UNIT – 2 (Semiconductors)

2.1 Introduction ofsemiconductors:

- ✓ A semiconductor has electrical conductivity between that of a conductor and an insulator. Semiconductors differ from metals in their characteristic property of decreasing electrical resistivity with increasing temperature. Semiconductors can also display properties of passing current more easily in one direction than the other, and sensitivity to light.

- ✓ Because the conductive properties of a semiconductor can be modified by controlled addition of impurities or by the application of electrical fields or light, semiconductors are very useful devices for amplification of signals, switching, and energy conversion. The comprehensive theory of semiconductors relies on the principles of quantum physics to explain the motions of electrons through a lattice of atoms.

- ✓ Semiconductors are the foundation of modern electronics, including radio, computers, and telephones. Semiconductor-based electronic components include transistors, solar cells, many kinds of diodes including the light-emitting diode (LED), the silicon controlled rectifier, photo-diodes, digital analog integrated circuits. Increasing understanding of semiconductor materials and fabrication processes has made possible continuing increases in the complexity and speed of semiconductor devices, an effect known as Moore's Law.

2.2 Properties ofsemiconductor

- ✓ The resistivity of semiconductors lies between a conductor and an Insulator. (It various from 10^{-4} to 0.5 Ωm).
- ✓ At 0 K it behave as insulator.
- ✓ They have negative temperature Coefficient of resistance. (when the temperature is increased large number of charge carriers are produced due to breaking of covalent bonds and hence these electrons move freely and gives rise to conductivity)
- ✓ In semiconductors, both electrons and holes are charge carriers.
- ✓ If we increase the temperature of semiconductor, its electrical conductivity also increases.
- ✓ They have an empty conduction band and almost filled valence band 0 K.
- ✓ They are formed by a covalent bonds.

- ✓ They have small energy gap (or) band gap.
- ✓ Semiconductors are material having electrical conductivity considerably grater than that of an insulator but significantly lower than that of a conductor.
- ✓ Germanium (Ge) and Silicon (Si) are Elemental semiconductors and are widely used in semiconductor devices.
- ✓ Gallium Arsenide (GaAs), Indium Phosphide (InP), Cadmium Sulphide (CdS), etc are known as **compound semiconductors**.

- ✓ These compound semiconductors which are formed from the combinations of the elements of groups III and V [Gallium phosphide (GaP), Gallium arsenide (GaAs), Indium phosphide (InP) Indium arsenide (InAs)] or group II and VI [Magnesium oxide (MgO), Magnesium silicon (MgSi) Zinc oxide (ZnO), Zinc sulphide (ZnS)] and are widely used in fabrication of optoelectronic devices. Such as LASER, LEDs etc…
- ✓ Semiconductors consists two charge carriers, namely electrons and holes, for conduction.
- ✓ The electrical conductivity of a pure semiconductor is significantly low and not be used in device fabrication.
- ✓ **These pure semiconductors are known as intrinsic semiconductors.**

- ✓ Through the technique of doping, the conductivity of a semiconductor can be increased in magnitude to a desire value for conduction.
- ✓ **Doped semiconductors are known as extrinsic semiconductors.**

- ✓ The remarkable feature of these extrinsic semiconductors is that current is transported in them by two different charge carriers, electrons and holes, and throught two different processes , drift and diffusion.
- ✓ Extrinsic semiconductors are widely used in fabrication of solid state devices. P-N junction diode, Transistors, Capacitors, Integrated circuits, etc.

2.3 Types of semiconductor

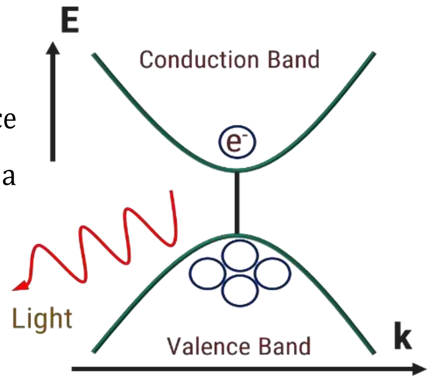
They are classified on the basis of type of energy emission:

(1) Direct and indirect bandgap semiconductor:

(2) Intrinsic and Extrinsic semiconductor:

(1) Direct and indirect bandgap semiconductor:

(a) Direct bandgap semiconductor:

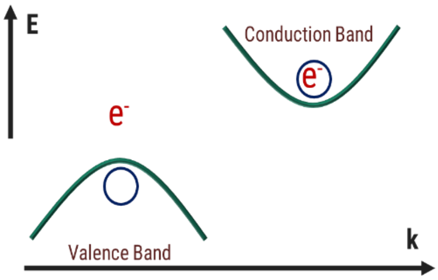


- ✓ In this type of semiconductor, when an excited electron falls back into valance band, the electron and holes recombine to produce light (release a photon).

  i.e. e^- + hole → hυ (photon)

- ✓ This process is called radiative recombination. (also known as spontaneous emission).

(b) Indirect bandgap semiconductor:



- ✓ In this type of semiconductor, when an excited electron falls back into valance band, the electron and holes recombine to produce light (release a photon).

- ✓ In a indirect bandgap semiconductor, when an excited electron falls back into the valence band, electrons and holes recombine to generate heat and this heat is dissipated in the material.

  i.e. e^- + hole → heat

- ✓ This process is known as non–radiative recombination.

(2) Intrinsic and Extrinsic semiconductor:

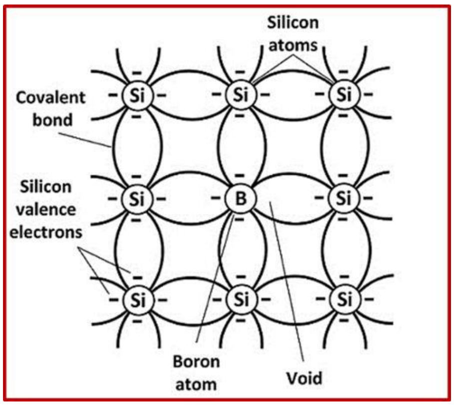
(a) Intrinsic semiconductor:

- ✓ A semiconductor in extremely pure form, without the addition of impurities is known as intrinsic semiconductors. Its electrical conductivity can be changed due to thermal excitation.
- ✓ At 0K the valance band is completely filled and the conduction band is empty.
- ✓ The carrier concentration (i.e.) electron density (or) hole density increases exponentially with increase in temperature.

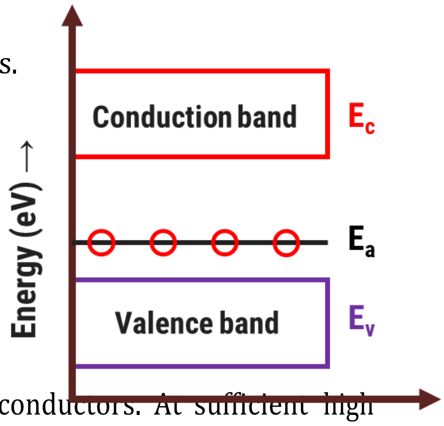
(b) Extrinsic semiconductor:

- ✓ A semiconductor in extremely impure form, with the addition of impurities is known as extrinsic semiconductors. Extrinsic semiconductor can be of two type:
  - (I) P – type semiconductors
  - (II) N – type semiconductors

(I) P – type semiconductors:

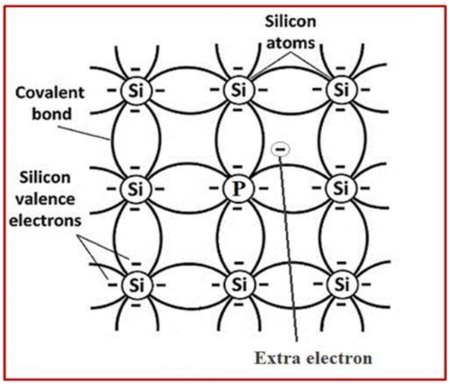


- ✓ It is formed by doping a trivalent impurity in Si or Ge. e.g. Ga, In, B.
- ✓ Let us assume, a trivalent element B is added to an intrinsic semiconductor Si. All the valence electrons of B will form covalent bonds with neighbouring Si atoms as shown in fig.
- ✓ The dopant is in need of an electron to complete its fourth covalent bond formation with Si. Thus holes acts as acceptors of electrons.
- ✓ These holes have slightly higher energy and creates an energy level called acceptor level just above valence band.



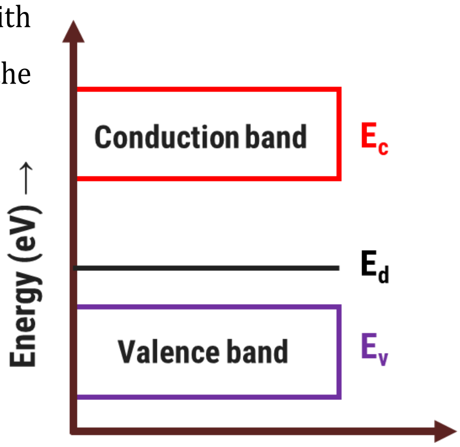
- ✓ As the dopant atoms accept electrons, they are also called Acceptors.
- ✓ An electron must gain energy of an order of E_a in order to create hole in valence band.
- ✓ The acceptor atoms get negatively ionized after accepting electrons from valence band at room temperature. This is how holes are created in valence bands.
- ✓ This is why holes are majority charge carriers in p – type semiconductors. At sufficient high temperatures, additional electron hole pairs are generated due to braking of covalent bond.

(II) N – type semiconductors:



- ✓ It is formed by doping a Pentavalent impurity in Si or Ge. e.g. P, As, Sb.
- ✓ Let us assume, a pentavalent element P is added to an intrinsic semiconductor Si.

- ✓ All the valence electrons of P will form covalent bonds with neighbouring Si atoms, leaving an extra electron (fifth electron) in the unbounded state as shown in fig.
- ✓ This extra electron is weakly bounded to the atom and enters into an energylevelindonorstate,justbelowtheconduction band.
- ✓ Asthese electronsarenottightlyboundtotheatom,allsuch electronsat roomtemperaturecangetexcitedintoconduction band,even forsmall amountofexternal energy.



- ✓ Asthe pentavalent atom donates electrons to conduction band, they are also called donor atoms.
- ✓ $E_d$istheminimumenergyrequiredforelectrontoenterinconductionband.So,inthis typeof semiconductors,freeelectronsarethemajoritychargecarriers.

