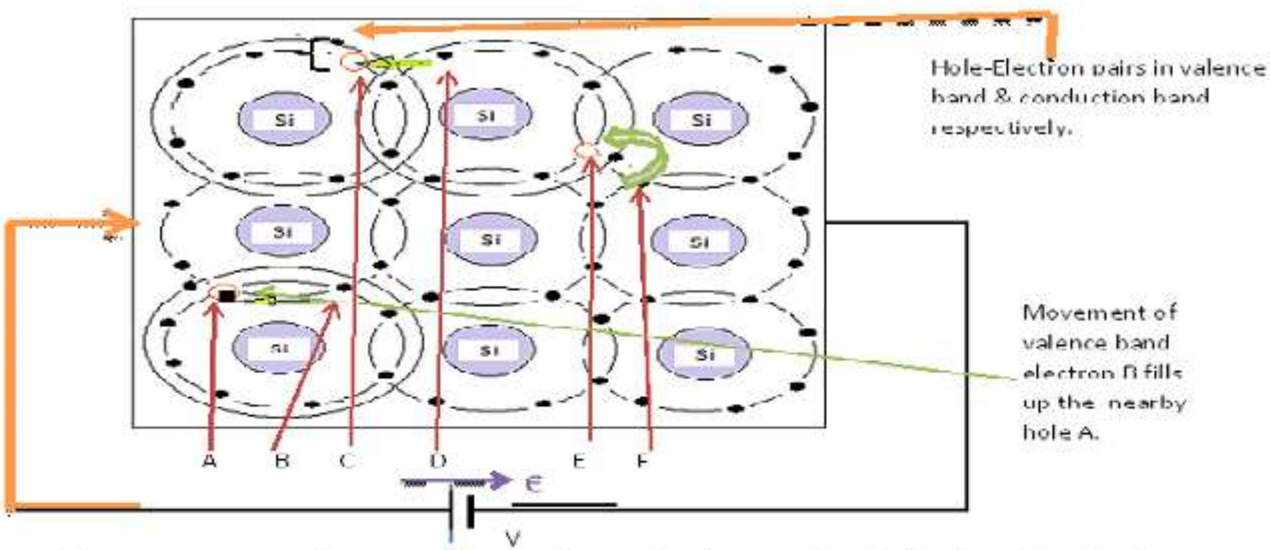


Fig. -7. Electron Current :- *Electrons of the conduction band are uniformly distributed within the intrinsic semiconductor in the form of an 'Electron Gas'. An external electric potential imparts motion from Negative potential to Positive potential .The resulting current flow is IN OPPOSITE DIRECTION.*

Hole Current :- *Direction of hole movement (green) and direction of current (brown) due to the Electric Field* ***Є***

Total current :- It is observed in Fig.-7 that the direction of current due to movement of electrons and holes are in the same direction. Thus total current is

$$I = I_h + I_e$$

In an Intrinsic Semiconductor, the number of electrons and holes are equal.

$$I_h = I_e$$

And $$I = 2\,I_h \;\&\; I = 2\,I_e$$

Drift Current & Diffusion Current

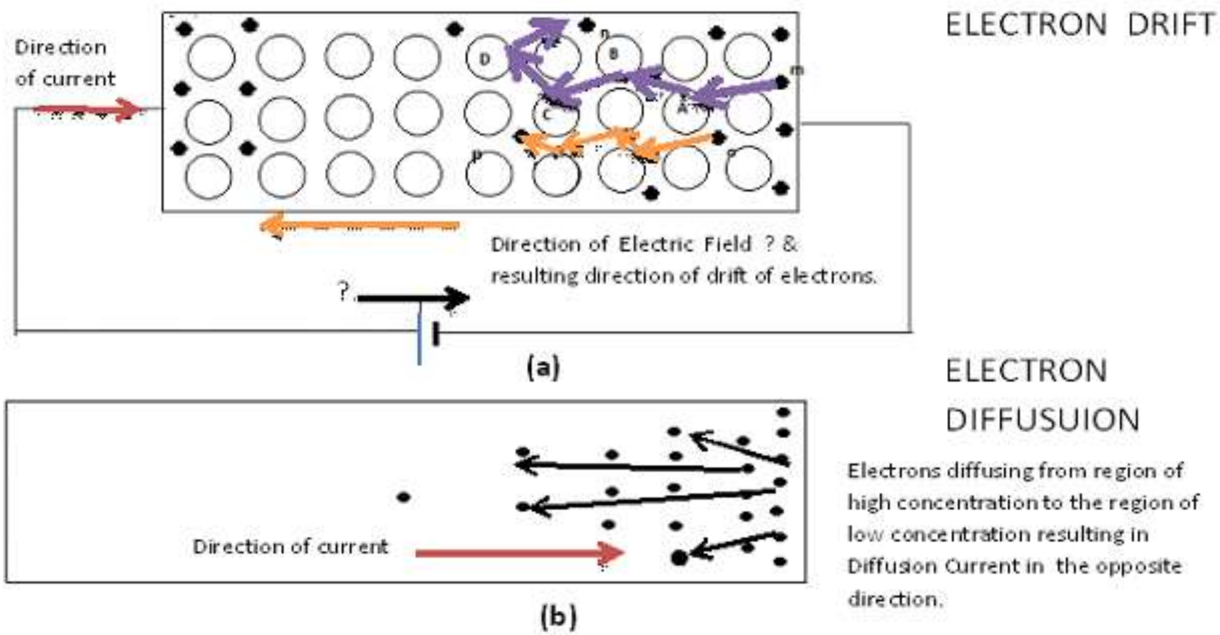


Fig. – 8 *Drift Current and Diffusion Current in semiconductors*

(c) For Ge (i) at 300^0K $n_i^2 = 2.756\text{x } 10^{31}\text{x } 300^3 \text{ x } e^{(-0.72/86x10^{-6}x300)}$

$= 5.65\text{x}10^{26}$

$n_i = 2.38\text{x}10^{13}$ intrinsic electrons/cm^3 (at 300^0K)

(ii) at $310^0K n_i^2 = 2.756\text{x } 10^{31}\text{x } 310^3 \text{ x } e^{(-0.72/86x10^{-6}x310)}$

$= 32.5\text{x}10^{26}$

$n_i = 5.7\text{x}10^{13}$ intrinsic electrons/cm^3 (at 310^0K)

(iii) at $290^0K n_i^2 = 2.756 \text{ x } 10^{31}\text{x } 290^3 \text{ x } e^{(-0.72/86x10^{-6}x290)}$

$= 1.95\text{x}10^{26}$

$n_i = 1.39\text{x}10^{13}$ intrinsic electrons/cm^3 (at 290^0K)

OBSERVATION:- As room temperature increases by 10^0 the concentration of free electrons (intrinsic concentration) increases two fold and when temperature decreases by 10^0 the intrinsic concentration reduces to half the value. ***THIS IS KNOWN AS "INTRINSIC EFFECT"***

INTRINSIC EFFECT :- This can be summarized as

1. **Current in an intrinsic semiconductor is proportional to the amount of electromagnetic energy in the surroundings.**
2. **Current in an intrinsic semiconductor varies by a factor of 2 for every 10^0 K change in surrounding temperature. Say, if current in an intrinsic semiconductor at a room temperature of 300^0K is 10 μA, then at 310^0K it will increase to 20 μA and at 290^0K it will decease to 5 μA.**

Drift Current :--

- Drift velocity of the electrons 'v_e' and Drift velocity of holes 'v_h' due to the electric field ϵ is proportional to ϵ are .

- The Proportionality Constants μ_e and μ_h are termed as '**Mobility of Electron**' and '**Mobility of Hole**' respectively. These have the unit in cm^2/(volt sec)

$$v_e = \mu_e \epsilon \qquad v_h = \mu_h \epsilon$$

If the concentration of electrons and holes are n_i and h_i respectively, then current density for current due to electrons and holes are given by

$$J_e = n_i\, q\, v_e \qquad J_h = n_i\, q_h v_h$$

$$J_e = n_i\, q\, \mu_e \epsilon \qquad J_h = n_i\, q_h \mu_h \epsilon$$

$$J_e = \sigma_e \epsilon \qquad J_h = \sigma_h \epsilon$$

Where q = charge of electron = 1.602×10^{-19} C

σ_e = Conductivity of the semiconductor due to electrons.

And σ_h = Conductivity of the semiconductor due to holes.

Total current density

$$J = J_e + J_h$$

$$J = n_i\, q\, \mu_e \epsilon + n_i\, q_h\, \mu_h \epsilon$$

$$J = (\mu_e + \mu_h) n_i\, q\, \epsilon$$

$$J = \sigma \epsilon \qquad .....(5)$$

Where σ, i.e. the conductivity of the semiconductor in units of 'Ohm per centimeter' (
given by $\sigma = (\mu_e + \mu_h) n_i\, q$

It may be noted that Eq. 5 is nothing but another representation of Ohm's Law.

Diffusion Current :-

- The term Diffusion Current is applicable only to semiconductors.
- Diffusion current is proportional to the concentration gradient of electrons

$$J_e \propto -q\frac{dn}{dx}$$

The constant of proportionality is the '**Diffusion Constant'**, D_e

Thus Current Density due to diffusion of Electrons

$$J_e = qD_e\frac{dn}{dx}$$

- The ' Diffusion Constant' D_e is related to 'Mobility of electron' μ_e as

$$\frac{D_e}{\mu_e} = V_T$$

Similarly for Holes in the VB ,Current Density due to diffusion

$$J_h = q_h \; D_h \frac{dh}{dx}$$

- The ' Diffusion Constant' D_h is related to 'Mobility of hole' μ_h as

$$\frac{D_h}{\mu_h} = V_T.$$

- This relationship is known as the **Einstein's Equation**. The quantity V_T is called 'Volt Equivalent of Temperature' and it is given by

$$V_T = \frac{kT}{q} \qquad .....(6)$$

Where k = Boltzmann Constant = 1.381×10^{-23} J/^{0}K = 8.62×10^{-5} eV/^{o}K.

T = Room Temperature in ^{0}K.

q = Charge of the electron = 1.602×10^{-19} C

Substituting these constants and assuming room temperature of 300^0K

$$V_T = \frac{T}{11600}$$

$$V_T = \frac{300}{11600} = 0.02586 \text{ V} \quad \text{or} \quad 26 \text{ mV} \qquad \text{....(7)}$$

NOTE :: To be noted that in case of semiconductors , in any given instant of time there will either be the diffusion of electrons only, or diffusion of holes only, but not both together. This is unlike Drift Current, which is caused by drift of electrons as well as holes, together.

