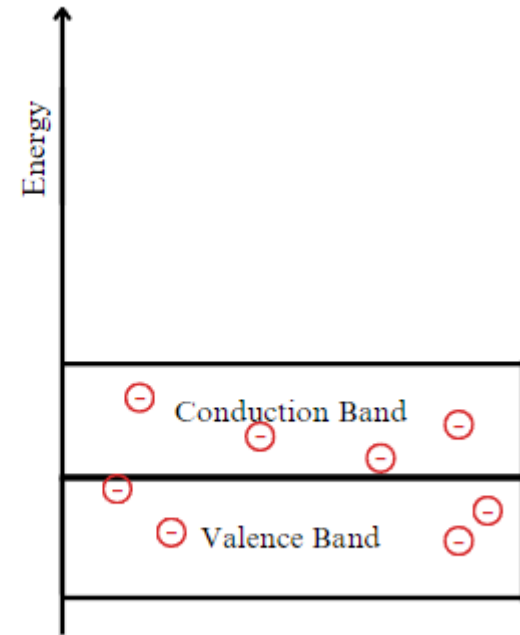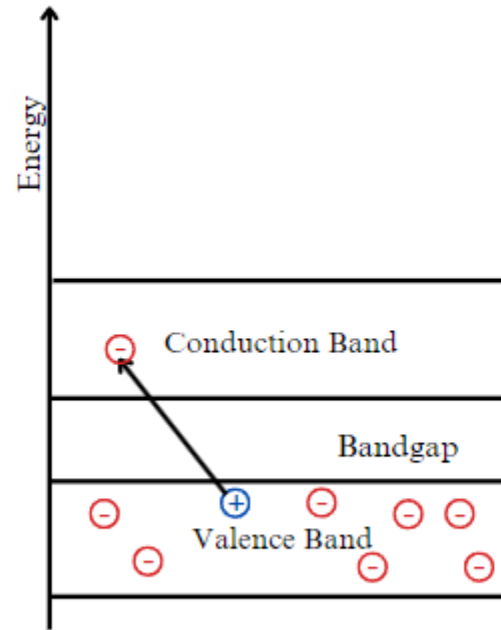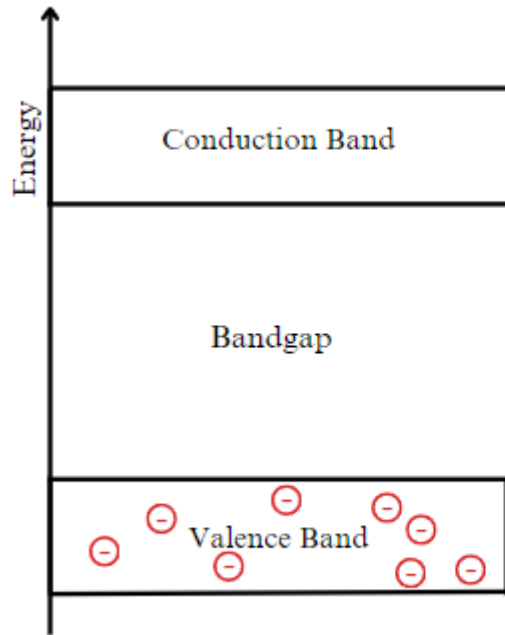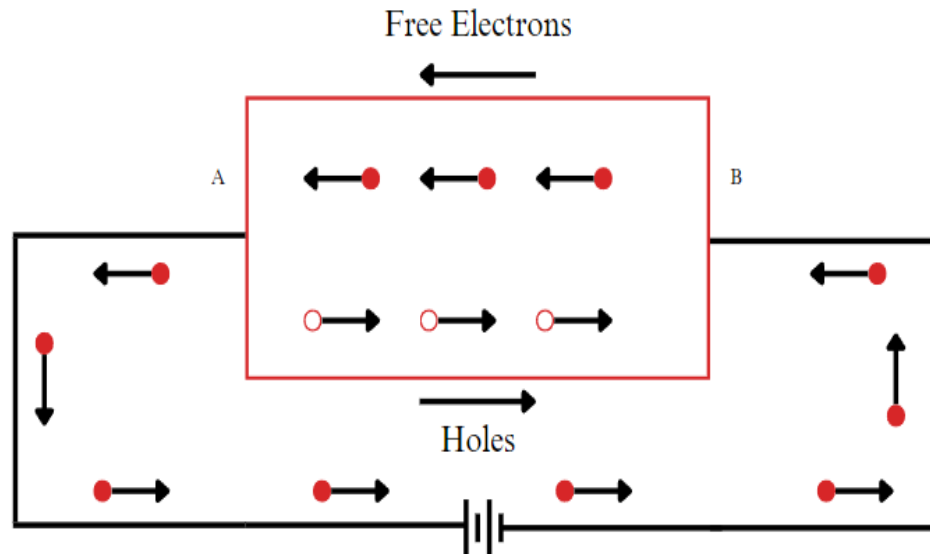# SEMICONDUCTOR PHYSICS

ENERGY BANDS IN INSULATORS, SEMICONDUCTORS AND CONDUCTORS

INTRINSIC SEMICONDUCTOR

- A Semiconductor in its purest form without any impurities.
- Eg: Silicon, Germanium

Properties of intrinsic Semiconductors

- 1. Low conductivity
- 2. Equal electron and hole concentration
- 3. Temperature dependence of conductivity
- 4. Crystalline structure of the material
- 5. Band Gap energy
- 6. Sensitivity to impurities