2.3.1 Differencebetweenintrinsicandextrinsicsemiconductors

Intrinsic semiconductor	Extrinsic semiconductor
Itispuresemiconductorwithoutimpurity.	Impuritiesareaddedinthissemiconductors.
The number of free electrons in conduction band and holes in valence band are same/equal.	Numberfreeelectronsandholesarenotsame.
Electrical conductivity is low.	Electrical conductivity is high.
Electrical conductivity is a function of temperature only.	Electrical conductivity is a function of temperatureandimpuritiesboth.
Examples are crystalline forms of pure silicon (Si) and germanium (Ge).	Examples are silicon and germanium doped with impurities like Boron, Phosphorous, etc...

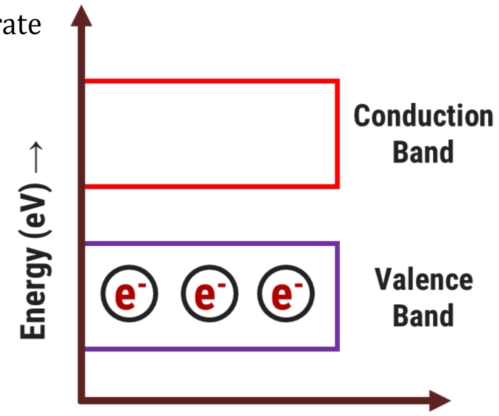
2.3.2 DifferencebetweenP-typeandN-typesemiconductors

P-type semiconductors	N-type semiconductors
In this type of semiconductor impurities like boron, aluminium, and gallium are added.	In this type of semiconductor impurities like Phosphorus,arsenic,antimonyareadded.

Holes are majority carriers and electrons are minority carriers.	Electrons are majority carriers and holes are minority carriers.
Densityofholesismuchgreaterthandensityof electrons i.e. $n_h > n_e$.	Density of electrons is much greater than density of holes i.e. $n_e > n_h$.
The acceptor energy level is close to valence band andawayfromconductionband.	The donor energy level is close to conduction band and away from valence band.
Fermi level lies between acceptor level and valence band.	Fermi level lies between donor level and conduction band.
Impurity level creates a vacancy of electrons i.e. holes	Impurity atom provides an extra electron.

2.4 Equilibrium carrierstatistics

- ✓ The energy gap between valence and conduction band is relatively very small. Hence, at room temperature, some electrons may possess enough thermal energy to cross over the band gap and enter conduction band.
- ✓ These excited electrons leave behind a vacancy called 'Hole'.
- ✓ In an intrinsic electrons, for every excited electrons, moving to conduction band there is a hole created in valence band.
- ✓ Thus,inanintrinsicsemiconductor: $n_e = n_h$ (densityofelectron=densityofholes)
- ✓ Here,whenanelectronmovestofillahole,anotherholeiscreatedatoriginalelectron source.
- ✓ When a voltage is applied, electrons in conduction band accelerate towards positive terminal and holes in valence band move towards negative terminal.
- ✓ So, we can say that conduction takes place due to the movement of both charge carriers.
- ✓ At a temperature T, charge carriers possess an average kinetic energy (E) and the mean thermal velocity υ_{th},



∴ Drift velocity: $\upsilon_d = \mu$ e

- ✓ Aswedenotethedriftvelocityofelectronwith υ_{de} andthatofholewith υ_{dh} andmobility of electron and hole with μ_e and μ_h respectively,
- ✓ Currentdensityduetoelectrons: $J_e = n_e\, e\, \upsilon_{de} = n_e\, e\, \mu_e\, E$
- ✓ Current density due to electrons: $J_h = n_h\, e\, \upsilon_{dh} = n_h\, e\, \mu_h\, E$

- ✓ From ohm's law $J = \sigma E$, electronic and hole conductivities are $\sigma_e = n_e e \mu_e$

  $\sigma_h = n_h e \mu_h$

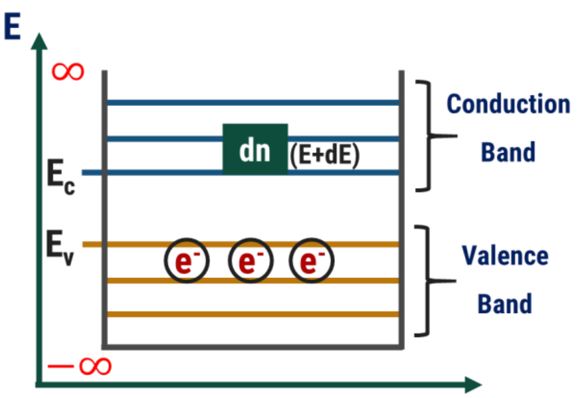
- ✓ The intrinsic conductivity $\boldsymbol{\sigma_i} = (n_e \mathbf{e} \boldsymbol{\mu_e} + \mathbf{n_h} \mathbf{e} \boldsymbol{\mu_h})$

Carrier concentration: Let us now calculate the electron concentration (n_e), in the conduction band and the hole concentration (n_h) in valence band.

- ✓ Definition: The number of electrons in the conduction band per unit volume (n_e) and the number of holes in the valence band per unit volume (n_h) of the material is known as carrier concentration or density of charge carriers.

2.4.1 Carrier Concentration: Density of electrons in conduction band **Calculation of electron density:**

- ✓ Let dn be the number of electrons whose energy lies in the energy interval E and (E+dE) in the conduction band. Then,



$\therefore dn = N(E)\, dE \cdot f(E)$

- ✓ $N(E)\, dE$ = density of states
- ✓ $f(E)$ = probability function for electrons

$$\therefore n_e = \int_{E_c}^{\infty} dn = \int_{E_c}^{\infty} N(E)\, dE \cdot f(E)$$

$$\therefore n_e = \int_{E_c}^{\infty} N(E)\, dE \cdot f(E) \ldots \ldots \ldots (1)$$

$$\therefore N(E)dE = \frac{\pi}{2}\left(\frac{8m_e^*}{h^2}\right)^{\frac{3}{2}} E^{\frac{1}{2}} dE$$

$$\therefore N(E)dE = \frac{\pi}{2}\left(\frac{8m_e^*}{h^2}\right)^{\frac{3}{2}} (E - Ec)^{\frac{1}{2}} dE \;\ldots\ldots\ldots (2)$$

$$f(E) = \frac{1}{1 + e^{\left(\frac{E - E_f}{k_B T}\right)}}$$

- ✓ At any temp, energy required by electron to move in conduction band is higher than k_BT.

$$E - E_F \gg k_BT = \frac{E - E_F}{k_BT} \gg 1 = e^{\frac{E-E_F}{k_BT}} \ggg 1$$

$$\therefore f(E) = \frac{1}{e^{\left(\frac{E - E_F}{k_B T}\right)}}$$

$$\therefore f(E) = e^{-\left(\frac{E - E_F}{k_B T}\right)}$$

$$\therefore f(E) = e^{\left(\frac{E_F - E}{k_B T}\right)} \;\ldots\ldots\ldots (3)$$

- ✓ Put the value of equation (2) & (3) in equation (1).

$$\therefore n_e = \int_{E_c}^{\infty} \frac{\pi}{2}\left(\frac{8m_e^*}{h^2}\right)^{\frac{3}{2}} (E - Ec)^{\frac{1}{2}} dE \times e^{\left(\frac{E_F - E}{k_B T}\right)}$$

To solve this equation, let us assume,

$E - E_c = x\, k_BT$

$\therefore E = E_c + x\, k_BT$

On differentiating, $dE = 0 + dx\, k_BT$

Based on assumption, limits will also change

$\therefore E \rightarrow E_c \qquad \therefore E_c - E_c \rightarrow x = 0$

$\therefore E \rightarrow \infty \qquad \therefore \infty - E_c \rightarrow x = \infty$

$$\therefore n_e = \int_{0}^{\infty} \frac{\pi}{2}\left(\frac{8m_e^*}{h^2}\right)^{\frac{3}{2}} \times (E - Ec)^{\frac{1}{2}} dE \times e^{\left(\frac{E_F - E}{k_B T}\right)}$$

$$\therefore n_e = \int_0^{\infty} \frac{\pi}{2}\left(\frac{8\, m_e^*}{h^2}\right)^{\frac{3}{2}} \times (E - E_c)^{\frac{1}{2}} dE \times e^{\left(\frac{E_F}{k_B T}\right)} \times e^{-\left(\frac{E}{k_B T}\right)}$$

$$\therefore n_e = \frac{\pi}{2}\left(\frac{8\, m_e^*}{h^2}\right)^{\frac{3}{2}} \times e^{\left(\frac{E_F}{k_B T}\right)} \int_0^{\infty} (E - E_c)^{\frac{1}{2}} dE \times e^{-\left(\frac{E}{k_B T}\right)}$$

$$\therefore n_e = \frac{\pi}{2}\left(\frac{8\, m_e^*}{h^2}\right)^{\frac{3}{2}} \times e^{\left(\frac{E_F}{k_B T}\right)} \int_0^{\infty} (x\, k_B T)^{\frac{1}{2}} \times k_B T\, dx \times e^{-\left(\frac{E_c + x\, k_B T}{k_B T}\right)}$$

$$\therefore n_e = \frac{\pi}{2}\left(\frac{8\, m_e^*}{h^2}\right)^{\frac{3}{2}} \times e^{\left(\frac{E_F}{k_B T}\right)} \int_0^{\infty} (x)^{\frac{1}{2}} (k_B T)^{\frac{1}{2}} \times k_B T \times e^{-\left(\frac{E_c}{k_B T}\right)} \times e^{-\left(\frac{x\, k_B T}{k_B T}\right)} dx$$

$$\therefore n_e = \frac{\pi}{2}\left(\frac{8\, m_e^*}{h^2}\right)^{\frac{3}{2}} \times e^{\left(\frac{E_F}{k_B T}\right)} \times e^{-\left(\frac{E_c}{k_B T}\right)} \times (k_B T)^{\frac{3}{2}} \int_0^{\infty} (x)^{\frac{1}{2}} e^{-(x)} dx$$