Silicon and Germanium

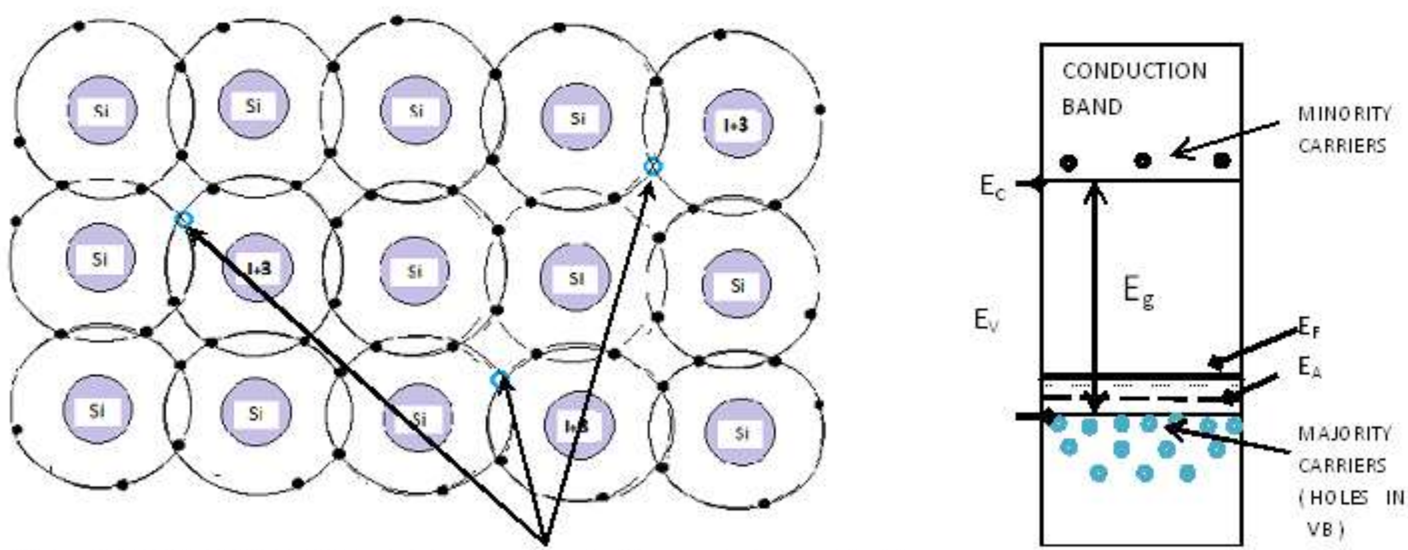
Table- 3 : Comparison of the physical properties of Ge & Si.

Property	Germanium	Silicon
Atomic Number	32	14
Atomic Weight	72.6	28.1
Density of packing of atoms in crystal (Atoms/cm^3)	4.4×10^{22}	5.0×10^{22}
Energy Gap E_g at 300^0 K (eV) Energy Gap at 0^0K E_{GO} (eV)	0.72 0.785	1.1 1.21
Intrinsic Concentration at 300^0 K n_i (cm^{-3})	2.5×10^{13}	1.5×10^{10}
Intrinsic Resistivity at 300^0 K (Ω-cm)	45	2,30,000
Mobility of Conduction Band Electrons μ_e (cm^2/ V-sec)	3,800	1,300
Mobility of Valence Band Holes μ_h (cm^2/ V-sec)	1,800	500
Diffusion Constant of Conduction Band Electrons $D_e = \mu_e V_T$ (cm^2/sec)	99	34
Diffusion Constant of Valence Band Holes $D_h = \mu_h V_T$ (cm^2/sec)	47	13

EXTRINSIC SEMICONDUCTOR

p-type Extrinsic Semiconductor and Acceptor Impurity

When a pure crystal, say a crystal of silicon or germanium is doped with a trivalent element such as boron (B), gallium (Ga) or indium (In), we have a p-type extrinsic semiconductor and the added impurity element is called an **Acceptor Impurity**.



Holes (MAJORITY CARRIERS) in the Valence Band of Acceptor Impurity Atoms

Fig. – 9 *Formation of p-type extrinsic semiconductor due to doping by trivalent impurity* I^{+3} *(Acceptor Impurity) and Energy Band Diagram .*

n-type Extrinsic Semiconductor and Donor Impurity

When a pure crystal of silicon or germanium is doped with a pentavalent element such as phosphorus (p), antimony (Sb) or arsenic (As), we have a n-type extrinsic semiconductor and the added impurity element is called a Donor Impurity.

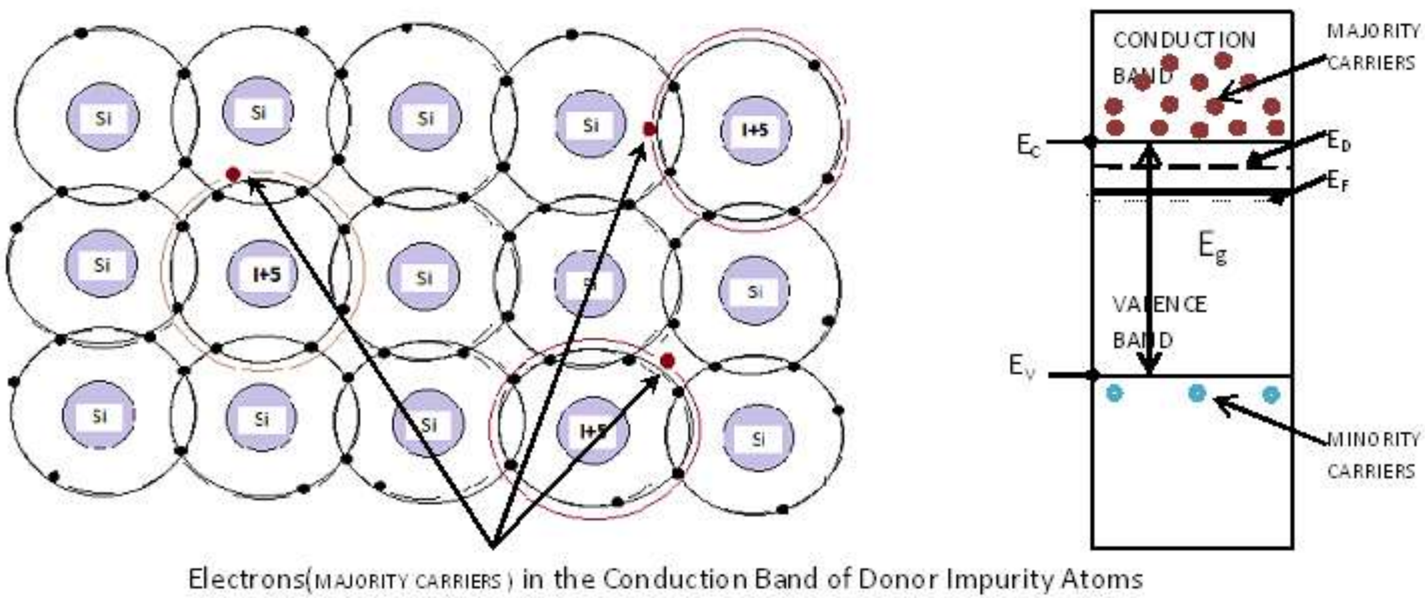


Fig. −10 *Formation of n-type extrinsic semiconductor due to doping by pentavalent impurity* I^{+5} *(Donor Impurity). And the Energy Band Diagram.*

Majority Carriers and **Minority carriers**

Holes created due to Doping with Acceptor impurity are the **Majority Carriers .**
The intrinsic effect also occurs in the extrinsic semiconductor. Due to this some electron-hole pairs are created. Among these, electrons in the Conduction Band are the **Minority carriers .**

Electrons created in the CB due to Doping with Donor impurity are the **Majority Carriers .**
Holes in the VB of the electron-hole pairs created due to Intrinsic Effect are the **Minority carriers .**

Carrier concentration in Extrinsic Semiconductor

- Mass Action Law stated that the product of the concentrations of free electrons 'n_i' and holes 'h_i' in an intrinsic semiconductor is a constant equal to n_i^2 .
- This relationship is valid for extrinsic semiconductors as well.
- Recall also that in an extrinsic semiconductor, that introduction of each dope atom results in the creation of one majority carrier. Neglecting the additional majority carriers generated by Intrinsic Effect, we can assume that --

Majority carrier concentration equals the concentration of doping.

$n_n \sim N_D$ AND $h_p \sim N_A$

- Now, Mass Action Law for a n-type semiconductor will take the form

$$n_n \,.\, h_n = n_i^2$$

The subscript n indicates that the quantities n_n and h_n represent concentration of **majority carrier electrons and minority carrier holes**, in the n-type semiconductor.

Substituting $n_n = N_D$

$$h_n = n_i^2 / N_D \qquad .....(8)$$

- And, Mass Action Law for a p-type semiconductor will take the form

$$h_p \,.\, n_p = n_i^2$$

The subscript p indicates that the quantities n_p and h_p represent concentration of **majority carrier holes and minority carrier electrons**, in the p-type semiconductor.

Substituting $h_p = N_A$

$$n_p = n_i^2 / N_A \qquad .....(9)$$

Example 1.2 :- Calculate the concentrations of electrons and holes in a n-type Si crystal which is doped with a donor concentration of 10^{17} per cm^3. Assume thermal equilibrium conditions at 300^0K.

Solution :: Since this is a n-type crystal, we have

$n_n \sim N_D = 10^{17}\ cm^{-3}$

This is the concentration of Majority Carrier electrons.

From Eq. 8 we have the concentration of holes (Minority Carriers) as

$h_n = n_i^2 / N_D$

From Table 1.3 the value of the constant n_i for Si is $n_i = 1.5 \times 10^{10}$

Substituting

$$h_n = \frac{(1.5 \times 10^{10})^2}{10^{17}} = 1.5 \text{ X } 10^3$$

Example 1.3 :- Calculate the concentrations of holes and electrons in a p-type Ge crystal which is doped with an acceptor impurity concentration of 10^{20} per cm^3. Assume thermal equilibrium conditions at 300^0K.

Solution :: Since this is a p-type crystal, we have

$h_p = N_A = 10^{20}\ cm^{-3}$

This is the concentration of Majority Carrier holes.

From Eq. 9 we have the concentration of electrons (Minority Carriers) as

$n_p = n_i^2 / N_A$

From Table 1.3 the value of the constant n_i for Ge is $n_i = 2.5 \times 10^{13}$

Substituting

$$n_p = \frac{(2.5 \times 10^{13})^2}{10^{20}} = 2.5 \text{ X } 10^6$$

OBSERVATIONS ::

OBSERVATIONS ::

1. It is observed that the concentration of the "minority Carrier" holes in the n-type semiconductor crystal is negligible compared to the concentration of the "Majority Carriers". The same is true for the p-type semiconductor crystal .

2. Minority Carrier Concentration in Si is 10^{-3} times that of Ge. In other words, Si forms a much better Extrinsic Semiconductor compared to Ge.