Derivation of density of electrons in conduction band

- The density of electrons in the conduction band, n, is given by the integral of the product of the density of states in the conduction band, Ƶ(E), and the probability of occupation, F(E), over all energies in the conduction band.
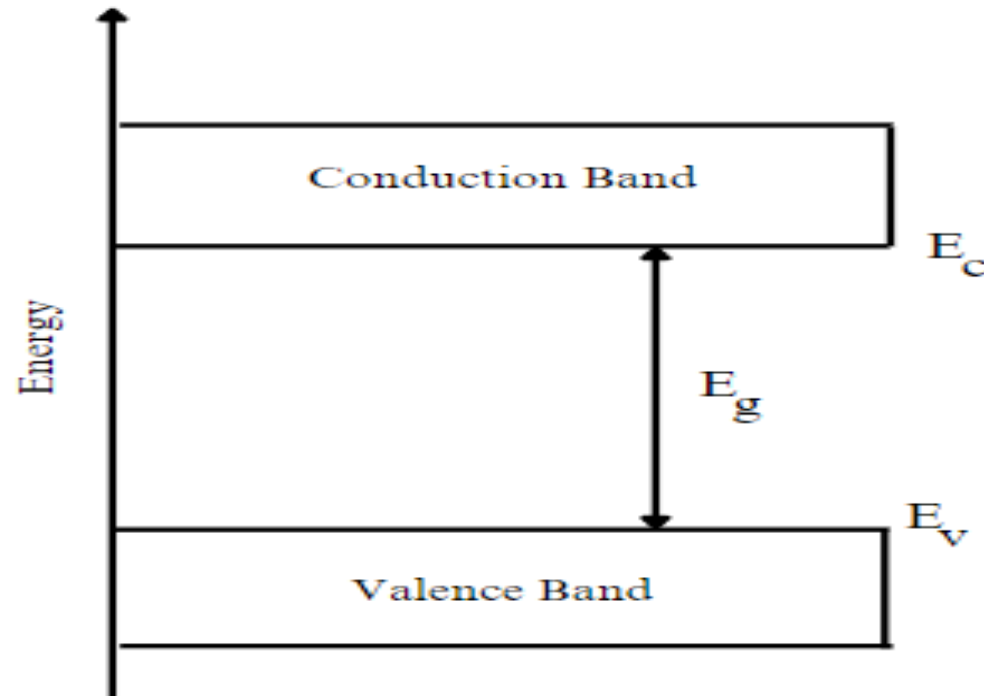
- Let dn be the number of electrons in the conduction band in an energy range E and E+dE

- Therefore;

- dn = Z(E)dE·F(E)   (1)

- Where, Z(E) is the density of energy states ie; energy states per unit volume , F(E) , the Fermi distribution function which gives the probability of occupancy of electrons among the energy levels.

- But from Statistical Mechanics,

- $Z(E)dE = \dfrac{4\pi}{h^3} \times (2m)^{\frac{3}{2}}\ E^{\frac{1}{2}}\ dE$ (2)

- Here m is the effective mass of electron , m_e^*

- E is E - Ec , where Ec is the energy at the bottom of the conduction band.

- $\therefore Z(E)dE = \frac{4\pi}{h^3} \times (2m_e^*)^{\frac{3}{2}} \ (E - E_C)^{\frac{1}{2}} \ dE$ $\qquad$ (3)

- $F(E) = \frac{1}{1+e^{\frac{(E-E_F)}{kT}}}$ $\qquad$ (4)

- $(E - E_F) \gg kT$ for all

- $\therefore$ Neglecting 1 in the denominator of equation (4)

- $F(E) = \dfrac{1}{1+e^{\frac{(E-E_F)}{kT}}} = \left[e^{\frac{(E-E_F)}{kT}} \right]^{-1}$

- $F(E) = e^{\frac{(E_F-E)}{kT}}$ (5)

- Substituting equation (3) and (5) in equation (1)

- $dn = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}}(E - E_C)^{\frac{1}{2}}dE \cdot e^{\frac{(E_F - E)}{kT}}$

- $\therefore\ n = \int_{Ec}^{\infty} dn = \int_{E_C}^{\infty} \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}}(E - E_C)^{\frac{1}{2}}dE \cdot e^{\frac{(E_F - E)}{kT}}$

-

- Let E-Ec=x

- E=x+Ec

- dE=dx

- Consider the lower limit Ec ; When   E=Ec ;   x=0

- When   E=∞   ;   x=∞

- $\therefore \quad n = \dfrac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}} e^{\frac{E_F}{kT}} \int_0^\infty x^{\frac{1}{2}} e^{\frac{-x-E_C}{kT}} dx$

- $\int_0^\infty x^{\frac{1}{2}} e^{-ax} dx = \dfrac{\sqrt{\frac{\pi}{a}}}{2a}$ (Standard Result)

-

- $\therefore \quad n = \dfrac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}} e^{\frac{E_F - E_C}{kT}} \quad \int_0^\infty \quad x^{\frac{1}{2}} e^{\frac{-x}{kT}} dx$

- $\int_0^\infty \quad x^{\frac{1}{2}} e^{\frac{-x}{kT}} dx = \dfrac{kT\sqrt{\pi kT}}{2} = \dfrac{(kT)^{\frac{3}{2}} \pi^{1/2}}{2}$

- $\therefore$ $n = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}}e^{\frac{E_F-E_C}{kT}}\frac{(kT)^{\frac{3}{2}}\pi^{\frac{1}{2}}}{2}$

- $n = \frac{2\pi}{h^3}(2m_e^*)^{\frac{3}{2}}e^{\frac{E_F-E_C}{kT}}(kT)^{\frac{3}{2}}\pi^{\frac{1}{2}}$

- $n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}}e^{\frac{E_F-E_C}{kT}}$ \hspace{2cm} (6)

-    Equation (6) represents the density of electrons in the conduction band of an intrinsic semiconductor.