Gamma Function

$$\int_0^{\infty} (x)^{\frac{1}{2}} e^{-(x)}\, dx = \frac{\sqrt{\pi}}{2}$$

$$\therefore n_e = \frac{\pi}{2}\left(\frac{8\, m_e^*}{h^2}\right)^{\frac{3}{2}} \times e^{\left(\frac{E_F - E_c}{k_B T}\right)} \times (k_B T)^{\frac{3}{2}} \times \frac{\sqrt{\pi}}{2}$$

$$\therefore n_e = \frac{\pi}{2}\left(\frac{4 \times 2\, m_e^*}{h^2}\right)^{\frac{3}{2}} \times e^{\left(\frac{E_F - E_c}{k_B T}\right)} (k_B T)^{\frac{3}{2}} \frac{(\pi)^{\frac{1}{2}}}{2}$$

$$\therefore n_e = \frac{(\pi)^{\frac{3}{2}}}{4}\left(\frac{(2)^2 \times 2\, m_e^*}{h^2}\right)^{\frac{3}{2}} \times e^{\left(\frac{E_F - E_c}{k_B T}\right)} (k_B T)^{\frac{3}{2}}$$

$$\therefore n_e = \frac{8}{4}\left(\frac{2\pi\, m_e^*\, k_B T}{h^2}\right)^{\frac{3}{2}} \times e^{\left(\frac{E_F - E_c}{k_B T}\right)}$$

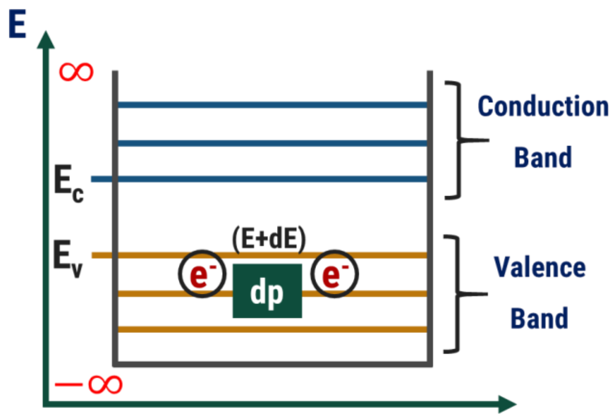
$$\therefore n_e = 2\left(\frac{2\pi\, m_e^*\, k_B T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{E_F - E_c}{k_B T}\right)} \quad \ldots\ldots (4)$$

Equation (4) suggestes “ Density of electrons in conduction band for Intrinsic semiconductors”.

2.4.2 CarrierConcentration:Densityofholesinvalenceband

Calculation of hole density:

- ✓ Letdpbethenumberofelectronswhoseenergyliesintheenergyinterval E and (E+dE) in the conduction band. Then,



$$\therefore dp = N(E)dE \cdot [1 - f(E)]$$

- ✓ N(E) dE = density of states
- ✓ 1 – f(E) = probability function for holes

$$\therefore n_e = \int_{E_c}^{\infty} dp = \int_{E_c}^{\infty} N(E)\, dE \cdot [1 - f(E)]$$

$$\therefore n_e = \int_{E_c}^{\infty} N(E)\, dE \cdot [1 - f(E)] \ldots\ldots\ldots (1)$$

$$\therefore N(E)dE = \frac{\pi}{2}\left(\frac{8\, m_h^*}{h^2}\right)^{\frac{3}{2}} E^{\frac{1}{2}} dE$$

$$\therefore N(E)dE = \frac{\pi}{2}\left(\frac{8\, m_h^*}{h^2}\right)^{\frac{3}{2}} (Ev - E)^{\frac{1}{2}} dE \ldots\ldots\ldots (2)$$

$$f(E) = \frac{1}{1 + e^{\left(\frac{E - E_f}{k_B T}\right)}}$$

Let us consider, $\left(\frac{E - E_F}{k_B T}\right) = x,$

$$\therefore 1 - f(E) = 1 - \frac{1}{1 + e^{(x)}}$$

$$\therefore 1 - f(E) = \frac{1 + e^{(x)} - 1}{1 + e^{(x)}}$$

$$\therefore 1 - f(E) = \frac{1}{\frac{1 + e^{(x)}}{e^{(x)}}}$$

$$\therefore 1 - f(E) = \frac{1}{e^{-(x)} + 1}$$

$$\therefore 1 - f(E) = \frac{1}{e^{-\left(\frac{E - E_F}{k_B T}\right)} + 1}$$

$$\therefore 1 - f(E) = \frac{1}{1 + e^{\left(\frac{E_F - E}{k_B T}\right)}}$$

Here, $E_F - E \gg k_B T = \frac{E_F - E}{k_B T} \gg 1 = e^{\frac{E_F - E}{k_B T}} \gg\gg 1$

$$\therefore 1 - f(E) = \frac{1}{e^{\left(\frac{E_F - E}{k_B T}\right)}}$$

$$\therefore 1 - f(E) = e^{-\left(\frac{E_F - E}{k_B T}\right)}$$

$$\therefore 1 - f(E) = e^{\left(\frac{E - E_F}{k_B T}\right)} \ldots\ldots\ldots (3)$$

Put the value of equation (2) & (3) In equation (1).

$$\therefore n_p = \int_{-\infty}^{E_v} N(E)\, dE \cdot [1 - f(E)]$$

$$\therefore n_p = \int_{-\infty}^{E_v} \frac{\pi}{2} \left(\frac{8 m^*}{h^2}\right)^{\frac{3}{2}} (E_v - E)^{\frac{1}{2}}\, dE \cdot e^{\left(\frac{E - E_F}{k_B T}\right)}$$

$$\therefore n_p = \int_{\infty}^{0} \frac{\pi}{2} \left(\frac{8 m^*}{h^2}\right)^{\frac{3}{2}} (E_v - E)^{\frac{1}{2}}\, dE \cdot e^{\left(\frac{E - E_F}{k_B T}\right)}$$

$$\therefore n_p = \int_{\infty}^{0} \frac{\pi}{2} \left(\frac{8 m^*}{h^2}\right)^{\frac{3}{2}} (E_v - E)^{\frac{1}{2}}\, dE \cdot e^{\frac{E}{k_B T}}\, e^{-\left(\frac{E_F}{k_B T}\right)}$$

To solve this equation, let us assume,

$E_v - E = x k_B T$ $\quad\quad$ $\therefore E = E_v - x k_B T$

On differentiating, $\quad\quad$ $\therefore 0 - dE = dx\, k_B T$

Based on assumption, limits will also change

$\therefore E \rightarrow -\infty \qquad \therefore E_v - (-\infty) \rightarrow x = \infty$

$\therefore E \rightarrow E_v \qquad \therefore E_v - E_v \rightarrow x = 0$

$$\therefore n_p = \frac{\pi}{2}\left(\frac{8m_h^*}{h^2}\right)^{\frac{3}{2}} \times e^{-\left(\frac{E_F}{k_B T}\right)} \int_{\infty}^{0} (E_v - E)^{\frac{1}{2}}\, dE \times e^{\left(\frac{E}{k_B T}\right)}$$

$$\therefore n_p = \frac{\pi}{2}\left(\frac{8m_h^*}{h^2}\right)^{\frac{3}{2}} \times e^{-\left(\frac{E_F}{k_B T}\right)} \int_{\infty}^{0} (x\, k_B T)^{\frac{1}{2}} - dx\, k_B T \times e^{\left(\frac{E_v - x k_B T}{k_B T}\right)}$$

$$\therefore n_p = \frac{\pi}{2}\left(\frac{8m_h^*}{h^2}\right)^{\frac{3}{2}} \times e^{-\left(\frac{E_F}{k_B T}\right)} \int_{\infty}^{0} (x)^{\frac{1}{2}} (k_B T)^{\frac{1}{2}} k_B T \times e^{\left(\frac{E_v}{k_B T}\right)} \times e^{-\left(\frac{x k_B T}{k_B T}\right)} - dx$$

$$\therefore n_p = \frac{\pi}{2}\left(\frac{8m_h^*}{h^2}\right)^{\frac{3}{2}} \times e^{-\left(\frac{E_F}{k_B T}\right)} \int_{\infty}^{0} (x)^{\frac{1}{2}} (k_B T)^{\frac{3}{2}} \times e^{\left(\frac{E_v}{k_B T}\right)} \times e^{-(x)} - dx$$

$$\therefore n_p = \frac{\pi}{2}\left(\frac{8m_h^*}{h^2}\right)^{\frac{3}{2}} \times e^{-\left(\frac{E_F}{k_B T}\right)} \times e^{\left(\frac{E_v}{k_B T}\right)} \times (k_B T)^{\frac{3}{2}} \int_{0}^{\infty} (x)^{\frac{1}{2}} \cdot e^{-(x)}\, dx$$

Gamma Function

$$\int_{0}^{\infty} (x)^{\frac{1}{2}} e^{-(x)}\, dx = \frac{\sqrt{\pi}}{2}$$

$$\therefore n_p = \frac{\pi}{2}\left(\frac{8m_h^*}{h^2}\right)^{\frac{3}{2}} \times e^{-\left(\frac{E_F}{k_B T}\right)} \times e^{\left(\frac{E_v}{k_B T}\right)} \times (k_B T)^{\frac{3}{2}} \times \frac{\sqrt{\pi}}{2}$$

$$\therefore n_p = \frac{\pi}{2}\left(\frac{4 \times 2m_h^*}{h^2}\right)^{\frac{3}{2}} \times e^{\left(\frac{E_v - E_F}{k_B T}\right)} \times (k_B T)^{\frac{3}{2}} \times \frac{(\pi)^{\frac{1}{2}}}{2}$$

$$\therefore n_p = \frac{(\pi)^{\frac{3}{2}}}{4}\left(\frac{(2)^2 \times 2m_h^*}{h^2}\right)^{\frac{3}{2}} \times e^{\left(\frac{E_v - E_F}{k_B T}\right)} \times (k_B T)^{\frac{3}{2}}$$

$$\therefore n_p = \frac{8}{4}\left(\frac{\pi\, 2\, m_h^*\, k_B T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{E_v - E_F}{k_B T}\right)}$$

$$\therefore n_p = 2\left(\frac{\pi\, 2\, m_h^*\, k_B T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{E_v - E_F}{k_B T}\right)} \quad \ldots\ldots\ldots (4)$$

Equation (4) suggestes " Density of holes in valence band for Intrinsic semiconductors."