SLIDE -1

LESSON – 2

THE P-N JUNCTION

- **A P-N junction is the physical union of a P-type Semiconductor with a N-type Semiconductor.**
- The p-n junctions form the backbone of the Electronics Industry and are found in all Semiconductor Based Electronic Devices.
- The single p-n junction functions as the Diode, which is primarily used to convert AC into DC.
- There are some special purpose diodes, manufactured for specific purposes, such as the LED , Photo Diode etc,
- The Bi Junction Transistor, that is used for amplifying and for the purpose of switching, is composed of two p-n junctions.
- Heavy Duty Power Control Equipments, that are capable of handling Mega-Watts of Electrical Power, are composed of a certain class of electronic devices, called Thyristors, which contain three p-n junctions.
- A Logic Gate is a circuit consisting of a number of switching transistors. Logic Gates in various combinations make various types of Digital Processors.

P-N Junction in Equilibrium Condition

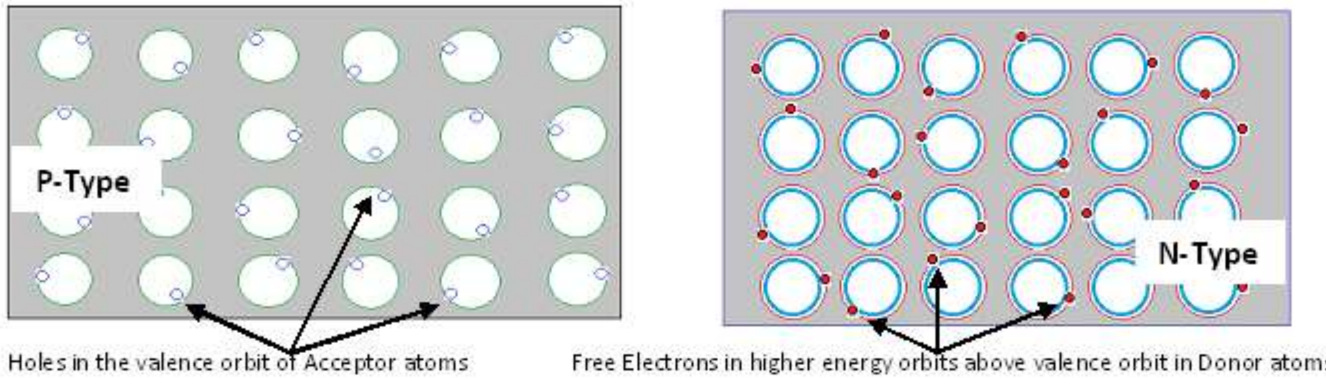


Fig- 1. *Extrinsic Semiconductor crystals showing Holes in the valence orbits of the Acceptor Atoms, which lie in the Valence Band(VB) in P-Type material and Free Electrons in the higher energy orbits of the Donor Atoms of the in N-Type material, which lie in the Conduction Band (CB).*

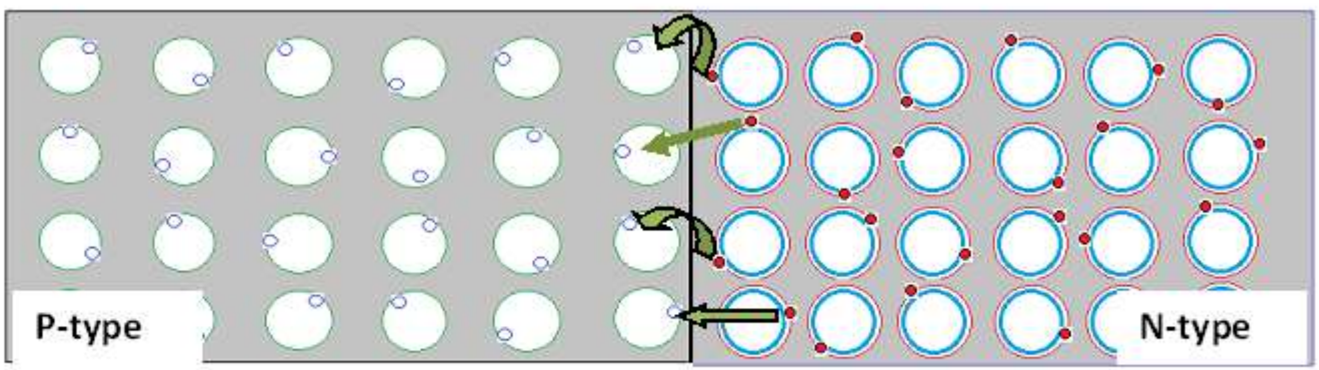


Fig- 2 : Movement of Majority Carriers across the junction. *Free Electrons of the higher energy Conduction Band (CB) orbits are crossing the junction from N-Type material and filling up holes in the lower energy Valence Band (VB) orbits across the junction in the P-Type material.*

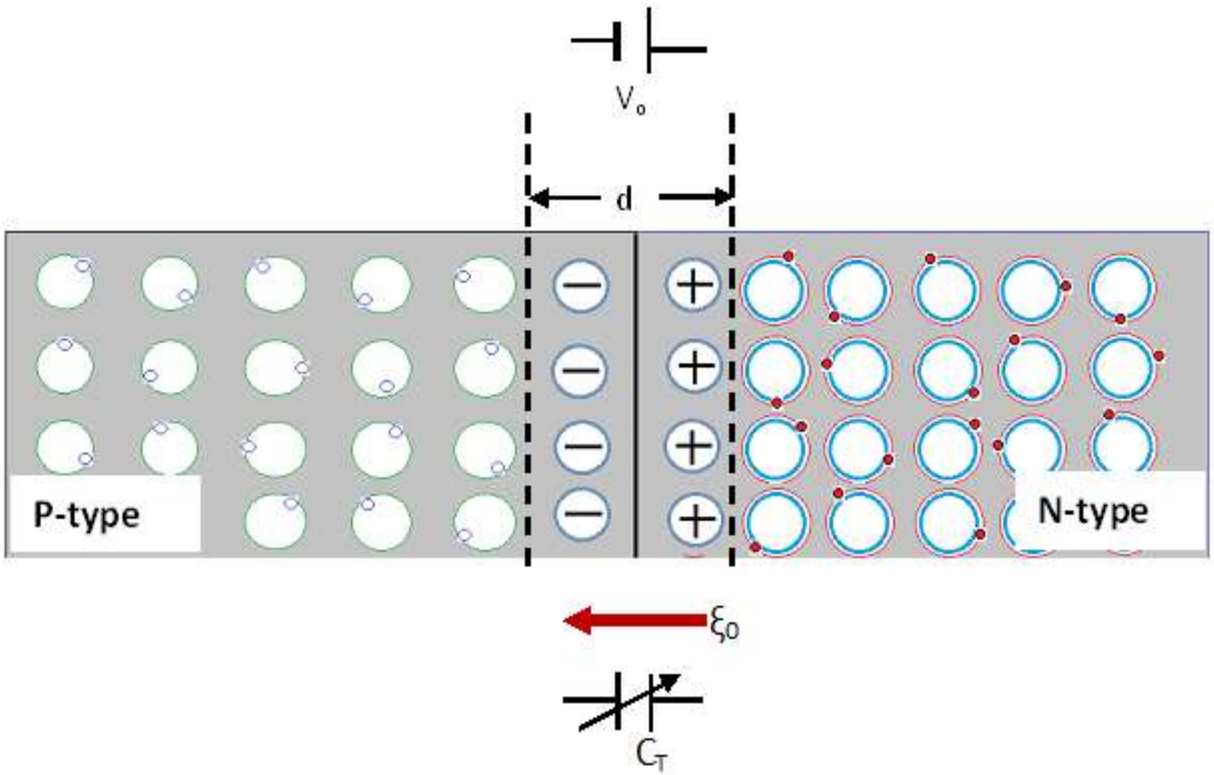


Fig- 3:* P-N Junction at equilibrium.** *Movement of the free electrons from the CB orbits of the neutral Donor atoms of N-Type material across the junction to fill up Holes of the VB orbits of the neutral Acceptor atoms of P-Type material has created the layer of positive and negative ions on opposite sides of the junction. This region of static ions is variously called as (a)* ***Depletion Region*, (b)* ***Barrier Region****, (c)* ***Transition Region*** *or (d)* ***Space-Charge Region.***

The Depletion Region:-

- Since this region, which has been **depleted** of majority carriers, and hence it is called the **Depletion Region.**

  The Depletion Region is also variously known as –

  1. **Space Charge Region**
  2. **Barrier Region**
  3. **Transition Region**

- **Thickness of the Depletion Region 'd' :- The Depletion Region thickness is inversely proportional to the doping concentration. The higher the concentration of doping the narrower the Depletion Region and vice-versa.**

- **Barrier Potential 'V_0'** :- The layer of positive and the negative ions repel any electron or hole trying to diffuse across the P-N Junction**.** The potential difference between these two charged layers charged layers is called **The Barrier Potential 'V_0' .** The magnitude of V_o for Si, 0.7 V, and in case of Ge 0.3 V (Assuming Room Temperature of 300^0 K).

- **Barrier Electric Field 'ξ_0' :-** The Barrier potential V_o = dV is between the charged layers. These two layers are separated by a distance 'd' = dx. Thus there exists an internal Electric Field $\xi_0 = - dV / dx$ which is oriented from positive potential to negative potential. This internal electric field is called **the Barrier Electric Field 'ϵ_0' .**

- **Transition Capacitance C_T :-** These two layers of Space Charge have a layer of Intrinsic Si between them. Intrinsic Resistivity of Si is 2,30,000 Ω-cm, which can be approximated as an insulator. This results in a Capacitance in the Transition Region, called **Transition capacitance C_T** . Under Reverse Bias condition, the thickness 'd' of the depletion region is proportional to the Reverse Bias potential. Thus C_T is inversely proportional to Reverse Bias. Hence it is shown as a variable capacitance in the Fig-3.