Density of Holes in Valence Band

- The density of holes in the valence band, p, is given by the integral of the product of the density of states in the valence band, Z(E)dE, and the probability of occupancy of holes in the valence band, [1 - F(E)] , over all energies in the valence band.

- Let dp be the number of holes available between the energy interval E and E+dE in the valence band

- Therefore; dp=Z(E)dE·(1-F(E))   (1)

- Since F(E) is the probability of occupancy of electrons 1-F(E) represents the probability of occupancy of holes.

- ∴ The number of holes in the valence band,

- $p = \int_{-\infty}^{E_V} dp = \int_{-\infty}^{E_V} (1 - F(E)) \cdot Z(E)dE$ (2)

- $1 - F(E) = 1 - \dfrac{1}{e^{\frac{E-E_F}{kT}} + 1}$ (3)

Density of states in the valence band,

- $Z(E)dE = \dfrac{4\pi}{h^3} \times (2m_h^*)^{\frac{3}{2}}(E_V - E)^{\frac{1}{2}}dE$ (4)

- $Z(E)dE = \dfrac{4\pi}{h^3} \times (2m_h^*)^{\frac{3}{2}}(E_V - E)^{\frac{1}{2}}dE$ (4)

- Where mh* is the effective mass of the hole.
- Substituting (3) and (4) in (2)

- $P = \int_{-\infty}^{E_V} \frac{4\pi}{h^3} \times (2m_h^*)^{\frac{3}{2}}(E_V - E)^{\frac{1}{2}}e^{\frac{E-E_F}{kT}}dE$

- $p = \frac{4\pi}{h^3} \times (2m_h^*)^{\frac{3}{2}}e^{\frac{-E_F}{kT}} \int_{-\infty}^{E_V} (E_V - E)^{\frac{1}{2}}e^{\frac{E}{kT}}dE$

- Let $\dfrac{Ev-E}{kT}$ be equal to x

- Then, $\dfrac{E}{kT} = \left(\dfrac{E_V}{kT}\right) - x$

- $dE = -kTdx$

- When E→ Ev then x→ 0
- And when E→-∞ then   x→∞

- $\therefore \quad p = \dfrac{4\pi}{h^3} \times (2m_h^*)^{\frac{3}{2}} e^{\frac{-E_F}{kT}} \displaystyle\int_{\infty}^{0} (kTx)^{\frac{1}{2}} e^{\frac{E_V}{kT}-x} dE(-kTdx)$

- $\quad\quad = \dfrac{4\pi}{h^3} \times (2m_h^* kT)^{\frac{3}{2}} e^{\frac{E_V-E_F}{kT}} \displaystyle\int_{\infty}^{0} (x)^{\frac{1}{2}} e^{-x} dx$

-

- $p = \dfrac{4\pi}{h^3} \times (2m_h^* kT)^{\frac{3}{2}} e^{\frac{E_V - E_F}{kT}} \dfrac{\sqrt{\pi}}{2}$

- $p = 2 \times \left(\dfrac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} e^{\frac{E_V - E_F}{kT}}$ (5)

- Equation (5) represents the density of holes in the valence band of the intrinsic semiconductor.

Intrinsic Carrier Concentration

- The number of electrons (n) in the conduction band, which is equal to the number of holes (p) in the valence band, in a perfectly pure semiconductor material at a given temperature is called the intrinsic carrier concentration (ni) .

- $ni = n = p$

- $ni^2 = np = 2 \times \left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} e^{\frac{E_F - E_C}{kT}} \times 2 \times \left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} e^{\frac{E_V - E_F}{kT}}$

- But $Ec - Ev = Eg$, the band gap energy

- $\therefore ni = 2 \times \left(\frac{2\pi kT}{h^2}\right)^{\frac{3}{2}} (m_e^* m_h^*)^{\frac{3}{4}} e^{\frac{-Eg}{2kT}}$

Variation of Intrinsic Carrier Concentration with Temperature

- The Intrinsic Carrier Concentration is given by:

$$ni = 2 \cdot \left(\frac{2\pi kT}{h^2}\right)^{\frac{3}{2}} (m_e^* m_h^*)^{\frac{3}{4}} \; e^{\frac{-E_g}{2kT}}$$

- Where ni is the intrinsic carrier concentration, Eg is the energy bandgap , kis Boltzmann's constant, T is absolute temperature.

• From the equation it is clear that as temperature increases, the intrinsic carrier concentration increases exponentially as more electrons jump from the valence band to the conduction band, creating more electron-hole pairs. At a given temperature, materials with larger band gaps have lower intrinsic carrier concentrations due to the requirement of more energy to excite electrons from the valence band to the conduction band.