2.4.3 Fermi level and its variation with temperature For intrinsic semiconductor:

Density of electrons in conduction band **(N_e)**= Density of holes in valence band **(N_h)**

$$2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{E_F-E_c}{k_B T}\right)} = 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{E_v-E_F}{k_B T}\right)}$$

$$\therefore (m_e^*)^{\frac{3}{2}} e^{\left(\frac{E_F-E_c}{k_B T}\right)} = (m_h^*)^{\frac{3}{2}} e^{\left(\frac{E_v-E_F}{k_B T}\right)} \quad \ldots\ldots\ldots (1)$$

$$\therefore (m_e^*)^{\frac{3}{2}} e^{\left(\frac{E_F-E_c}{k_B T}\right)} = (m_h^*)^{\frac{3}{2}} e^{\left(\frac{E_v-E_F}{k_B T}\right)}$$

$$\therefore \frac{(m_h^*)^{\frac{3}{2}}}{(m_e^*)^{\frac{3}{2}}} = \frac{e^{\left(\frac{E_F-E_c}{k_B T}\right)}}{e^{\left(\frac{E_v-E_F}{k_B T}\right)}}$$

$$\therefore \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} = e^{\left(\frac{E_F-E_c}{k_B T}\right)} \quad e^{-\left(\frac{E_v-E_F}{k_B T}\right)}$$

$$\therefore \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} = e^{\left(\frac{E_F-E_c}{k_B T}\right)} \quad e^{\left(\frac{E_F-E_v}{k_B T}\right)}$$

$$\therefore \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} = e^{\left(\frac{E_F-E_c+E_F-E_v}{k_B T}\right)}$$

$$\therefore \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} = e^{\left(\frac{2E_F-(E_c+E_v)}{k_B T}\right)}$$

$$\therefore \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} = e^{\left(\frac{2E_F}{k_B T}\right)} \times e^{-\left(\frac{E_c+E_v}{k_B T}\right)}$$

$$\therefore \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} = \frac{e^{\left(\frac{2E_F}{k_B T}\right)}}{e^{\left(\frac{E_c+E_v}{k_B T}\right)}}$$

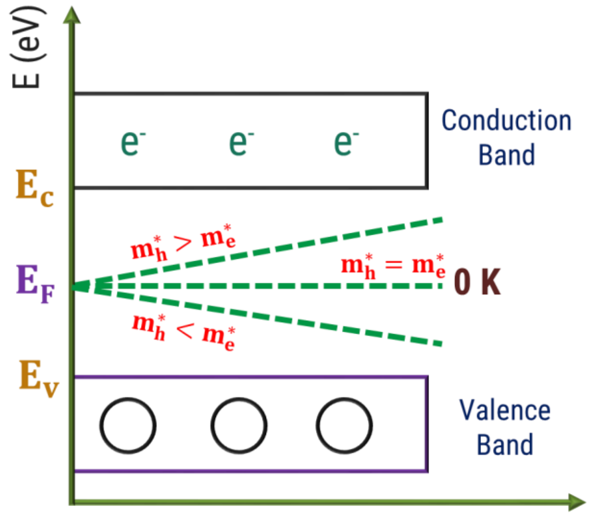
$$\therefore \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} \cdot e^{\left(\frac{E_c+E_v}{k_B T}\right)} = e^{\left(\frac{2E_F}{k_B T}\right)} \quad \ldots\ldots\ldots (2)$$

Taking log on both sides,

$$\therefore \log e^{\left(\frac{2E_F}{k_B T}\right)} = \log\left[\left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} \cdot e^{\left(\frac{E_c+E_v}{k_B T}\right)}\right]$$

$$\log[A \cdot B] = \log[A] + \log[B]$$

$$\therefore \log e^{\left(\frac{2E_F}{k_B T}\right)} = \log\left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} + \log e^{\left(\frac{E_c+E_v}{k_B T}\right)}$$



$$\therefore \frac{2E_F}{k_B T} = \left(\frac{3}{2}\log\left(\frac{m_h^*}{m_e^*}\right) + \frac{E_c+E_v}{k_B T}\right)$$

$$\therefore E_F = \frac{k_B T}{2}\left(\frac{3}{2}\log\left(\frac{m_h^*}{m_e^*}\right) + \frac{E_c+E_v}{k_B T}\right)$$

$$\therefore E_F = \frac{k_B T}{2}\,\frac{3}{2}\log\left(\frac{m_h^*}{m_e^*}\right) + \frac{k_B T}{2}\,\frac{E_c+E_v}{k_B T}$$

$$\therefore E_F = \frac{3k_B T}{4}\log\left(\frac{m_h^*}{m_e^*}\right) + \frac{E_c+E_v}{2}$$

When $m_h^* = m_e^*$ at T = 0 K then,

$$\therefore E_F = \frac{3k_B T}{4}\log\left(\frac{m_h^*}{m_e^*}\right) + \frac{E_c+E_v}{2}$$

$$\therefore E_F = \frac{E_c+E_v}{2}$$

When $m_h^* = m_e^*$ at T=0 K then, this equation shows fermi level (E_F) lies between E_c and E_v at T = 0 K temperature.

$$\therefore E_F = \frac{3k_B T}{4}\log\left(\frac{m_h^*}{m_e^*}\right) + \frac{E_c+E_v}{2}$$

If a small change in temp. occurs then, possibilities are:

(1) Increase in temp. $m_h^* > m_e^*$

(2) decrease in temp. $m_h^* < m_e^*$

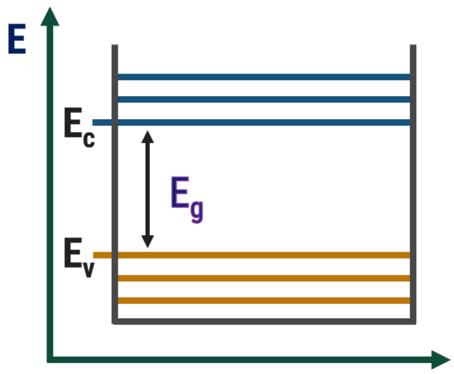
Q.1 Determine the position of Fermi level in silicon semiconductor at 300K. Given that the Bandgap is 1.12 eV, and $m_e^* = 0.12 m_0$ and $m_h^* = 0.28 m_0$ (m_0 = rest mass of an electron).

Ans. $E_g = 1.12\,eV = 1.12 \times 1.6 \times 10^{-19}$ Joule T = 300 K

$m_e^* = 0.12 m_0$

$m_h^* = 0.28 m_0$

$E_F = ?$



$$\therefore E_F = \frac{E_c+E_v}{2} + \frac{3k_B T}{4}\log\left(\frac{m_h^*}{m_e^*}\right)$$

$$\therefore E_F = \frac{E_g}{2} + \frac{3k_B T}{4}\log\left(\frac{m_h^*}{m_e^*}\right)$$

$$\therefore E_F = \frac{1.12\times1.6\times10^{-19}}{2} + \frac{3}{4}(1.38\times10^{-23}\times300)\log\left(\frac{0.28\,m_0}{0.12\,m_0}\right)$$

$$\therefore E_F = \frac{1.12\times1.6\times10^{-19}}{2} + \frac{3}{4}(1.38\times10^{-23}\times300)\ln\left(\frac{0.28\,m_0}{0.12\,m_0}\right)$$

$$\therefore E_F = 8.96\times10^{-20} + \frac{3}{4}(4.14\times10^{-21})\ln(0.84729)$$

$$\therefore E_F = 9.22\times10^{-20}\ \text{Joule}$$

$$\therefore E_F = \frac{9.22\times10^{-20}}{1.60\times10^{-19}}$$

$$\therefore E_F = 0.5764\ \text{eV}$$

2.4.4 Law of Mass action

- ✓ This law states that for a given semiconductor (intrinsic or extrinsic) product of charge carrier concentration remains a constant at any given temperature if doping is varied.

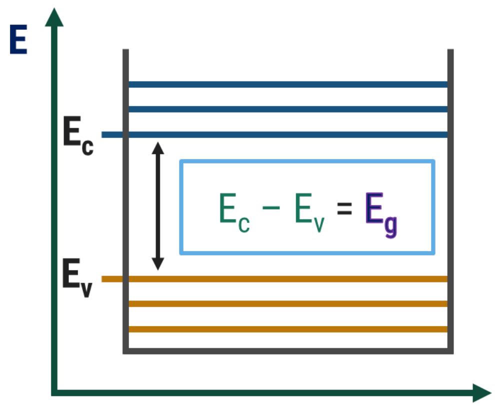
  i.e. $n_e \times n_h = n_i^2 = \text{constant}$

- ✓ Where, n_i is the carrier concentration (intrinsic charge carrier density), based on law of mass action.

$$\therefore n_i^2 = n_e \times n_h$$

$$\therefore n_i^2 = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{E_F - E_c}{k_B T}\right)} \times 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{E_v - E_F}{k_B T}\right)}$$

$$\therefore n_i^2 = 2^2 (m_e^*)^{\frac{3}{2}} \left(\frac{2\pi k_B T}{h^2}\right)^3 e^{\left(\frac{E_F - E_c}{k_B T}\right)} \times (m_h^*)^{\frac{3}{2}} e^{\left(\frac{E_v - E_F}{k_B T}\right)}$$



$$\therefore n_i^2 = 2^2 (m_e^* m_h^*)^{\frac{3}{2}} \left(\frac{2\pi k_B T}{h^2}\right)^3 e^{\left(\frac{E_F - E_c + E_v - E_F}{k_B T}\right)}$$

$$\therefore n_i^2 = 2^2 (m_e^* m_h^*)^{\frac{3}{2}} \left(\frac{2\pi k_B T}{h^2}\right)^3 e^{\left(\frac{E_v - E_c}{k_B T}\right)}$$

$$\therefore n_i = 2 (m_e^* m_h^*)^{\frac{3}{4}} \left(\frac{2\pi k_B T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{E_v - E_c}{2 k_B T}\right)}$$

$$\therefore n_i = 2 (m_e^* m_h^*)^{\frac{3}{4}} \left(\frac{2\pi k_B T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{-E_g}{2 k_B T}\right)}$$

- ✓ This equation gives value of intrinsic carrier concentration.
- ✓ For an intrinsic semiconductor, $n_e = n_h = n_i$