Energy Band Diagram of P-N Junction at Equilibrium: -

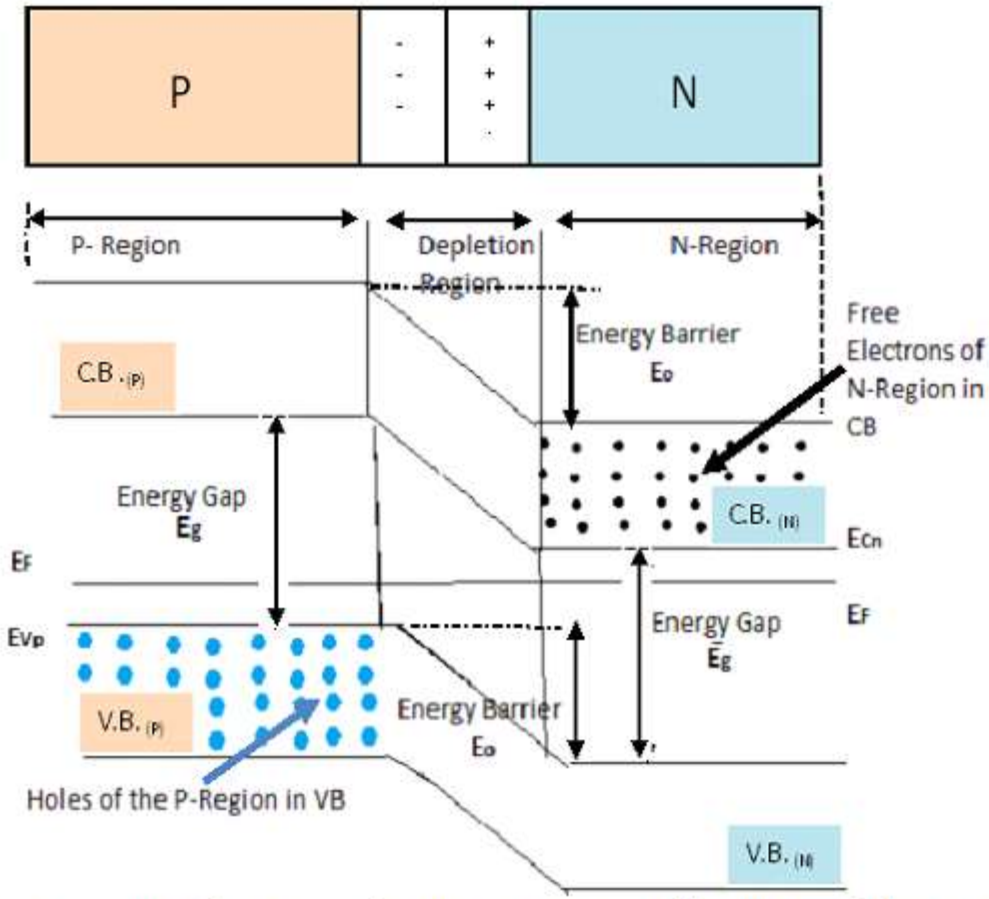


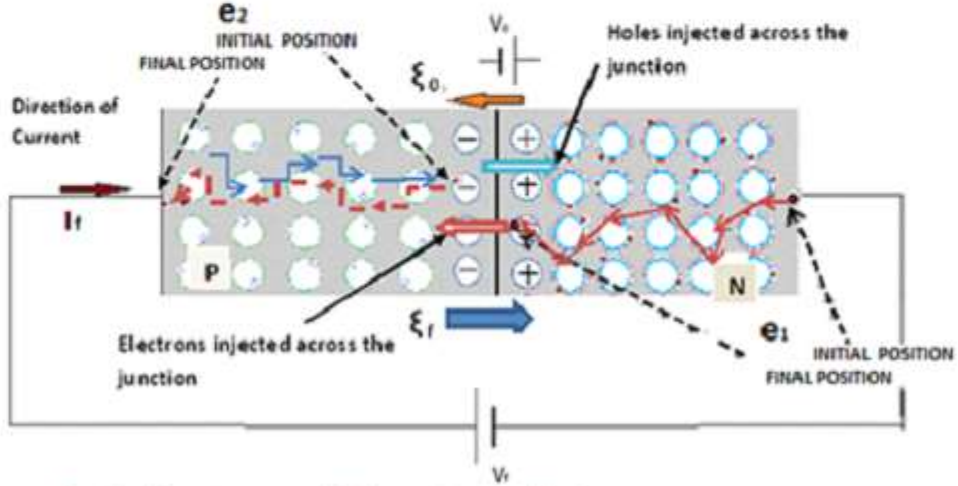
Fig. - 4. *Energy Band Diagram of P-N junction at equilibrium. Both the C.B. and the V.B. of P-Type are at higher energy levels compared to the corresponding energy bands of N-Type, separated by Energy Barrier E_o.*

Summary of the behavior of the P-N junction at equilibrium condition :–

- As soon as the P-N junction is formed, some Majority Carrier CB Electron of the donor dope atom diffuses across, leaving behind a positive ion. This electron fills up a hole in the VB of the P-Side, a negative ion is formed. Thus a **Space Charge Region** is formed, which is variously called as **The Depletion Region**, **The Barrier Region** or **The Transition Region**.
- Since the space Charge Region is entirely due to the Doping Atoms, **the width of this region is inversely proportional to the Doping Density or Doping Concentration.**
- Due to the Space Charges, an Internal Electric Field ξ_o, called the Barrier Electric Field and an Internal Potential Difference V_o, called the Barrier Potential develops.
- The orientation of ϵ_o and polarity of V_o is such that it prevents any further crossing of majority carriers across the junction at equilibrium**.** The Barrier Electric Field pushes away majority carriers respectively, of the N and the P regions from the junction. **Thus there is no current flow at equilibrium.**
- **Fermi Energy level E_F,** signifies the probability of existence of electrons in a semiconductor crystal . Individually, in the P-Type crystal, the Fermi Level E_F is very near to E_{VP} . In the N-Type crystal, the position of E_F is very near to E_{CN}. At equilibrium, E_F of the composite P-N crystal must be at a constant level. Therefore the energy bands of the N-type and P-type materials must align so that the lowermost energy levels of both VB and CB of the P-type material gets aligned with the uppermost energy level of the corresponding bands of the N-type material. **Thus there exists an Energy Barrier or Energy Gradient E_o. The numerical value of Barrier Potential V_o equals the Energy Barrier E_o for a given semiconductor material. For example ,** at 300^0K, Barrier Potential V_0 for Si equals 0.7 V and Energy Barrier E_o equals 0.7 eV. In case of Ge Barrier Potential V_0 equals 0.3 V and Energy Barrier E_o equals 0.3 eV.

P-N Junction at Forward Bias

ξ_o is the Internal Barrier Electric Field



ξ_f is the External Electric Field due to Forward Bias

*Fig-. **5** Application of Forward Bias to P-N junction results in (i) The reduction of the width of the Depletion Region ii) The reduction of Barrier Potential and the Barrier Electric Field, AND (iii) The injection of Majority Carriers across the junction. All of these effects result in the flowing of a current I_f in the direction shown above. Direction of movement of electrons is shown with RED arrows and that of holes is shown with BLUE arrows.*

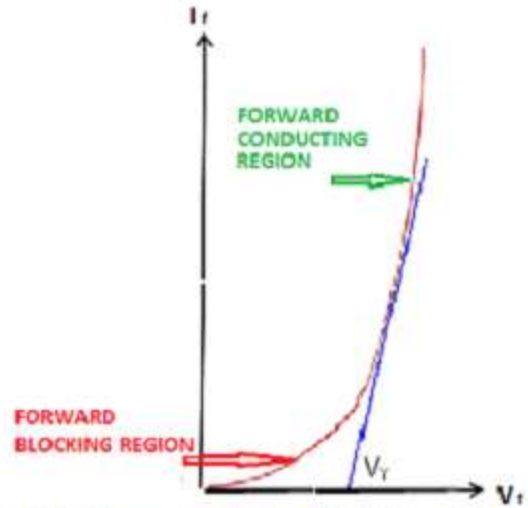


Fig- 7 . *V-I Characteristic of P-N Junction at Forward Bias.*

Summary of the behavior of the P-N junction at Forward Bias condition:–

By Carrier Injection Theory

- When a Forward Bias is applied, the applied external potential V_f and the Electric Field ξ_f are opposing the Barrier Potential V_0 as well as the Barrier Electric Field $\xi_{0.}$ Hence V_0 as well as ξ_0 decrease.
- Some of the Space Charges get neutralized due to the polarity of the applied external potential and, thus width of the depletion region also decreases.
- The Net Electric Field ξ_f' is oriented from P towards N. Thus it tries to push the holes (+ve) of the P-region into the N-region and electrons (-ve) of the N-region into the P-region.
- This flow of holes and electrons (-ve) add up to give rise to the Forward Current I_f, which flows in the direction from P towards N. This I_f is due to the process of the majority carrier injection across the junction.
- The applied potential V_f and resulting current I_f follow an exponential relationship. At smaller values of V_f the current I_f is of the order of µA and the rate of increase of I_f w.r.t. V_f is also very small . Since the current across the P-N Junction is negligible the corresponding region of the V-I Characteristic is called the **"Forward Blocking Region".**
- As the Forward Bias increases beyond a Limiting Value $V_?$, the Forward Current begins to rise very sharply. Thus in this region of the V-I characteristic, conductance is very high. Accordingly, this region is called the **"Forward Conducting Region".**
- In order to make a PN junction fully conducting, Forward Bias $V_f = V_?$. This quantity $V_?$, is called either **(a) Threshold Voltage , or (b) Cut-in-Voltage, or (c) Knee Voltage.**
- $V_?$ is nothing but the Barrier Potential V_0 of the Equilibrium Condition. Thus in case of Si Threshold Voltage $V_? = 0.7$ V; in case of Ge Threshold Voltage $V_? = 0.3$ V.

ENERGY BAND DIAGRAM OF P-N JUNCTION AT FORWARD BIAS :-

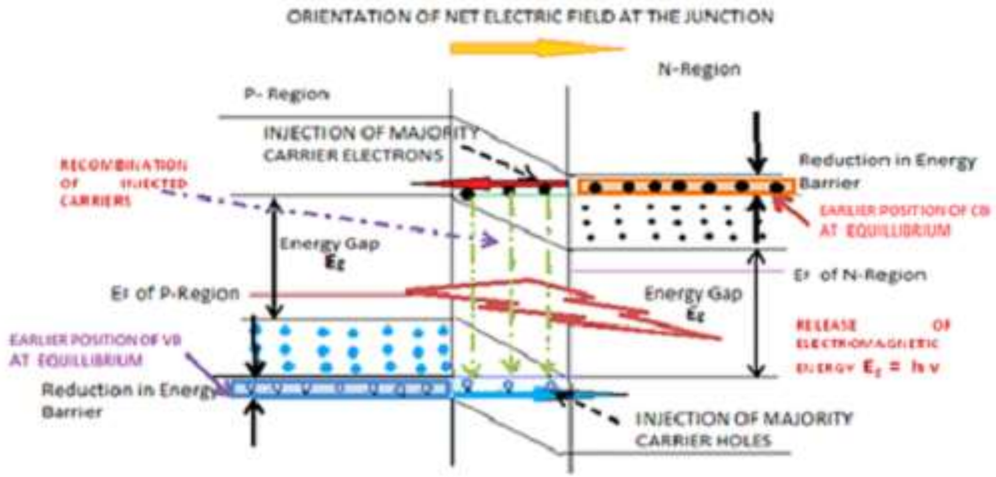


Fig- 6 *Application of Forward Bias results in the re-alignment of the Energy Bands in such a way that the Energy Bands of the N-Region slide upwards and those of the P-Region slide downwards. This results in the reduction of Energy Barrier. The orientation of the Net Electric Field upon the application of Forward Bias is in the direction from P towards N. This results in the injection of majority carriers as shown by the respective arrows (Blue for Hole injection and Red for Electron Injection), which results in current I_f in the direction from P towards N.*

By Energy Band theory :-

- In Equilibrium Condition, Energy Barrier E_0 prevented the movement of majority carriers. Due to the external Forward Bias, The Energy Barrier will be reduced. Thus the energy bands of the P-type material slide downwards and those of the N-type material slide upwards by an amount proportional to the applied forward bias.