Extrinsic Semiconductor (Qualitative)

• The conductivity of an intrinsic semiconductor can be significantly altered by the addition of impurities. This process is called doping and the impurities added are called dopants. A semiconductor which has undergone doping is called extrinsic semiconductor. There are two types of extrinsic semiconductors:

n-type semiconductor
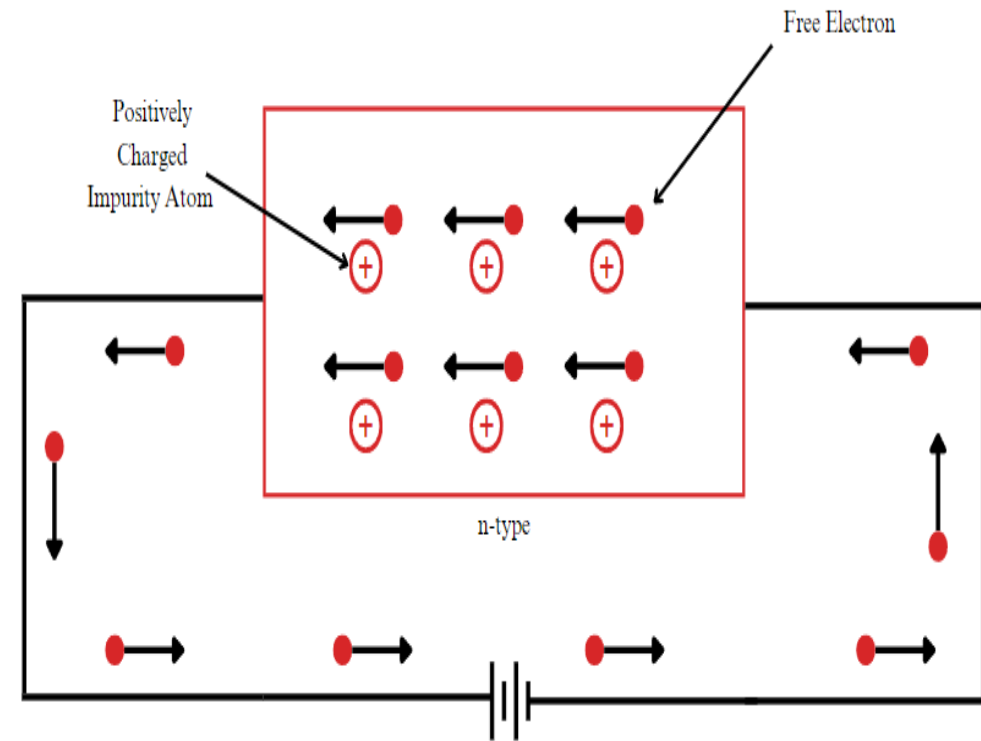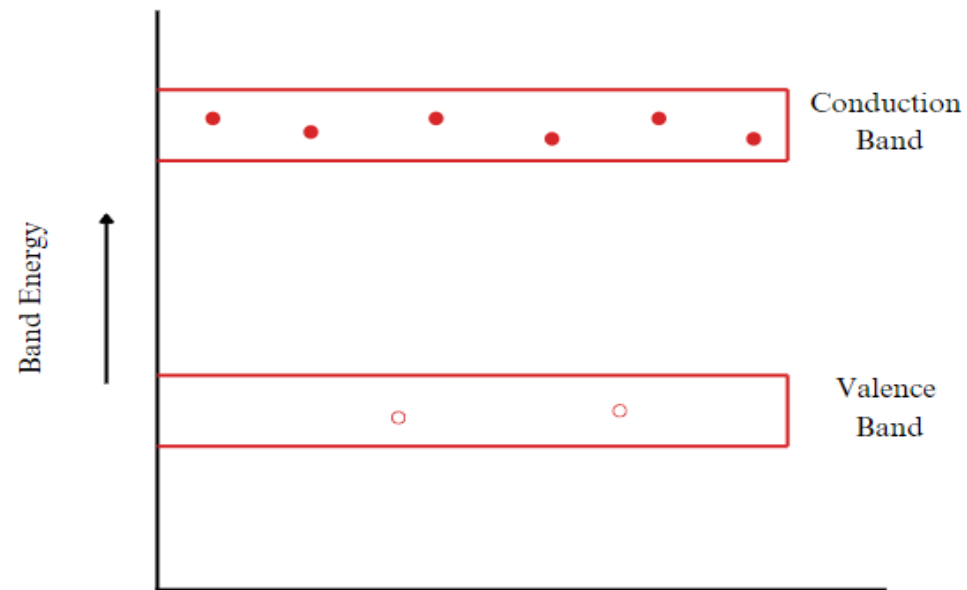
- The conductivity of an intrinsic semiconductor is varied considerably by changing the temperature and by adding the impurities. When an intrinsic semiconductor is doped with pentavalent impurities like phosphorus, arsenic, antimony, free electrons are generated,thereby making the electrons, the majority carriers. Holes become the minority carriers and the Fermi level shifts towards the conduction band.