2.4.5 Mobility and Conductivity

- ✓ Charge carriers in semiconductor is assumed to be moving freely inside a semiconductor. In case of intrinsic semiconductor, both electrons and holes contribute to the electrical conductivity.
- ✓ Conductivity due to electrons is given by: $\sigma_e = n_e\, e\, \mu_e$
- ✓ Conductivity due to holes is given by: $\sigma_h = n_h\, e\, \mu_h$
- ✓ Total conductivity for an intrinsic semiconductor:

$$\sigma_i = \sigma_e + \sigma_h$$

$$\therefore \sigma_i = n_e\, e\, \mu_e + n_h\, e\, \mu_h \qquad \text{we know, } n_e = n_h = n_i$$

$$\therefore \sigma_i = n_i\, e\, \mu_e + n_i\, e\, \mu_h$$

$$\therefore \sigma_i = n_i\, e\, (\mu_e + \mu_h)$$

- ✓ Substituting the value of ni,

$$\therefore \sigma_i = 2\,(m_e^* m_h^*)^{\frac{3}{4}} \left(\frac{2\pi k_B T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{-E_g}{2 k_B T}\right)}\; e\,(\mu_e + \mu_h)$$

$$\therefore \sigma_i = 2e\,(m_e^* m_h^*)^{\frac{3}{4}} \left(\frac{2\pi k_B T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{-E_g}{2 k_B T}\right)} (\mu_e + \mu_h)$$

$$\therefore \sigma_i = C \times e^{\left(\frac{-E_g}{2 k_B T}\right)} \quad \ldots\ldots\ldots (1)$$

- ✓ From equation (1), it can be seen that σ_i depends on the negative exponential of forbidden energy gap, temperature and on mobility of electrons and holes.
- ✓ Taking logarithm on both sides of equation (1)

$$\therefore \ln \sigma_i = \ln C - \frac{E_g}{2 k_B T}$$

- ✓ From equation we can say that, conductivity increases with temperature.

Q.1 For an intrinsic silicon, room temperature electrical conductivity is 4×10^{-4} ℧m^{-1}. Electron and hole mobilities are 0.14 m^2/V sec and 0.040 m^2/V sec respectively. Calculate the electron and hole concentration at room temperature.

Ans. $\sigma_i = 4 \times 10^{-4}\ (\Omega m)^{-1}$

$\mu_e = 0.14\ m^2/V sec$ $\mu_h =$

$0.040 m^2/V sec$ $n_i = ?$

$$\therefore \sigma_i = n_i\, e\, (\mu_e + \mu_h)$$

$$\therefore n_i = \frac{\sigma_i}{e(\mu_e + \mu_h)}$$

$$\therefore n_i = \frac{4 \times 10^{-4}}{(1.6 \times 10^{-19})\,(0.14 + 0.040)}$$

$$\therefore n_i = \frac{4 \times 10^{-4}}{2.88 \times 10^{-20}}$$

$$\therefore n_i = 1.38 \times 10^{16}/m^3$$

From law of mass action, we have $n_e = n_h = n_i$

$$\therefore n_e = n_h = 1.38 \times 10^{16}/m^3$$

Q.2 Find the resistance of an intrinsic germanium rod 1 cm long, 1 mm wide and 1 mm thick at 300 K. Here, $n_i = 2.5 \times 10^{19}/m^3$, $\mu_e = 0.39\ m^2/V sec$, $\mu_h = 0.19\ m^2/V sec$.

Ans. $L = 1cm = 10^{-2}$ m

$b = 1mm = 10^{-3}$ m $t =$

$1mm = 10^{-3}$ m $T =$

300 K

$\mu_e = 0.39\ m^2/V sec$ μ_h

$= 0.19 m^2/V sec$ $R = ?$

$$\therefore \sigma_i = n_i\, e\, (\mu_e + \mu_h)$$

$\therefore \sigma_i = (2.5 \times 10^{19})(1.6 \times 10^{-19})(0.39 + 0.19)$

$\therefore \sigma_i = 2.32\ (\Omega m)^{-1}$

Area = breadth × thickness Area = $(10^{-3} \times 10^{-3}$ $m^2)$

we know, $R = \dfrac{\rho l}{A}$

$$\therefore R = \frac{10^{-2}}{2.32\,(10^{-3} \times 10^{-3})}$$

$\therefore R = 4310\ \Omega$

Q.3 In an intrinsic semiconductor, energy gap is 1.2 eV. What is the ratio between its conductivity at 600 K and at 300 K.

Ans. $E_g = 1.2\ eV = 1.2 \times 1.6 \times 10^{-19}$ J $T_1 = 600$ K

$T_2 = 300K$

$\dfrac{\sigma_1}{\sigma_2} = ?$

Let σ_1 be the electrical conductivity at T_1K and σ_2 be the electrical conductivity at T_2K.

$$\therefore \frac{\sigma_1 = C \times e^{\left(\frac{-E_g}{2 k_B T_1}\right)}}{\sigma_2 = C \times e^{\left(\frac{-E_g}{2 k_B T_2}\right)}}$$

$$\therefore \frac{\sigma_1}{\sigma_2} = e^{\left(\frac{-E_g}{2 k_B}\left[\frac{1}{T_1} - \frac{1}{T_2}\right]\right)}$$

$$\therefore \frac{\sigma_1}{\sigma_2} = e^{\left(\frac{-1.2 \times 1.6 \times 10^{-19}}{2 \times 1.38 \times 10^{-23}}\left[\frac{1}{600} - \frac{1}{300}\right]\right)}$$

$$\therefore \sigma_1 = e^{11.59}\,\sigma_2$$

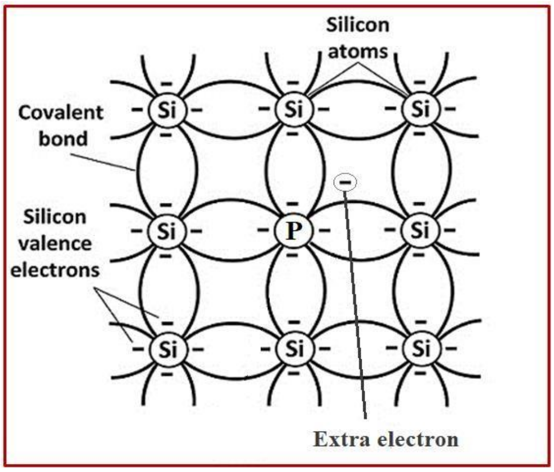
$$\therefore \frac{\sigma_1}{\sigma_2} = 108416.886$$

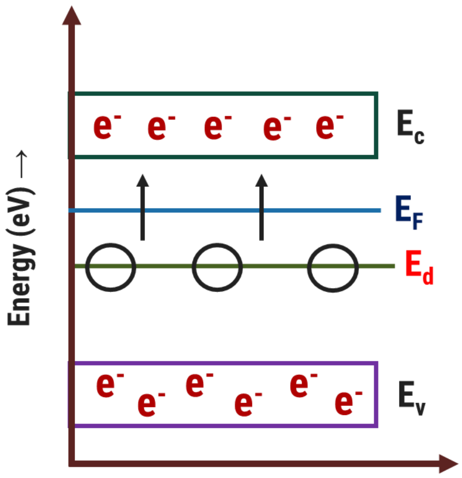
$$\therefore \frac{\sigma_1}{\sigma_2} = 1.08 \times 10^5$$

2.4.6 Extrinsic semiconductors: Carrier concentration (n-type) Expression

forcarrierconcentrationinn-typesemiconductors:

- ✓ Before deriving the equation for n-type semiconductor, let us first derive the equation for fermi level.





- ✓ LetNdbethedonorconcentrationi.e.numberofatomsperunitvolumeofmaterialand Ed be the donor energy level.
- ✓ Letusassumethat$E_c - E_F > k_B T$,so,densityofelectronsinconductionbandisgivenby

$$\therefore n_e = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{E_F - E_c}{k_B T}\right)} \quad \ldots\ldots (1)$$

- ✓ At $T = 0$ K, the fermi level lies between E_c and E_d and also, all donor levels are filled with electrons (donor atoms).
- ✓ With increase in temperature, more donor atoms moves to conduction band and density of electrons in conduction band increases. Then density of ionized donor atoms must be (N_d^+).

$\therefore N_d^+ = N_d\,[1 - f(E_d)]$ ... ... (2)

- ✓ Here N_d is number of donor atoms. (Donors will give it's electrons to conduction band).

  $1 - f(E)$ is the probability of holes.

We know, $f(E) = \dfrac{1}{1 + e^{\left(\frac{E_d - E_f}{k_B T}\right)}}$

$\therefore 1 - f(E) = 1 - \dfrac{1}{1 + e^{\left(\frac{E_d - E_f}{k_B T}\right)}}$

$\therefore 1 - f(E) = 1 - \left[1 + e^{\left(\frac{E_d - E_f}{k_B T}\right)}\right]^{-1}$

- ✓ By binominal expansion: $(1 + x)^{-1} = (1 - x)$

$\therefore 1 - f(E) = 1 - \left[1 - e^{\left(\frac{E_d - E_f}{k_B T}\right)}\right]$

$\therefore 1 - f(E) = e^{\left(\frac{E_d - E_f}{k_B T}\right)}$ ... ... (3)

- ✓ Substitute equation 3 in equation 2.

$\therefore \mathbf{N_d^+ = N_d\, e^{\left(\frac{E_d - E_f}{k_B T}\right)}}$ ... ... **(4)**

- ✓ At very low temperature no. electrons or holes pair is generated, where electrons are in conduction band.