- Due to the reduction of Energy Barrier, some of the CB Electrons of the N-side are now aligned above the lowermost energy level of the CB of the P-side. Similarly, some of the VB holes of the P-side are now lying below the uppermost energy level of the VB of the N-side. These electrons and holes do not have any Energy Barrier. Since the net Electric Field ξ' at the junction is oriented from P-towards-N, these electrons and holes are injected into the respective opposite sides. This injection of Majoroty Carriers result in the current I_f,.
- As the Forward Bias is increased, the Energy barrier E_0' is further reduced, resulting in a gradual exponential increase of current. At a certain value of Forward Bias $V_f = V_?$ (Where $V_?$ equals the Barrier Potential V_0), the Energy Barrier is completely overcome. In this situation, the CB and VB of each side P and N respectively, are aligned with each other. In this situation, the exponential rise in the Forward Current I_f w.r.t. V_f becomes very sharp.
- Injected Carriers across the junction become the Minority Carriers on the other side. Minority Carriers in an Extrinsic Semiconductor are quickly neutralized by the opposite type of carriers. This process of transition of an electron from a higher energy level to a lower energy level will result in the release of a quanta of electromagnetic energy equal to the Band Gap Energy E_g = h v, Thus any PN junction will release electromagnetic energy as a result of forward bias. In PN junctions made of Si or Ge energy is released in the form of Heat. In PN junctions made of alloys of In and Ga, energy is released in the form of infra-red or visible light (LED).

P-N Junction at Reverse Bias

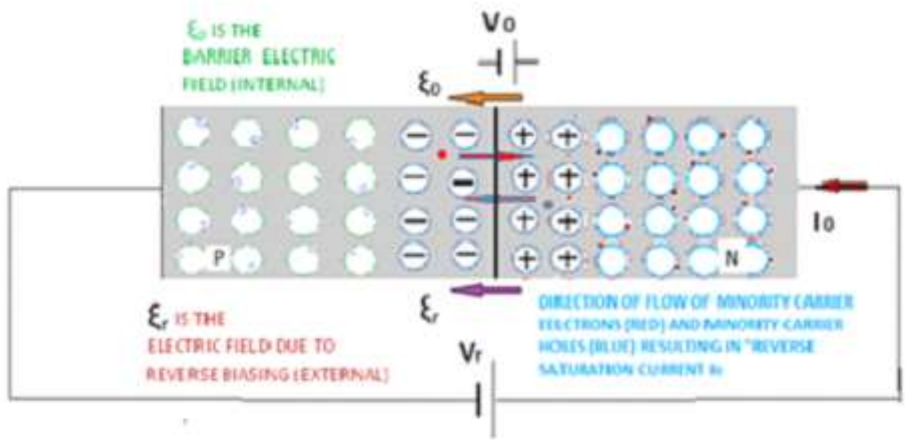
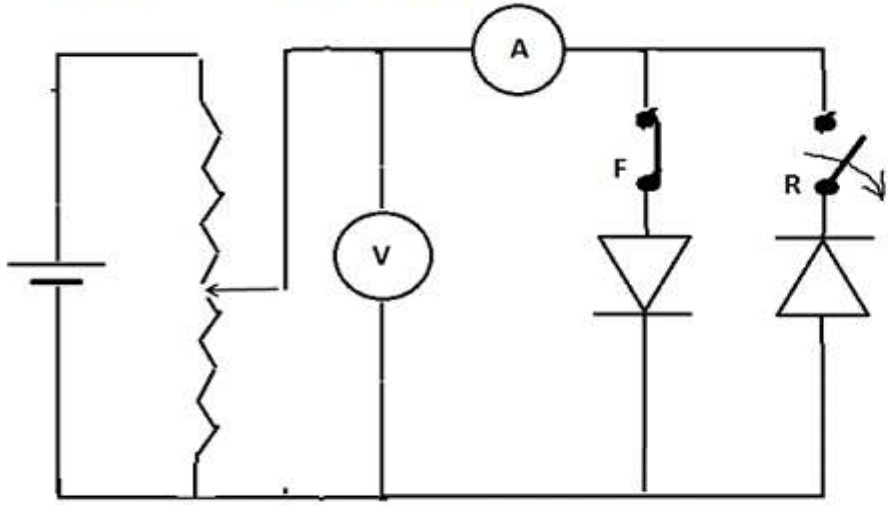


Fig- 9 *Application of Reverse Bias to P-N junction results in (i) Increase in the width of Depletion Region,(ii) The increase of Barrier Potential* (iii) *The increase of Net Electric Field at the junction* AND (iv) Injection of Minority Carriers across the junction. *Direction of injection of electrons is shown with RED arrows and that of holes is shown with BLUE arrows. All of these result in the* ***Reverse Saturation Current*** *I_o in the direction shown above. This current I_o is independent of applied Reverse Bias but dependent on ambient temperature.*

V-I CHARACTERISTIC OF A P-N JUNCTION



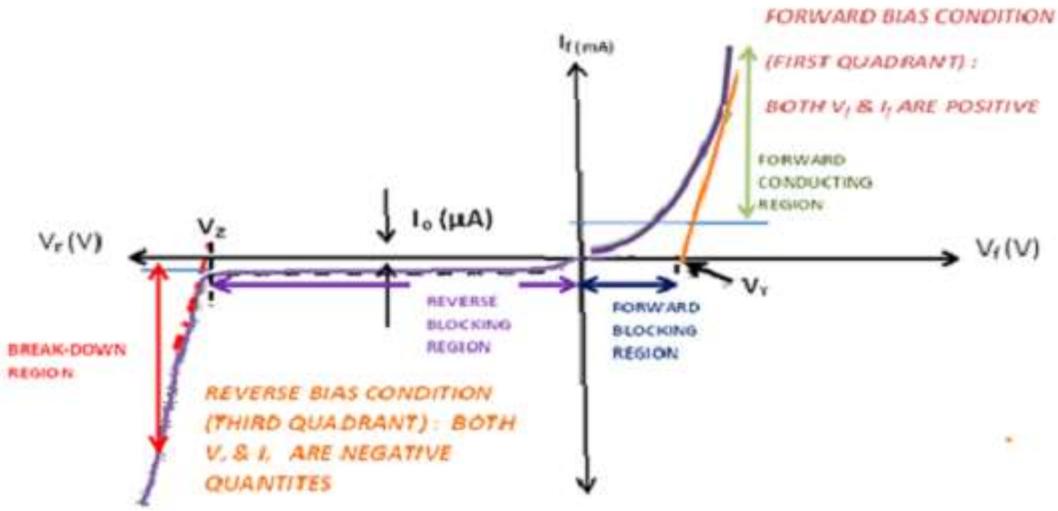


Fig- 10 :- *Complete V-I Characteristic of a P-N Junction at both Forward Bias and Reverse Bias showing various regions and with typical values of the current and voltage.*

ENERGY BAND DIAGRAM OF P-N JUNCTION AT REVERSE BIAS :-

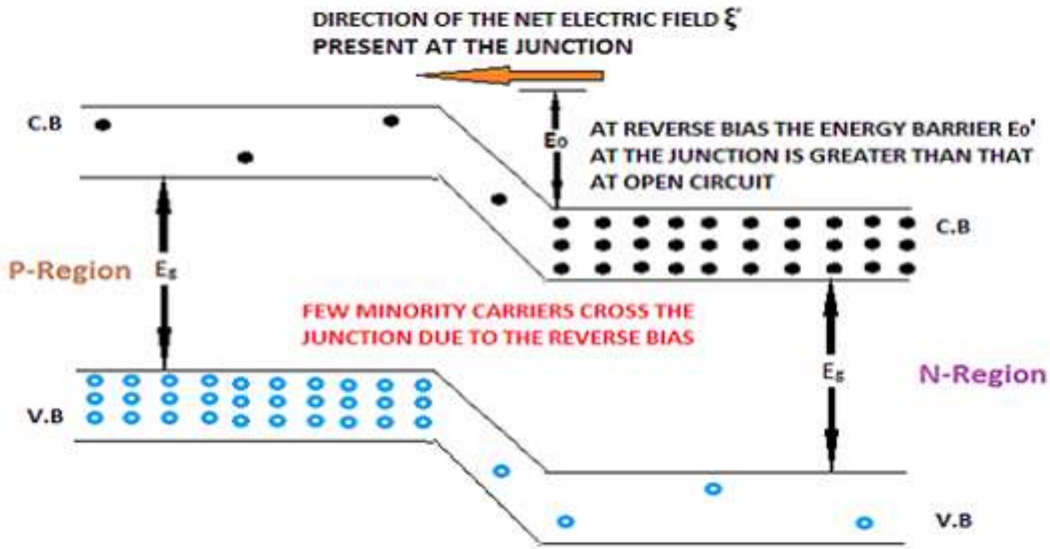
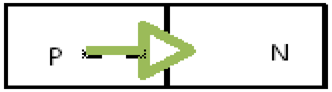


Fig 11 :- *Due to the application of Reverse Bias, both the energy bands CB & VB of the N-Type material move down and those of the P-Type material move up. As a result, the net Energy Barrier increases. Thus none* of the Majority Carriers are able to cross the junction. However, *due to Intrinsic Effect, Minority Carriers are produced ,as usual, in the entire semiconductor crystal. Those minority carriers that are generated inside the depletion region are propelled by the Barrier Electric Field as follows. Intrinsically generated Electrons are moved in the direction opposite to the orientation of the Barrier Electric Field, i.e. from P-side towards N-side and intrinsically generated holes are moved in the direction of the orientation of the Barrier Electric Field, i.e. from N-side towards P-side. Thus, the current I_0, due to this, flows in the direction from N-towards-P. This is the "Reverse Saturation Current", as explained earlier.*

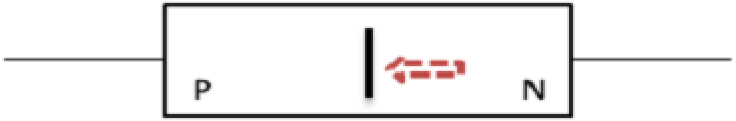
P-N Junction Diode & The Diode Symbol

From our discussion of the P-N Junction we may summarize the few of the salient points as follows –