- Example: Silicon doped with Phosphorus, Germanium doped with Arsenic etc

p-type semiconductor:
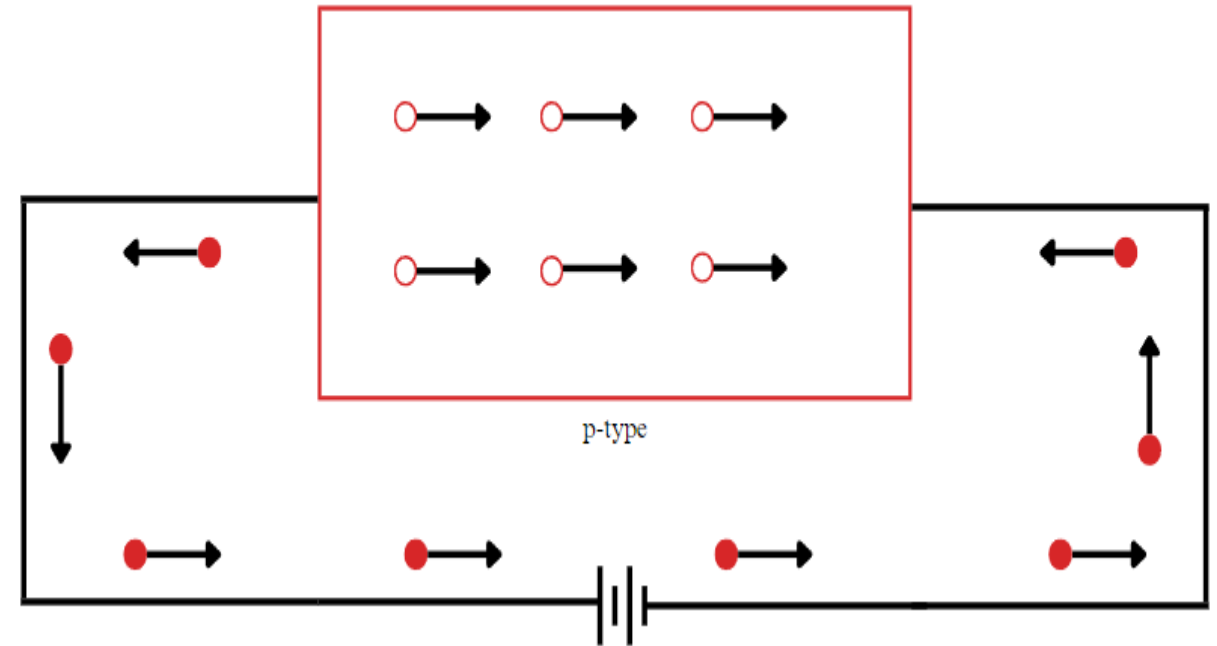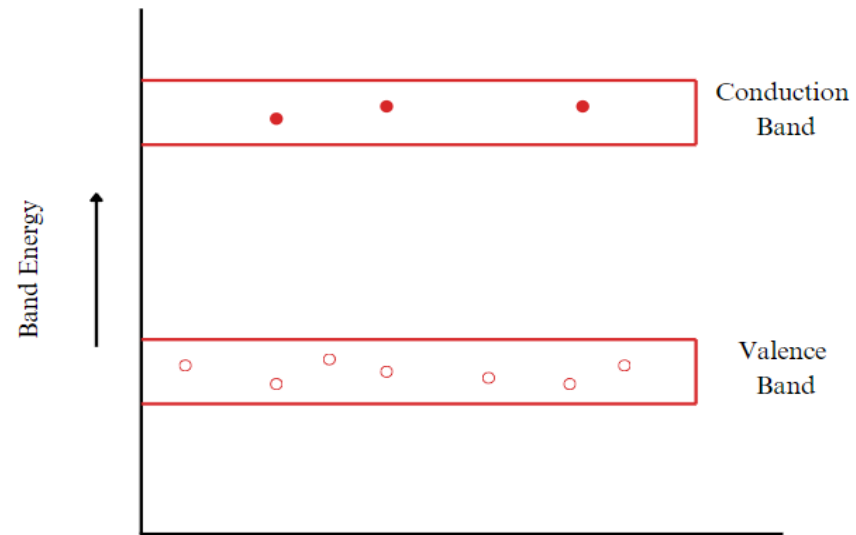
- When an intrinsic semiconductor is doped with trivalent impurities like boron, aluminum, gallium, holes are generated,thereby making the holes the majority carriers. Electrons become the minority carriers and the Fermi level shifts towards the valence band.

- Example: Silicon doped with Boron, Germanium doped with Aluminum etc

Properties of Extrinsic Semiconductors

- 1.   Conductivity: The conductivity is high compared to intrinsic semiconductors due to the increased number of charge carriers.

- 2.   Charge carriers: Depending on the type of dopants, the majority charge carriers may be electrons or holes.

- 3.   Position of the Fermi level :For n-type semiconductor, the Fermi level shifts towards the conduction band for p-type , it shifts towards the valence band.

. Formation of a p-n Junction

- The sequential processes involved in the formation of a p-n junction can be listed as:

- 1.   Bringing p region and n region together

- 2.   Diffusion of carriers

- 3.   Depletion region formation

- 4.   Developing a Potential barrier

- A p-n junction is formed by suitably joining a p-type and an n-type semiconductor. This interface between the two materials is called p-n junction, which is in effect, the control element of semiconductor devices.