$\therefore \mathbf{n_e = N_d^+}$

$$\therefore n_e = 2\left(\frac{2\pi m_e^* k T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{E_F - E_c}{k_B T}\right)}$$

$$\therefore N_d^{+} = 2\left(\frac{2\pi m_e^* k T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{E_F - E_c}{k_B T}\right)}$$

- ✓ From equation (4)

$$\therefore N_d\, e^{\left(\frac{E_d - E_f}{k_B T}\right)} = 2\left(\frac{2\pi m_e^* k T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{E_F - E_c}{k_B T}\right)}$$

- ✓ Takinglogonbothsides

$$\therefore \ln N_d + \ln e^{\left(\frac{E_d - E_f}{k_B T}\right)} = \ln 2\left(\frac{2\pi m_e^* k T}{h^2}\right)^{\frac{3}{2}} + \ln e^{\left(\frac{E_F - E_c}{k_B T}\right)}$$

$$\therefore \ln N_d + \frac{E_d - E_f}{k_B T} = \ln\left[2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{\frac{3}{2}}\right] + \frac{E_F - E_c}{k_B T}$$

$$\therefore \frac{E_F - E_c}{k_B T} - \frac{E_d - E_f}{k_B T} = \ln N_d - \ln\left[2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{\frac{3}{2}}\right]$$

- ✓ Multiplying by $k_B T$ and simplify above equation

$$\therefore E_F - E_c - E_d + E_f = k_B T \ln N_d - \ln\left[2\left(\frac{2\pi m_e^* k T}{h^2}\right)^{\frac{3}{2}}\right]$$

$$\therefore 2E_F - (E_d + E_c) = k_B T \ln \frac{N_d}{\left[2\left(\frac{2\pi m_e^* k T}{h^2}\right)^{\frac{3}{2}}\right]}$$

$$\therefore 2E_F = (E_d + E_c) + k_B T \ln \frac{N_d}{2}\left[\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{-\frac{3}{2}}\right]$$

$$\therefore E_F = \frac{(E_d + E_c)}{2} + \frac{k_B T}{2} \ln \frac{N_d}{2}\left(\frac{2\pi m_e^* k T}{h^2}\right)^{-\frac{3}{2}} \quad \ldots\ldots\ldots (5)$$

- ✓ Above equation gives the value of Fermi energy in N-type semiconductor

- ✓ Expression for carrier concentration in conduction band for N-type semiconductor

$$\therefore n_e = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{E_F-E_c}{k_B T}\right)} \quad \ldots\ldots\ldots (1)$$

- ✓ Let us first simplify the term: $e^{\left(\frac{E_F-E_c}{k_B T}\right)}$

$$\therefore e^{\left(\frac{E_F-E_c}{k_B T}\right)} = e^{\left(\frac{E_F}{k_B T}\right)} e^{-\left(\frac{E_c}{k_B T}\right)}$$

$$\therefore e^{\left(\frac{E_F-E_c}{k_B T}\right)} = e^{\left(\frac{\frac{(E_d+E_c)}{2}+\frac{k_B T}{2}\ln\frac{N_d}{2}\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{-\frac{3}{2}}}{k_B T}\right)} e^{-\left(\frac{E_c}{k_B T}\right)}$$

$$\therefore e^{\left(\frac{E_F-E_c}{k_B T}\right)} = e^{\left(\frac{(E_d+E_c)}{2k_B T}+\frac{k_B T}{2k_B T}\ln\frac{N_d}{2}\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{-\frac{3}{2}}\right)} e^{-\left(\frac{E_c}{k_B T}\right)}$$

$$\therefore e^{\left(\frac{E_F-E_c}{k_B T}\right)} = e^{\frac{(E_d+E_c)}{2k_B T}} e^{\frac{1}{2}\ln\frac{N_d}{2}\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{-\frac{3}{2}}} e^{-\left(\frac{E_c}{k_B T}\right)}$$

$$\therefore e^{\left(\frac{E_F-E_c}{k_B T}\right)} = e^{\frac{(E_d+E_c-2E_c)}{2k_B T}} e^{\frac{1}{2}\ln\frac{N_d}{2}\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{-\frac{3}{2}}}$$

$$\therefore e^{\left(\frac{E_F-E_c}{k_B T}\right)} = e^{\frac{(E_d+E_c-2E_c)}{2k_B T}} e^{\ln\left[\frac{N_d}{2}\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{-\frac{3}{2}}\right]^{\frac{1}{2}}}$$

$$\therefore e^{\left(\frac{E_F-E_c}{k_B T}\right)} = e^{\frac{(E_d-E_c)}{2k_B T}} \left[\frac{N_d}{2}\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{-\frac{3}{2}}\right]^{\frac{1}{2}}$$

$$\therefore e^{\left(\frac{E_F-E_c}{k_B T}\right)} = e^{\frac{(E_d-E_c)}{2k_B T}} \left(\frac{N_d}{2}\right)^{\frac{1}{2}} \left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{-\frac{3}{4}} \quad \ldots\ldots\ldots (6)$$

- ✓ Substitute this value in equation (1)

$$\therefore n_e = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{E_F-E_c}{k_B T}\right)} \quad \ldots\ldots\ldots (1)$$

$$\therefore n_e = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{\frac{3}{2}} e^{\frac{(E_d-E_c)}{2k_B T}} \left(\frac{N_d}{2}\right)^{\frac{1}{2}} \left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{-\frac{3}{4}}$$

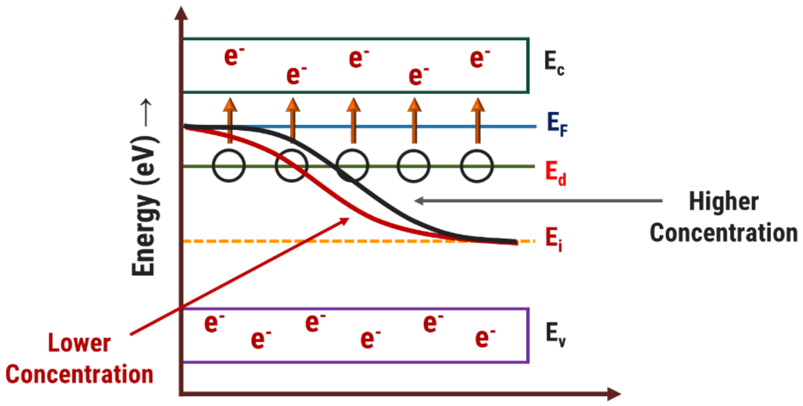
$$\therefore n_e = (2)^{\frac{1}{2}}(2)^{\frac{1}{2}}\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{\frac{3}{4}} e^{\frac{(E_d-E_c)}{2k_B T}} \left(\frac{N_d}{2}\right)^{\frac{1}{2}}$$

$$\therefore n_e = (2N_d)^{\frac{1}{2}}\left(\frac{2\pi m^* k T}{h^2}\right)^{\frac{3}{4}} e^{\frac{(E_d - E_c)}{2k_BT}}$$

- ✓ **Variation of Fermi level with temperature and impurity concentration:**

$$\therefore n_e = (2N_d)^{\frac{1}{2}}\left(\frac{2\pi m^* k T}{h^2}\right)^{\frac{3}{4}} e^{\frac{(E_d - E_c)}{2k_BT}}$$

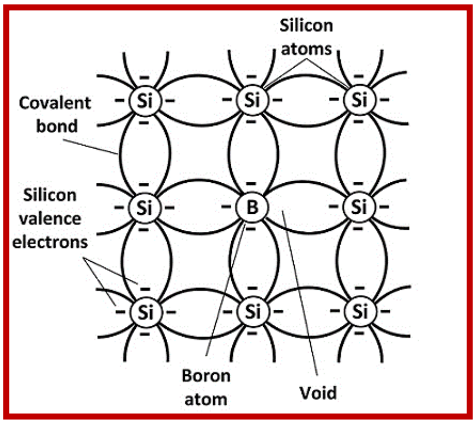
- ✓ We can say, from above equation that fermi level increases with increase in temperature.
- ✓ Now, as temperature increases, more donor atoms gets positively ionized due to donation of electrons in conduction band and the fermi level lies between E_c and E_d.
- ✓ At a particular temperature, when all donor atoms are ionized, electron-hole pairs are generated due to breaking of covalent bonds. Thus we can say that the fermi level gradually shifted towards the intrinsic fermi level E_i.
- ✓ In the figure, the variation of fermi level with high and low donor concentration indicated.
- ✓ From the figure, it is clear that shifting of fermi level with rise of temperature is shown in case of high donor concentration.

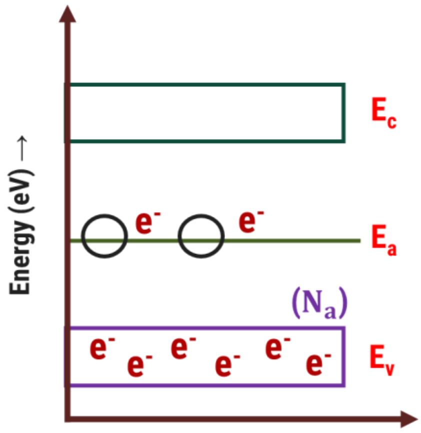


2.4.7 Extrinsic semiconductors: Carrier concentration (p-type) Expression

for carrier concentration in n-type semiconductors:

- ✓ Before deriving the equation for p-type semiconductor, let us first derive the equation for fermi level.
- ✓ Let N_a be the acceptor concentration i.e. number of atoms per unit volume of material and E_a be the acceptor energy level.





- ✓ Let us assume that $E_a - E_F > k_B T$, so, density of holes in valence band is given by

$$\therefore n_p = 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{E_V - E_F}{k_B T}\right)}$$

- ✓ At T=0K, the fermi level lies between E_V and E_a and also, all acceptor levels are remains empty.
- ✓ With increase in temperature, more acceptor atoms gets negatively ionized due to transfer of electrons from the valence band.
- ✓ Then density of ionized acceptor atoms must be (N_a^-).

$$\therefore N_a^- = N_a\, f(E_a) \;\ldots\ldots\ldots (2)$$

- ✓ Here N_a is number of acceptor atoms. (Acceptors accepts electrons from valence band and become negatively ionized).
- ✓ f(E) is the probability of electrons.
- ✓ We know, $f(E) = \frac{1}{1+e^{\left(\frac{E_a - E_f}{k_B T}\right)}}$
- ✓ Also, fermi level lies between ($E_a - E_F$) in above equation is positive and grater than $k_B T$.

$$\therefore f(E) = \frac{1}{e^{\left(\frac{E_a - E_f}{k_B T}\right)}}$$

$$\therefore f(E) = e^{\left(\frac{E_F - E_a}{k_B T}\right)} \;\ldots\ldots\ldots (3)$$

- ✓ Substitute equation 3 in equation 2.

$$\therefore N_a^- = N_a e^{\left(\frac{E_F - E_a}{k_B T}\right)} \quad \ldots\ldots\ldots(4)$$

- ✓ Atverylowtemp.noelectronorholepairisgenerated.Where,holesareinvalenceband is equal to the density of ionized acceptors atoms.