- When we apply a Forward Bias a current flows due to injection of Majority Carriers across the junction from each side, resulting in a large amount of current flowing in the direction from P-side to N-side as depicted by means of the arrow below



- When the Forward bias exceeds the quantity $V_?$ the current rises very sharply with respect to applied forward bias. The value of Dynamic Resistance is of the order of only a few ohms. This is the Forward Conducting Mode of the diode.
- Thus we can say that at Forward bias a current will flow from P towards N and a voltage drop of $V_?$ will exist across the device.
- When we apply a Reverse Bias, current is only due to Minority Carriers and of the order of only few nannoamperes (in case of Si). he dynamic resistance of the P-N junction at Reverse bias is very large, i.e., of the order of hundreds of Megaohms. Thus we can say that at reverse Bias the P-N Junction blocks the flow of current. This can be depicted as follows --



Combining these two depictions Symbol of the device as shown below

Fig-12. :- *The symbol of the DIODE shows that current flow is allowed from P-side (Anode) to N-side (Cathode) while it is blocked in the opposite direction.*

Small Signal Model of the Forward Biased Diode
(Piece-Wise Linear Model of Diode)

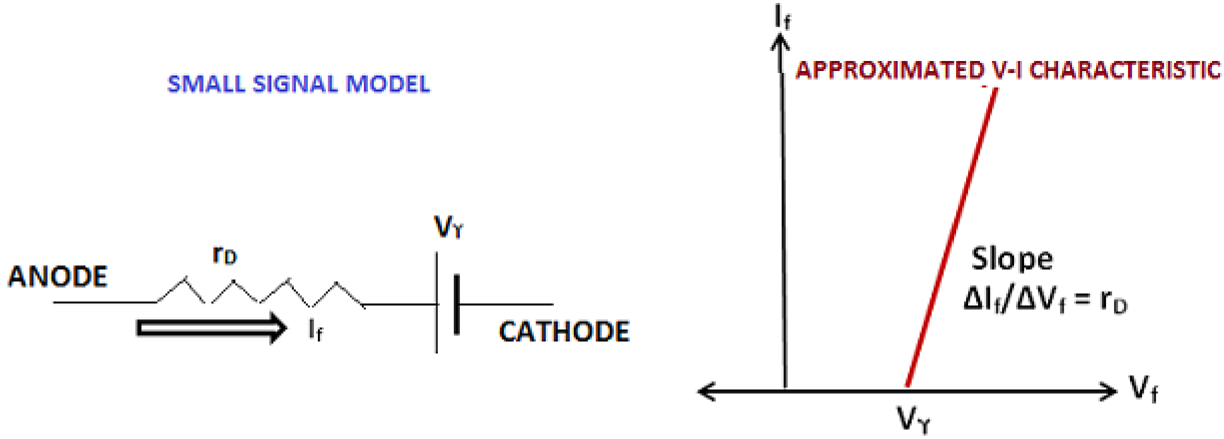


Fig 13 :- *Equivalent Circuit of a Forward Biased Diode. The quantity $V_?$ is dependent on the semiconductor material. For Ge $V_?$ = 0.3 V and for Si $V_?$ = 0.7 V. The quantity Dynamic Resistance r_D is given by equation 2.15. From calculation using this equation, as well as from the tables given in Fig – 2.15 it is observed that his resistance is very small and it's order of magnitude of the order of a few ohms only.*

LESSON -3

CURRENT IN P-N JUNCTION DIODE

Shockley's Equation (P-N Junction Current Equation)

Total current in any semiconductor is always the sum of the current due to electrons and that due to holes.

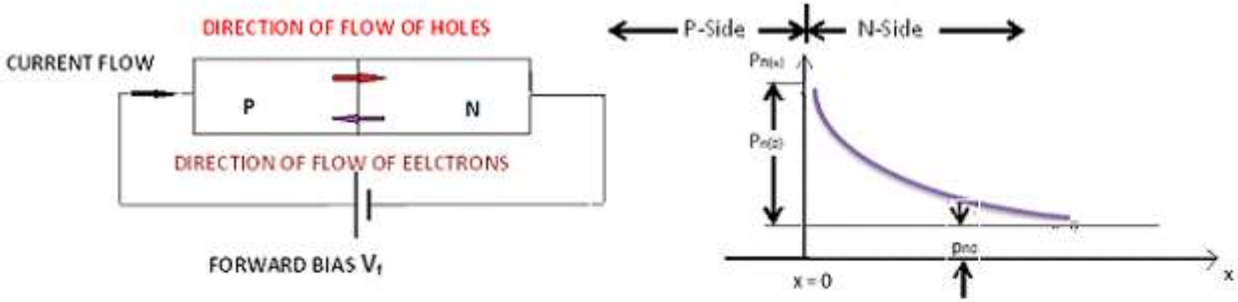


Fig-2.14 :- *Figure shows increase in "Hole Concentration"* $P_{n(x)}$ *at the junction, (where x = 0), due to the application of Forward Bias. Injected Holes are Minority Carriers in the N-Side. Thus they quickly recombine with the Majority Carrier Electrons in the N-Side so that the Hole Concentration exponentially decreases to the equilibrium value of* p_{n0}.

Let the current due to the injected holes, at the point x = 0 , be $I_{pn(0)}$.

Let the current due to the injected electrons, at the point x = 0 , be $I_{np(0)}$.

Total Current

$$I = I_{pn(0)} + I_{np(0)} \qquad .....(1)$$

Consider Current due to Holes

Due to the External Electric Potential Difference V, large number of holes will be injected at x = 0. Increase in Hole Concentration at x=0 is given by an expression known as "**Einstein's Equation of Carrier Diffusion**" as-

$$p_{n(0)} = p_{no}\, e^{V/V_T} \qquad .....(2)$$

(i) $p_{n(0)}$ is the net concentration of holes at the junction at x = 0.

(ii) p_{no} = The equilibrium concentration of minority carrier holes in the N-Side

(iii) V = The applied potential difference across the P-N junction

(iv) V_T = The 'Volt Equivalent of Temperature' given by Eq . -6 in Lesson -1 as

$$V_T = \frac{k\,T}{q}$$

Substituting ,

k = Boltzmann Constant = 1.381 x 10^{-23} J/^{0}K ; q = Charge of hole = + 1.602 x 10^{-19} C

and T is the Room Temperature in ^{0}K.

$$V_T = \frac{T}{11600}$$

The increase in the Concentration of Holes due to injection at x = 0 is

$$P_{n(0)} = p_{n(0)} - p_{no} \qquad .....(3)$$

- Injected Holes are Minority Carriers on the N-Side. Minority Carriers quickly recombine with the Majority Carriers
- Concentration of the injected holes $p_{n(x)}$ in the N-Side begins to decrease exponentially. This is shown in the figure above.

$$p_{n(x)} = p_{no} - P_{n(0)} \; e^{\frac{-x}{Lp}} \qquad .....(\mathbf{4})$$

L_p is called the "Diffusion Length" of injected holes in the N-Side.

Injected holes diffuse into the N-Side . Diffusion Current is proportional to "Hole Density Gradient". Since the concentration of holes is decreasing exponentially, the Hole Density Gradient is a negative quantity. Thus Diffusion Current due to injected holes in the N-Side $\mathbf{I_{pn}}$, is

$$I_{pn} \propto \mathbf{q} \,.\, \mathbf{A}. \left(- \frac{d\, p_{n(x)}}{d\, x} \right)$$

'+q' is the charge of the Hole, 'A' is the area of cross section of the junction and

$p_{n(x)}$ is expressed by equation (4).

The proportionality constant is the 'Diffusion Constant of Holes' denoted by 'D_p'.

$$I_{pn} = - \mathbf{q} \,.\, \mathbf{A}.\, D_p \left(\frac{d\, p_{n(x)}}{d\, x} \right)$$

- Taking d /d x of equation (4) and substituting above we get

$$I_{pn} = \frac{q.A.Dp.Pn(0)}{Lp}\ e^{-x/Lp} \qquad .....(5)$$

- Substituting for $P_{n(0)}$ from eq (3) and $p_{n(0)}$ from eq (2) we get

$$P_{n(0)} = p_{no}\, e^{V/V_T} - p_{no} = p_{no}\left(e^{V/V_T} - 1\right)$$

- Substituting the above in eq (5) and putting x = 0, we get the current due to holes crossing the junction from P-Side to N-Side (at x = 0) as

$$I_{pn(0)} = \frac{q.A.Dp}{Lp}.\, p_{no}\left(e^{V/V_T} - 1\right) \qquad .....(6)$$

- Proceeding in a similar way the current due to injection of electrons across the junction, $I_{np(0)}$, at x = 0 as

$$I_{np(0)} = \frac{q.A.Dn}{Ln}.\, n_{po}\left(e^{V/V_T} - 1\right) \qquad .....(7)$$

D_n is the "Diffusion Constant of Electrons" ,
L_n is the "Diffusion Length" of injected electrons in the P-Side
and n_{po} is the "Equilibrium Concentration" of minority carrier electrons in the P-Side.

- Now substituting for $I_{pn(0)}$ & $I_{np(0)}$ in equation (1) we get the current in the P-N Junction due to the applied bias as

$$I = \frac{q.A.Dp}{Lp}.p_{no}\left(e^{V/V_T} - 1\right) + \frac{q.A.Dn}{Ln}.n_{po}\left(e^{V/V_T} - 1\right)$$

$$\therefore I = \left\{\frac{q.A.Dp}{Lp}.pno + \frac{q.A.Dn}{Ln}.npo\right\}\left(e^{V/V_T} - 1\right)$$

- In this 'q', 'A',' D_p', 'L_p', 'D_n', 'L_n', 'p_{no}' and 'n_{po}' are all constants. Using these we define another constant quantity "I_0", as in Eq.- 9.
- we get the current in a P-N junction as

$$I = I_0\left(e^{V/V_T} - 1\right) \qquad \text{.....(8)}$$

Where

$$I_0 = \left\{\frac{q.A.Dp}{Lp}.pno + \frac{q.A.Dn}{Ln}.npo\right\} \qquad \text{....(9)}$$

Equation – 8 is known as "Shockley's Equation". This is applicable to both Forward Bias as well as Reverse Bias.

Equation - 9 represents the "Reverse Saturation Current" in a P-N Junction .