- The p-n junction is fabricated by special techniques. One such commonly used technique is called Alloying. Here, a small mass of a trivalent impurity like Indium is placed on an n-type semiconductor,like n-type Germanium.Then it is heated to about 500^0C . This impurity and the n-type crystal melts together to form a puddle.Then the temperature is lowered allowing it to solidify. The atoms of Indium are adjusted in the semiconductor to form a single crystal.This region of the crystal where the concentration of indium is high , creates a p- region.Thus a p-n junction is fabricated.

p-n junction
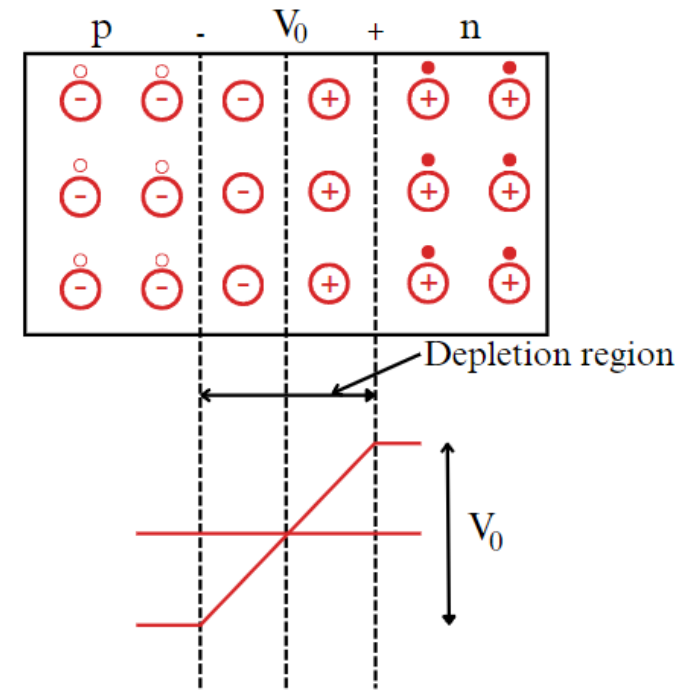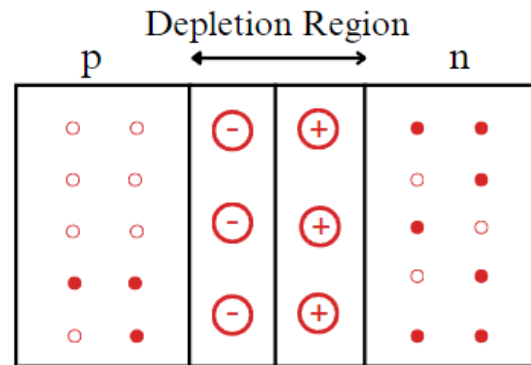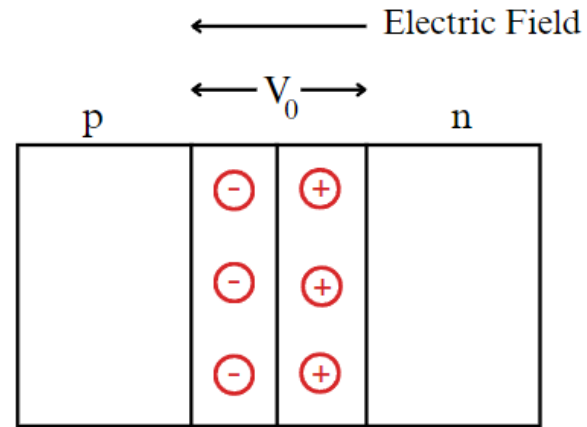
- As soon as the junction is formed, some of the free electrons in the n-region crosses the junction and combines with the holes in the p-region. Thus the n-region near the junction becomes positively charged and the P region near the junction becomes negatively charged. This negative charge prevents further crossing of electrons across the junction. This region which is devoid of moving charges is called Depletion Region, because the region is depleted or emptied of charge carriers.

- The positive and negative charges in the depletion region set up an electric field which is a barrier to the flow of electrons from the n-region to the p- region. Thus the depletion region acts as an insulator.It is very thin and its width depends on doping concentration. There develops a potential difference across this depletion region and is known as the Barrier potential or Junction Potential. The junction potential depends on factors like, type of the semiconductor material,extent of doping and temperature. For Si , the barrier potential is 0.7V and for Ge it is 0.3V.

Fermi Level in Semiconductors - Intrinsic and Extrinsic

- In an intrinsic semiconductor, at a given temperature the number of electrons in the conduction band equals the number of holes in the valence band i.e; n = p

- $2 \times \left(\dfrac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}} e^{\frac{E_F - E_C}{kT}} = 2 \times \left(\dfrac{2\pi m_h^* kT}{h^2} \right)^{\frac{3}{2}} e^{\frac{E_V - E_F}{kT}}$

- $$\left(\frac{m_e^*}{m_h^*}\right)^{\frac{3}{2}} = e^{\frac{E_V + E_C}{kT}} \times e^{\frac{-2E_F}{kT}}$$

- $$e^{\frac{2E_F}{kT}} = \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} e^{\frac{E_V + E_C}{kT}}$$

- Taking log on both sides to solve for E_F, the fermi energy ;

- $$\frac{2E_F}{kT} = \frac{3}{2} ln\left(\frac{m_h^*}{m_e^*}\right) + \left[\frac{(E_V + E_C)}{kT}\right]$$

- $$E_F = \frac{3kT}{4} ln\left(\frac{m_h^*}{m_e^*}\right) + \frac{(E_V + E_C)}{2}$$

- This is the equation of Fermi level in an intrinsic semiconductor.

At T=0,

$$E_F = \frac{(E_V + E_C)}{2} = \frac{(E_C - E_V)}{2} + E_V = \frac{E_g}{2} + E_V$$

- If Ev is taken as the zero level then,

- $E_F = \dfrac{E_g}{2}$

- In an intrinsic semiconductor the Fermi level lies exactly at the middle of the energy band gap ie; equidistant from both conduction and valence bands as it has equal number of electrons and holes in the conduction band and valence band respectively. That also implies that the probability of finding an electron in either band is equal. The Fermi level can shift slightly with temperature since it is at the exact middle of the bandgap at absolute zero.