  $\mathbf{n_a = N_a^-}$

$$\therefore n_p = 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{E_V - E_F}{k_B T}\right)}$$

$$\therefore N_a^- = 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{E_V - E_F}{k_B T}\right)}$$

From equation (4)

$$\therefore N_a e^{\left(\frac{E_F - E_a}{k_B T}\right)} = 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{E_V - E_F}{k_B T}\right)}$$

Taking log on both sides

$$\therefore \ln N_a + \ln e^{\left(\frac{E_F - E_a}{k_B T}\right)} = \ln 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{\frac{3}{2}} + \ln e^{\left(\frac{E_V - E_F}{k_B T}\right)}$$

$$\therefore \ln N_a + \frac{E_F - E_a}{k_B T} = \ln\left[2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{\frac{3}{2}}\right] + \frac{E_V - E_F}{k_B T}$$

$$\therefore \frac{E_V - E_F}{k_B T} - \frac{E_F - E_a}{k_B T} = \ln N_a - \ln\left[2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{\frac{3}{2}}\right]$$

Multiplying by $k_B T$ and simplify above equation

$$\therefore E_V - E_F - E_F + E_a = k_B T \ln N_a - \ln\left[2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{\frac{3}{2}}\right]$$

$$\therefore E_V - E_F - E_F + E_a = k_B T \ln N_a - \ln\left[2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{\frac{3}{2}}\right]$$

$$\therefore -2E_F + (E_V + E_a) = k_B T \ln \frac{N_a}{\left[2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{\frac{3}{2}}\right]}$$

$$\therefore 2E_F = (E_V + E_a) - k_B T \ln \left[\frac{N_a}{2}\left(\frac{2\pi m_h k_B T^*}{h^2}\right)^{-\frac{3}{2}}\right]$$

$$\therefore E_F = \frac{(E_V + E_a)}{2} - \frac{k_B T}{2} \ln \frac{N_a}{2}\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{-\frac{3}{2}} \ldots\ldots\ldots (5)$$

$$\therefore n_p = 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{E_V - E_F}{k_B T}\right)} \ldots\ldots\ldots (1)$$

Letusfirstsimplifytheterm $e^{\left(\frac{E_V - E_F}{k_B T}\right)}$

$$\therefore e^{\left(\frac{E_V - E_F}{k_B T}\right)} = e^{\left(\frac{E_V}{k_B T}\right)} e^{-\left(\frac{E_F}{k_B T}\right)}$$

$$\therefore e^{\left(\frac{E_V - E_F}{k_B T}\right)} = e^{\left(\frac{E_V}{k_B T}\right)} e^{\left(-\frac{\frac{(E_V + E_a)}{2} - \frac{k_B T}{2} \ln \frac{N_a}{2}\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{-\frac{3}{2}}}{k_B T}\right)}$$

$$\therefore e^{\left(\frac{E_V - E_F}{k_B T}\right)} = e^{\left(\frac{E_V}{k_B T}\right)} e^{\left(\frac{(-E_V - E_a)}{2k_B T} + \frac{k_B T}{2k_B T} \ln \frac{N_a}{2}\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{-\frac{3}{2}}\right)}$$

$$\therefore e^{\left(\frac{E_V - E_F}{k_B T}\right)} = e^{\left(\frac{E_V}{k_B T}\right)} e^{\frac{(-E_V - E_a)}{2k_B T}} e^{\frac{1}{2} \ln \frac{N_a}{2}\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{-\frac{3}{2}}}$$

$$\therefore e^{\left(\frac{E_V - E_F}{k_B T}\right)} = e^{\frac{(2E_V - E_V - E_a)}{2k_B T}} e^{\frac{1}{2} \ln \frac{N_a}{2}\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{-\frac{3}{2}}}$$

$$\therefore e^{\left(\frac{E_V - E_F}{k_B T}\right)} = e^{\frac{(E_V - E_a)}{2k_B T}} e^{\ln\left[\frac{N_d}{2}\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{-\frac{3}{2}}\right]^{\frac{1}{2}}}$$

$$\therefore e^{\left(\frac{E_V - E_F}{k_B T}\right)} = e^{\frac{(E_V - E_a)}{2k_B T}} \left(\frac{N_a}{2}\right)^{\frac{1}{2}} \left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{-\frac{3}{4}} \ldots\ldots\ldots (6)$$

Substitute this value in equation (1)

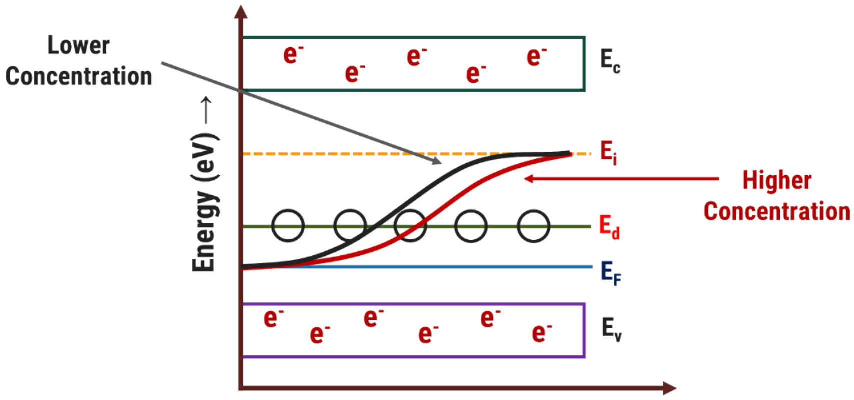
$$\therefore n_p = 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{\frac{3}{2}} e^{\frac{(E_V - E_a)}{2k_BT}} \left(\frac{N_a}{2}\right)^{\frac{1}{2}} \left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{-\frac{3}{4}}$$

$$\therefore n_p = (2)^{\frac{1}{2}} (2)^{\frac{1}{2}} \left(\frac{2\pi m^* k_B T}{h^2}\right)^{\frac{3}{4}} e^{\frac{(E_V - E_a)}{2k_BT}} \left(\frac{N_a}{2}\right)^{\frac{1}{2}}$$

$$\therefore n_p = (2N_a)^{\frac{1}{2}} \left(\frac{2\pi m^* k_B T}{h^2}\right)^{\frac{3}{4}} e^{\frac{(E_V - E_a)}{2k_BT}}$$

Variation of Fermi level with temperature and impurity concentration:

- ✓ From the above equation, it is seen that as temperature gets slowly increased, more and more acceptor atoms get negatively ionized due to transfer of electrons from valence band and fermi level lies between E_v and E_a.



2.5 Carrier Generation and Recombination

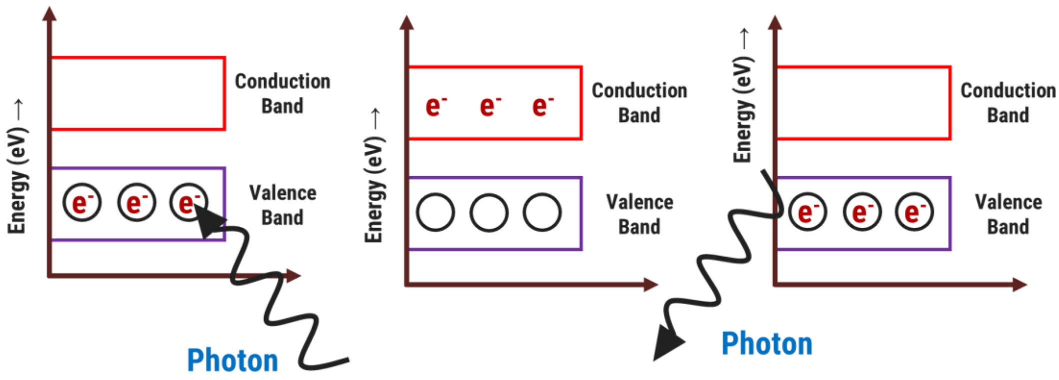
Carrier Generation:

- ✓ "It is a process where electron–hole pairs are created by exciting an electron from valence band to conduction band, thereby creating a hole in valence band.

Recombination:

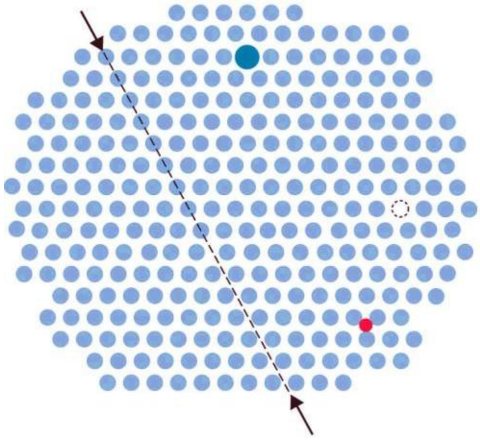
- ✓ "Recombination is reverse process where electrons and holes from conduction band and valence band respectively recombine and are annihilated (destroyed)."
- ✓ In the above process, both the carriers eventually disappears.

- ✓ Theenergydifferenceofinitialandfinalstageofanelectronisgivenoffasphononsor photons.



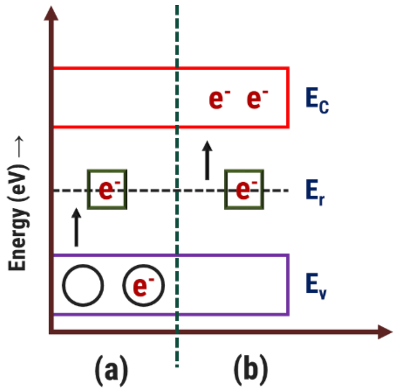
- ✓ This is known as direct recombination or band–to–band transition.
- ✓ An electron from conduction band falls back to valence band and releases energy in the form ofphoton.
- ✓ Thereverseprocessi.e.generationofelectronholepairsistriggeredbysufficient energetic photons, which transfers its energy to a valence band electron, moving it to conduction band and leaving behind a hole in valence band.
- ✓ Energy of incident photon has to be at least of the magnitude of the bandgap.
- ✓ In recombination the transition from excited states to lower energy states, momentum has to be conserved.
- ✓ Theenergyabsorbedoremittedbyphotonisgivenby:$\mathbf{E=h\nu}$Here,h=Planck's constant and ν = Frequency of emitted photons
- ✓ Asthemomentumofphotonisverysmall,nomomentumtransferispossible,sodirect band to band transition is possible.
- ✓ If $n_e \cdot n_h - n_i^2 > 0$, Carrier recombination dominates
- ✓ If $n_e \cdot n_h - n_i^2 < 0$, Carrier generation dominates
- ✓ **Applications:**
- ✓ Absorption is active process in photodiodes, solar cell and other semiconductor photodetectors, where as photon emission is the principle of operation in laser diodes, semiconductor lasers.