Justification of the shape of the V-I Characteristic of P-N Junction

In Lesson-2 we got the V-I Characteristic of a P-N Junction in the Fig-10. In this section we justify the shape of the V-I Characteristic in terms of the Shockley's Equation.The quantity V_T, called 'The Volt Equivalent of Temperature' is given by

$$V_T = \frac{k\,T}{q}$$

$$V_T = \frac{T}{11600}$$

If we assume a room temperature of 300 ^{0}K then the value of V_T works out to

$$V_T = 300/11600 = 0.02586\ V \approx 26\ mV$$

Now, for a forward bias say V = 0.08 V, the exponential term e^{V/V_T} is calculated as

$$e^{0.08/0.026} = 21.8 << 1.$$

Thus, if we neglect '1' in the Shockley's Equation, we get the expression for the current as an exponential.

$$I = I_0 \,.\, e^{V/V_T}$$

This is shown by the Exponential Portion in the figure

Now, if we consider a reverse bias of V_r = - 0.2 V we get the term

$$e^{-0.2/0.026} = 0.00045.$$

Substituting this value in the Shockley's equation, we get

$$I = I_0\left(e^{-0.2/0.026} - 1\right) = I_0\,(0.00045 - 1) \approx -I_0 .$$

Thus we get a constant value of reverse current, signified by the negative sign, as depicted in the Fig-10,

Various Regions in the V-I Characteristic of P-N Junction

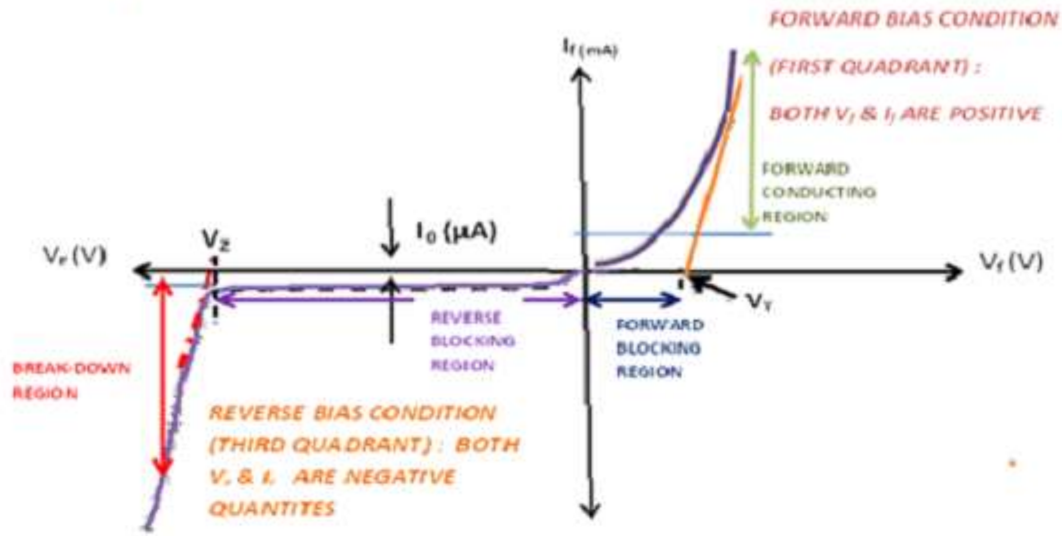
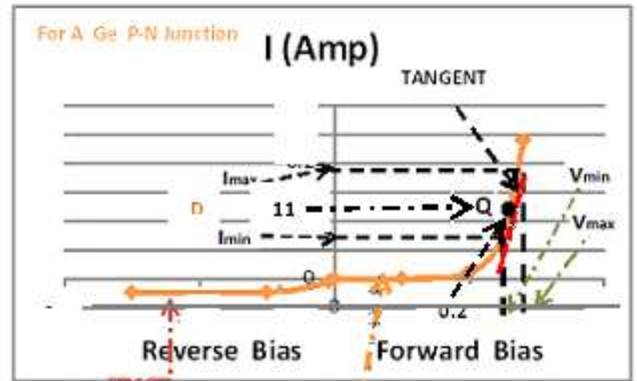
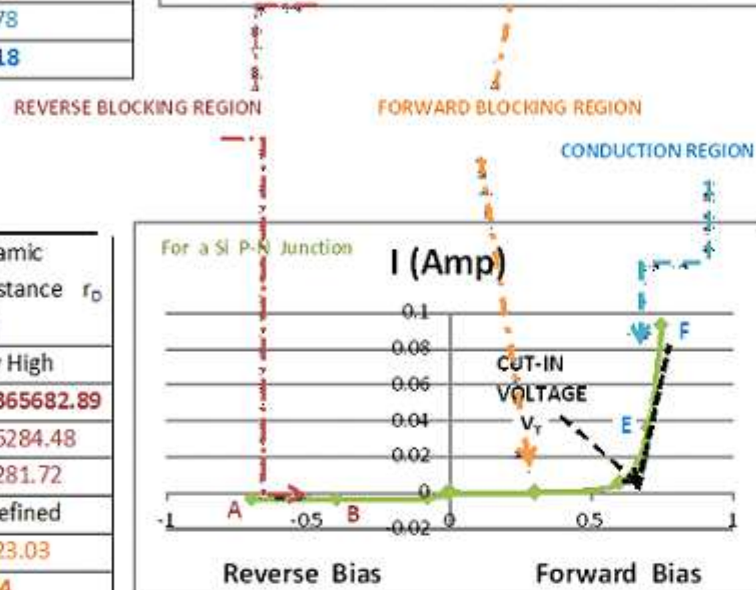


Fig- 10 :- *Complete V-I Characteristic of a P-N Junction at both Forward Bias and Reverse Bias showing various regions and with typical values of the current and voltage.*

V-I Characteristics of Ge and Si Diodes plotted using Shockley's Equation

	V (Volt)	I (mAmp)	Dynamic Resistance r_D (Ω)
	-0.3	-0.005	Very High
A	**-0.1**	**-0.005**	**1877915.8**
B	-0.08	-0.005	161933.77
	-0.008	-0.001	20900.24
	0	0	Undefined
C	0.1	0.23	435.48
D	**0.2**	**11.0**	**9.28**
	0.25	75.4	0.78
E	**0.28**	**239.3**	**0.18**
F			





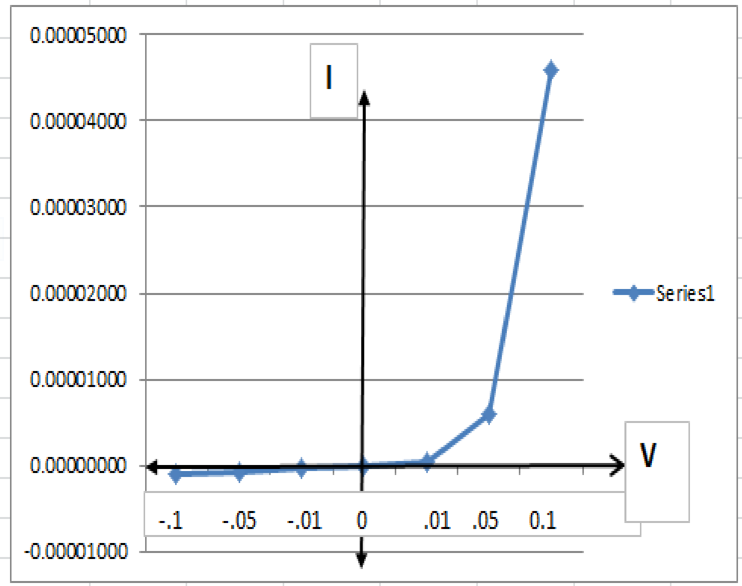
	V (Volt)	I (mAmp)	Dynamic Resistance r_D (Ω)
A	-0.7	-5E-05	Very High
B	**-0.4**	**-5E-05**	**828365682.89**
	-0.08	-5E-05	2266284.48
	-0.008	-7E-05	132281.72
	0	0	Undefined
C	0.3	0.016	18723.03
D	**0.6**	**5.17**	**58.24**
	0.7	35.69	3.31
E	**0.75**	**92.64**	**0.87**
F			

Fig 11 :- *Tabulation of some Reverse and Forward Bias voltage values and the associated currents, calculated in terms of Shockley's Equation for both Ge (Above) and Si (Below) , along with the plot of these values (V-I Characteristic). The shape of the V-I Characteristic deduced earlier is thus verified. Also shown are the values of the Dynamic Resistance at different regions of*

Calculated for

Ge With I_o = 1 μA

V	I	V	R_f	r_D
-0.5	-0.00000100	-0.5	500000	18725071
-0.1	-0.00000098	-0.1	102182.8	400657.7
-0.05	-0.00000085	-0.05	58558.74	74828.48
-0.01	-0.00000032	-0.01	31319.73	25369.87
0	0.00000000			
0.01	0.00000047	0.01	21319.73	7444.729
0.05	0.00000584	0.05	8558.744	1250.917
0.1	0.00004581	0.1	2182.802	295.2742
0.13	0.00014741	0.13	881.8751	93.13575
0.16	0.00046952	0.16	340.7709	29.377
0.19	0.00149073	0.19	127.4543	11.57688
0.21	0.00321831	0.21	65.25159	5.36437
0.23	0.00694662	0.23	33.10965	2.485685
0.25	0.01499269	0.25	16.67479	0.921893
0.28	0.04753444	0.28	5.890466	0.290785
0.31	0.15070360	0.31	2.057018	0.07257
0.35	0.70189355	0.35	0.498651	0.498651



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	-0.008	-0.001	20900.24
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C	0.1	0.23	435.48
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	0.25	75.4	0.78
E	**0.28**	**239.3**	**0.18**
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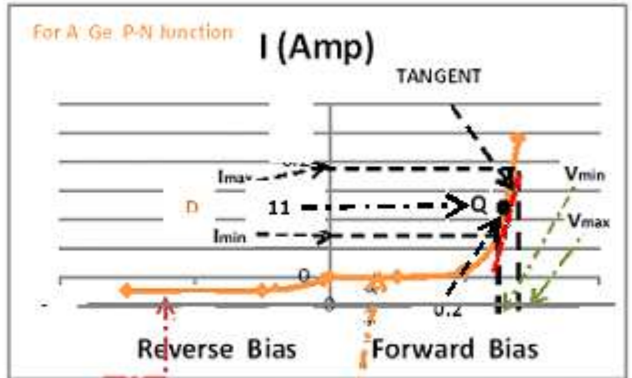

	V (Volt)	I (mAmp)	Dynamic Resistance r_D (Ω)
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B	**-0.4**	**-5E-05**	**828365682.89**
	-0.08	-5E-05	2266284.48
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	0	0	Undefined
C	0.3	0.016	18723.03
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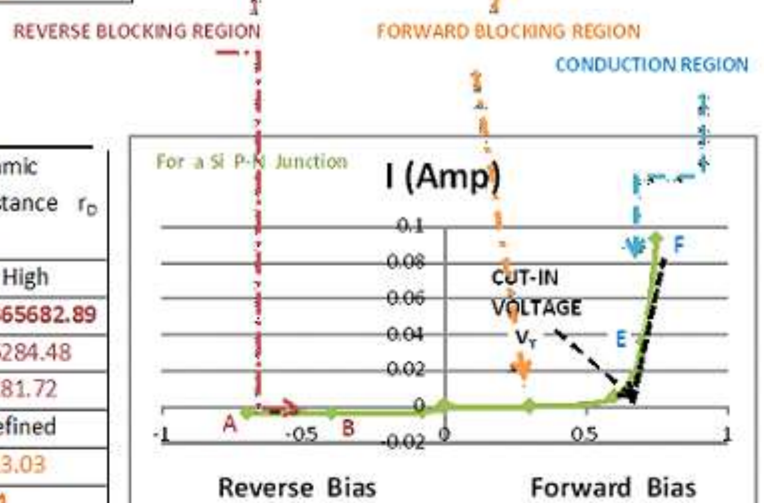
F			



Electrical Parameters of P-N Junction:-

(i) Static Resistance :- Static Resistance of a P-N Junction is defined as the resistance offered by the junction when the voltage and the current in the junction are constant . In other words, Static Resistance is the DC Resistance of the P-N Junction.