Fermi Level of Intrinsic Semiconductor
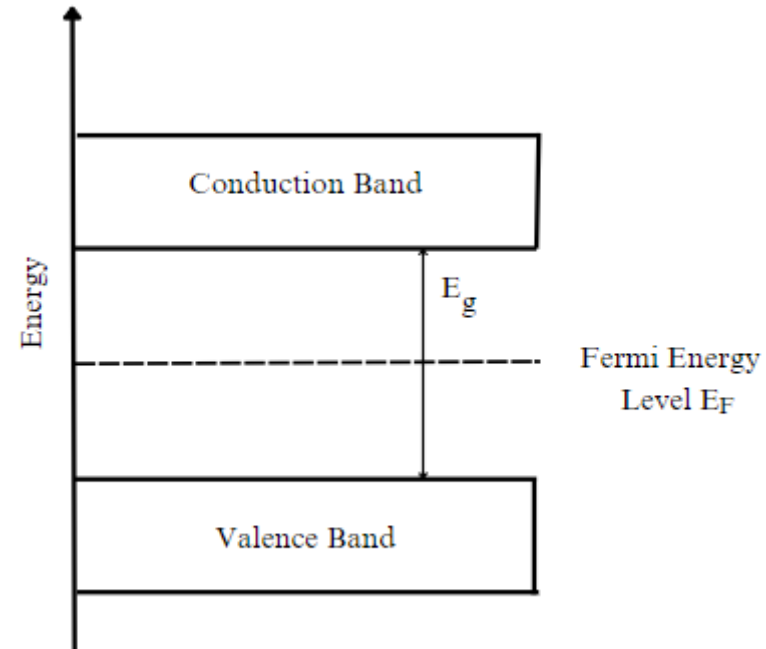
- In an extrinsic semiconductor, the position of the Fermi level is significantly influenced by the type and concentration of impurities present.

- In an n-type semiconductor, the pentavalent impurity atoms donate electrons to the semiconductor atoms (therefore they are called donor impurities). These electrons are accommodated in an energy level called donor energy level. This level will be near the conduction band slightly below it.

- The Fermi level shifts towards the conduction band and is in between conduction band and donor energy level as there is a higher probability of finding electrons near the conduction band due to the added donor impurity. At T=0, EFi is at the middle of EC and ED i.e; fermi level shifts from EFi to EFn.

- $E_{Fn} = \dfrac{E_C + E_D}{2}$

• At low temperature the electrons in the conduction band are from the donor atoms. As temperature increases, intrinsic carriers dominate.Hence the fermi level shifts downwards. At a particular temperature called the depletion temperature, the fermi level coincides with the donor energy level.

Diode Equation (Derivation)

- Diode equation gives the relation between the current flowing through a diode and the external voltage applied across it.

-

- Total current I of diode,

- $I = I_p + I_n$; where I_p is the hole current and I_n is the electron current

- Now; The hole current, $I_p \alpha \, \Delta P_n$ (Change in hole density in the n-region)

- The electron current , $I_n \alpha \, \Delta N_p$ (Change in electron density in the p-region)

- By Boltzmann relation ; Hole density in p-region $P_p = P_n e^{\frac{V_B}{V_T}}$ (1)

- Where V_B is the Barrier potential across the depletion layer and V_T is the Voltage equivalent of temperature

- $V_T = \dfrac{kT}{e} = \dfrac{T}{11600}$

- At room temperature; T= 27°C = (27 + 273) K = 300 K

- $\therefore$ V_T = 26 mV

- When there is no biasing ; $V_B = V_0$

-

- $\therefore$ Equation (1) becomes , $P_p = P_n e^{\frac{V_0}{V_T}}$ (2)

-

- When forward biased, V_0 is decreased

- $V_B = V_0 - V$; where V is the applied Voltage)

- When forward biased, the hole density in the n-region increases from P_n to $P_n + \Delta P_n$;since some of the holes from the p-region enter the n-region when forward biased.

- Consider Equation (1)

-

- $P_p = (P_n + \Delta P_n)e^{\frac{V_0 - V}{V_T}}$

-

- $P_p = (P_n + \Delta P_n)e^{\frac{V_0}{V_T}}e^{\frac{-V}{V_T}}$

-

$$\Delta P_n = P_p e^{\frac{-V_0}{V_T}}\left[e^{\frac{V}{V_T}} - 1\right] \qquad (4)$$

- The hole current, $I_p \alpha\ \Delta P_n$

- $\therefore\ I_p \alpha\ P_p e^{\frac{-V_0}{V_T}} \left[e^{\frac{V}{V_T}} - 1 \right]$

- $I_p =\ I_{sp} \left[e^{\frac{V}{V_T}} - 1 \right]$;where I_{sp} is the Proportionality constant

- Similarly ; Electron current

- $I_n = I_{sn} \left[e^{\frac{V}{V_T}} - 1 \right]$

- $\therefore$ Total current,

- $I = I_p + I_n$

- $I = I_{sp} \left[e^{\frac{V}{V_T}} - 1 \right] + I_{sn} \left[e^{\frac{V}{V_T}} - 1 \right]$

- $I = (I_{sp} + I_{sn}) \left[e^{\frac{V}{V_T}} - 1 \right]$

- $I = I_0 \left[e^{\frac{V}{V_T}} - 1 \right]$; where I_o is the reverse saturation current

- $I_0 = (I_{sp} + I_{sn})$ which is fully temperature dependent. It is an unwanted component.