Ohm's law with DC current and voltage

$$\mathbf{V = I\,R}$$

$$\mathbf{R = V / I} \qquad .....(10)$$

Example 2.1:- Refer to Fig.**11** Consider the point '**D**' for Ge Diode in the table and the graph **(Colour 'Orange').** The coordinates of the point '**D**', V = 0.2 V and I = 11 mA

$$R = V / I = 0.2 / 0.011 = 18.18\,\Omega$$

(ii) Dynamic Resistance :- Dynamic Resistance of a P-N Junction is defined as the resistance offered by the junction when the voltage and the current in the junction are varying, i.e. Dynamic Resistance is the AC Resistance of the P-N Junction.

Ohm's Law with AC current and voltage. $v = i\,R_{AC}$,

Thus $r_D = r_{AC} = v / i$ Where v & i are AC quantities.

The AC voltage and current quantities oscillate about the mean values $\mathbf{V_O}$ and $\mathbf{I_O}$ **with** maximum values of V_{max} and I_{max} and a minimum values of V_{min} and I_{min} respectively.

AC Voltage and Current $v = \Delta V = V_{max} - V_{min}$ and $i = \Delta I = I_{max} - I_{min}$.

Ssubstituting , the Dynamic Resistance

$$r_D = r_{AC} = v / i = \Delta V / \Delta I = (V_{max} - V_{min}) / (I_{max} - I_{min}) .$$

Dynamic Resistance at a certain portion of the V-I graph is the 'RECIPROCAL OF THE SLOPE of the graph' at that point .

The quantity r_D can also be expressed as follows –

$$r_D = \frac{dV}{dI} \qquad .....(11)$$

Example 2.2 :- Refer to Fig.**11** Consider the points '**E**' and '**F**' in **(Colour 'Blue')** in the table and graph for Si Diode. **(Colour 'Blue').** V_{min} = 0.7 V and V_{max} = 0.75 V. & I_{min} = 32.69 mA and I_{max} = 92.64 mA

? v = Δ V = (V_{max} - V_{min}) = (0.75 – 0.7) = 0.05 V

and i = Δ I = (I_{max} - I_{min}) = (92.64 – 32.69) = 59.95 mA .

? $r_D = r_{AC}$ = v / i = Δ V / Δ I = (0.75 – 0.7) /(92.64 – 32.69) = 0.834 Ω.

Empirical Formula for Dynamic Resistance :-

$$r_D = r_{AC} = \Delta V / \Delta I$$

Shockley's equation. $I = I_0 \, . \, e^{V/V_T}$

The slope of the graph of a given equation is the first derivative of the equation w.r.t. the independent variable. Thus the 'Slope' of the Shockley's equation is

$$\frac{dI}{dV} = {}^{1}/_{V_T} \; \{ I_0 \, . \, e^{V/V_T} \} = I / V_T$$

∴ r_D = Reciprocal of the Slope = V_T / I

Where $V_T = \frac{kT}{q}$ Or $V_T = \frac{T}{11600}$ At T = 300 ⁰K, V_T = 0.026 V = 26 mV.

Substituting this we get the Empirical Formula for Dynamic Resistance of a P-N Junction as

? r_D = 0.026 (in the unit of V) / I (in the unit of A) = 26 (mV) / I (mA) in units of Ω

$$r_D = \frac{26 \text{ mV}}{I_D \text{mA}} \;\; \Omega \qquad .....(12)$$

EXAMPLE :- Using Empirical Formula, taking Mid-Point between points "E" & "F"

Mid-Point Current

$I_D = \frac{(92-35)}{2}$ = 28 mA $\qquad r_D = \frac{26 \text{ mV}}{28 \text{ mA}}$ = **0.93 Ω**

(Approximately same as Example 2.2)

(iii) Transition Capacitance :- **The capacitance of the Depletion Region (also known as Transition Region) is called the Transition Capacitance, denoted by C_T .**

Recall that the width of the depletion Region is dependent upon the applied bias. In other words C_T is a variable capacitance.

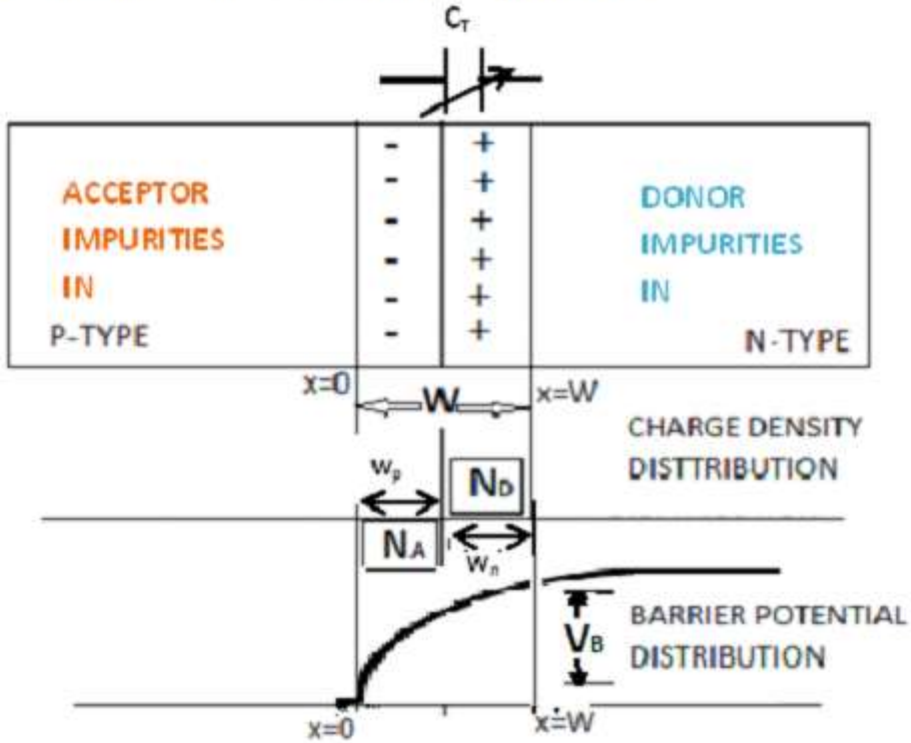


Fig- 12. :- *Charge Density Distribution and Barrier Potential Distribution at a P-N Junction. N_A = Concentration of Acceptor Impurities : N_D = Concentration of Donor Impurities : W = Width of the Depletion Region : V_0 = Magnitude of Barrier Potential.*

The quantity Capacitance of a capacitor is defined as the "The Charge Stored per Unit Potential Difference".

Thus $C_T = \frac{dQ}{dV}$ (A)

- Thus the 'Charge Density' of the negative ions in the P-side is proportional to the density of Acceptor impurities, i.e. N_A and the 'Charge Density' of the positive ions in the N-side is proportional to the density of Donor impurities, i.e. N_D .
- Again, the number of positive ions is exactly equal to the number of negative ions. Therefore the net charge in the semiconductor crystal is zero. If the width of the Depletion Region on the P-side is 'w_p' and that on the N-side is 'w_n' , then we have

$-q\ N_A\ w_p = +q\ N_D\ w_n$

Where – q is Electron Charge & +q is Hole Charge

? $q\ N_D\ w_n + q\ N_A\ w_p = 0$

Assuming $N_D –= N_A$ so that $w_n = w_p$

$q\ N_A\ (w_p + w_n)) = q\ N_A\ W = 0$

Where $w_p + w_n = W$ & net 'Charge Density' equals $q\ N_A$.

(Where W is the width of the Depletion Region)

The Net Barrier Potential V_B appears across the width of the Depletion Region. The relationship between Charge Density and Potential Difference is given by "Poisson's Equation' as

$$\frac{d^2V}{dx^2} = \frac{q\ N_A}{\epsilon}$$

Where 'ϵ' is the Electrostatic Permittivity of the semiconductor.

Integrating this twice over the Depletion Region , from x = 0 to x = W we get

Where 'ϵ' is the Electrostatic Permittivity of the semiconductor.

Integrating this twice over the Depletion Region , from x = 0 to x = W we get

$$\int_0^W \frac{d^2V}{dx^2} = \int_0^W \frac{dV}{dx} = V_B$$

$$V_B = \int_0^W \frac{qN_A}{\epsilon}\, dx = \frac{qN_A}{2\epsilon} W^2$$

$$\text{Or} \quad V_B = \frac{qN_A}{2\epsilon} W^2 \qquad \text{...(B)}$$

The width of the Depletion Region is directly proportional to the net Barrier Potential at the junction and varies in proportion to the square root of V_B'.

Area of cross section of the junction is 'A', the total charge in the depletion region

$$Q = q\, N_A\, W\, A$$

Substituting this in equation (A) (Since 'q' , 'N_A' and 'A' are constant quantities), we get,

$$C_T = q\, N_A\, A\, \frac{dW}{dV}$$

Under a "Reverse Bias" of V_B = V, and substituting for V_B, given by equation (B).

$$\frac{dV_B}{dW} = \frac{qN_A\, W}{\epsilon}$$

$$\therefore \frac{dW}{dV} = \epsilon / q\, N_A$$

Substituting this in the expression for C_T , as above, we get

$$C_T = \frac{\epsilon\, A}{W} \qquad \text{.....(13)}$$

Note.

- The expression (13) is exactly the same as that for a Parallel Plate Capacitor with metal plates of area 'A', separated by a distance 'W' and filled with a dielectric material of electrostatic permittivity 'ϵ'.
- From the equation (B) above, it is noted that "Width of the Depletion Region varies as the Square Root of applied reverse bias V_B".
- From Fig-13 it is observed that the "Width of the Depletion Region is proportional to the Concentration N_A and N_D of Acceptor and Donor Impurities respectively".