- $I = I_0 \left[e^{\frac{V}{V_T}} - 1 \right]$; where I is the diode current,V is the external supply voltage (+ve for forward bias, -ve for reverse bias),I_o is the reverse saturation current.

- This is the diode current equation.

- Incorporating the material constant, the Diode equation can be written as ,

- $I = I_0 \left[e^{\frac{V}{\eta V_T}} - 1 \right]$

- η is material constant
- $\eta = 1$ for Ge
- $\eta = 2$ for Si

V-I Characteristics of a p-n Junction

- The voltage applied across the p-n junction and current through it can be represented graphically. This is termed as the V-I characteristics of a p- n junction .
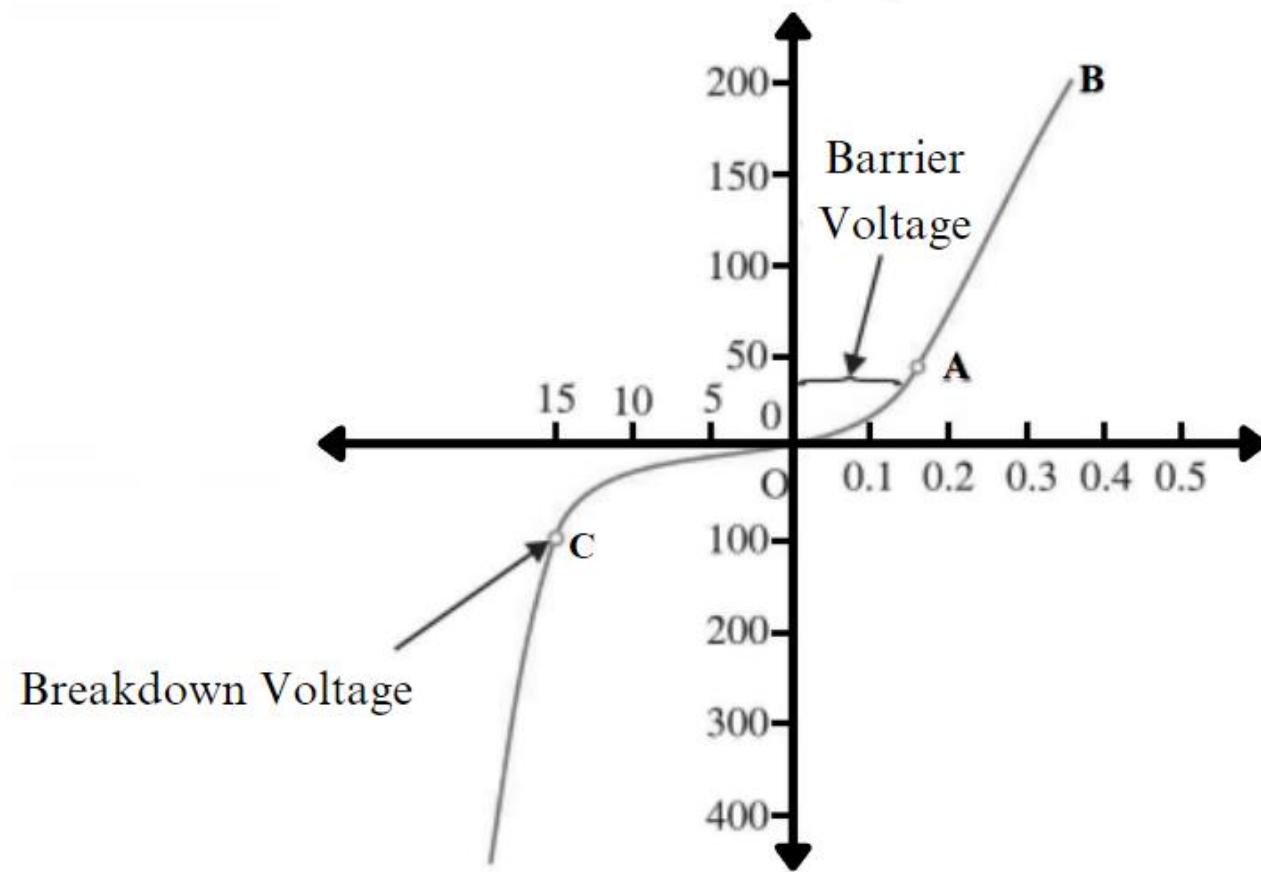
- Zero Bias or No Bias Region:
- This happens at zero external voltage, when the key K is open. Due to the potential barrier at the junction, no current flows across it. So the circuit current is zero. This is indicated by the point O in the graph.

- **Forward Bias Region:**

• Here the p- n junction is connected in the forward biased condition: ie; p-region is connected the positive terminal and n- region to the negative terminal.When forward biased, the barrier potential at the junction begins to reduce. The current increases very slowly with the applied voltage, since the external voltage is used for overcoming the potential barrier at the junction. This is represented by OA in the graph.It is clear from the Diode equation that there is an exponential relationship between current and voltage; hence obviously the graph will be non-linear. After some forward voltage called knee voltage (0.3 V for Ge and 0.7V for Si), the current begins to increase rapidly with increase in external voltage. Here, the diode behaves as an ordinary conductor.The plot is nearly linear and it is shown as AB. This forward bias region is used for the practical applications like rectification, amplification, and other electronic circuits.