Phonon Transition (Shockley – Read – Hall (SRH) recombination)



- ✓ Also known as Indirect or Trap–assisted recombination.
- ✓ Thisprocessistrapassisted,passingthroughalattice defect at energy level Er within semiconductor bandgap.
- ✓ Thistrapcanbecausedbypresenceofanyforeignatom or structuraldefect.

Generation:



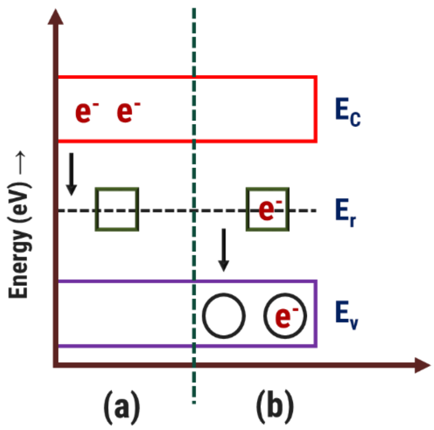
- ✓ Hole emission:

  An electron from valence band is trapped, leaving a hole in valenceband (holeisemittedfromemptytraptovalence band.) Fig.(a)

- ✓ Electron emission:

  Atrappedelectronmovesfromthetrapenergylevelto conduction band.Fig.(b)

Recombination:



- ✓ Electron Capture:

  Anelectronfromconductionbandiscapturedbyanempty trapinthe bandgap.Thisexcessenergy(E_c–E_r)istransferred tothecrystallattice (phonontransmission).Fig.(a)

- ✓ Hole Captured:

  Atrappedelectronmovestovalencebandandneutralizesa hole(The holeiscapturedbytrap).Aphononwithenergy(E_r – E_v) is generated. Fig.(b)

- ✓ Theelectroncapturerateisproportionaltotheelectronconcentration(n_e)in conduction band. The hole capture rate is proportional to the hole concentration (n_h) in valence band.

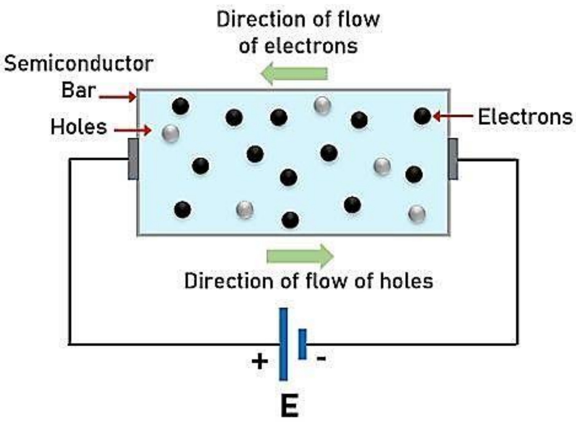
- ✓ The hole and electron emission rates are proportional to the concentration of empty trapes and filled trapes respectively.

Applications:

- ✓ Non radiative/phonon transmission is an unwanted process in optoelectronics, lowering the light generation efficiency and increasing heat loss.

2.6 Carrier transport: Diffusion and Drift **Drift**

Current:



- ✓ "The flow of charge carriers, which is due to applied voltage or electric field is called drift current."
- ✓ In semiconductors there are two types of charge carriers i.e. holes and electrons.
- ✓ When voltage is applied to semiconductors, free electrons moves towards the positive terminal of battery and holes moves towards the negative terminal.
- ✓ The average velocity that an electron or hole achieves, due to applied voltage or electric field is called "Drift velocity".
- ✓ Drift velocity of electrons is given by: $V_e = \mu_e E$
- ✓ Drift velocity of holes is given by: $V_h = \mu_h E$
- ✓ Drift current density due to free electrons: $J_e = n_e \mu_e E$
- ✓ Drift current density due to free electrons: $J_h = n_e \mu_h E$

$\therefore n_e = n_h = n_i$

- ✓ Total drift current density:

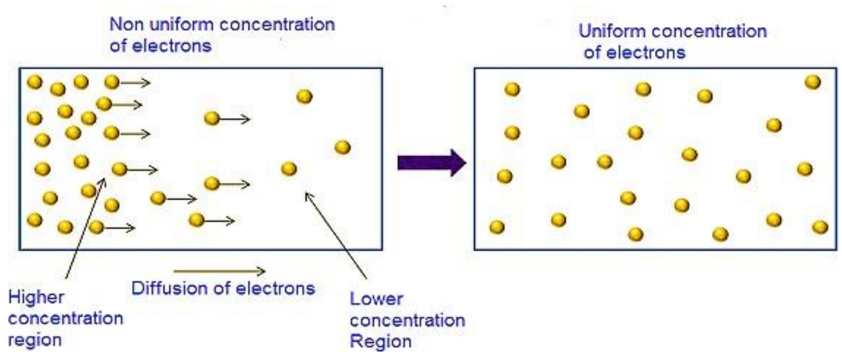
$J = J_e + J_h$

$J = n_e\mu_e E + n_e\mu_h E$ $J = n_e E$

$(\mu_e + \mu_h)$

Diffusion Current:

- ✓ "Current produce due to the motion of charge carriers from a region of higher concentration to a region of lower concentration region."
- ✓ Regions having more no. of electrons is called higher concentration region and that with less no. of electrons is called lower concentration region.
- ✓ The above process occurs in semiconductors that are non uniformly doped.
- ✓ Let us consider an n–type semiconductor with non uniform doping.
- ✓ Due to non uniform doping, more no. of electrons are present on the left side, whereas lesser no. of electrons are present on the right side.
- ✓ The number of electrons on left side is more, as a result of which they will experience repulsive force from each other.
- ✓ Diffusion current occurs without an external voltage or electric field applied.



Drift current	**Diffusion current**
Drift current requires external voltage.	Diffusion current does not require external voltage.
It is present in both conductors and semiconductors.	It is present only in semiconductors.
Can be present in intrinsic and extrinsic semiconductors.	Can be present only in extrinsic semiconductors with uneven doping.

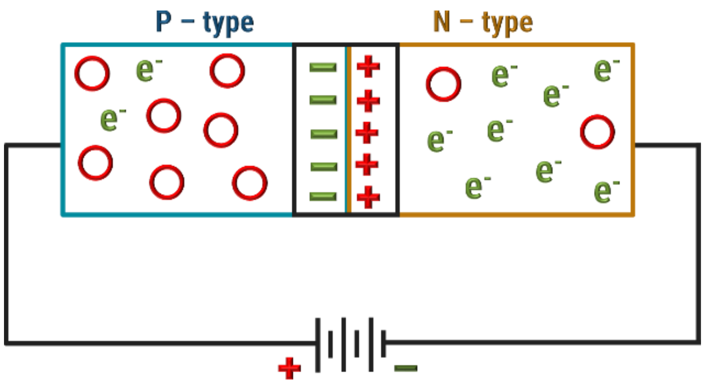
Itsvalueisgenerallyhighinreversebias.	Itsvalueisgenerallyhighinforwardbias.
Driftcurrentiscausedbyelectricfield.	Diffusioncurrentiscausedbyvariationin carrier concentration.

2.7 P–N Junction

- ✓ When a p-type semiconductor is fused (intimately joined) to an n-type semiconductor, a PN junction is formed.
- ✓ A p-n junction diode is a two terminal device which allows electric current only in one direction, while blocks the electric current in opposite or reverse direction.
- ✓ A p-n junction diode is formed when an N-type semiconductor is fused with a P-type semiconductor creating a semiconductor diode. The immobile ions, at the junction creates a zone that is devoid of charge carriers (majority charge carriers).
- ✓ "This zone, depleted or devoid of charge carriers is called 'Depletion region'."
- ✓ The thickness of the depletion region is of an order of 10^{-6} m.
- ✓ To change the thickness of depletion barrier width and improve conduction in PN junction diode we apply external voltage as a battery which is known as external biasing.

Forward biasing:

- ✓ When the external voltage applied to the junction is in such a direction that it cancels the potential barrier, thus permitting current flow, the junction is said to be in forward biased condition.

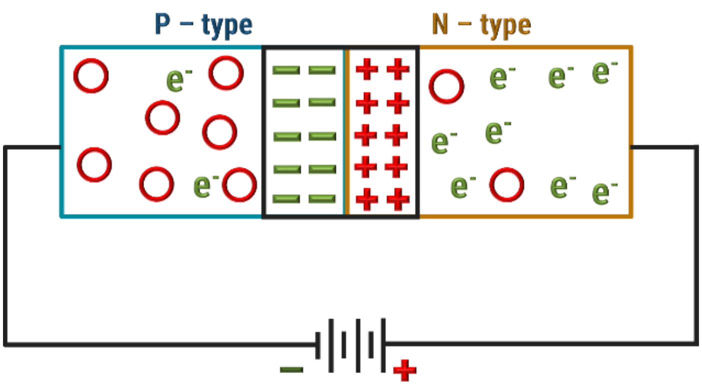


- ✓ To apply forward bias, connect positive terminal of the battery to p-type and negative terminal to n-type as shown in figure.
- ✓ The applied forward potential establishes an electric field which acts against the field due to potential barrier. Therefore, the resultant field is weakened and the barrier height is reduced at the junction as shown in figure. Therefore, the resultant field is weakened and the barrier height is reduced at the junction.
- ✓ As potential barrier voltage is very small (0.1 to 0.3 V), therefore, a small forward voltage is sufficient to completely eliminate the barrier.
- ✓ Once the potential barrier is eliminated by the forward voltage, junction resistance becomes almost zero and a low resistance path is established for the entire circuit. Therefore, current flows in the circuit. This is called forward current.

With forward biastop-n junction, the following points are worth noting:

- ✓ The potential barrier is reduced and at some forward voltage (0.1 to 0.3 V), it is eliminated altogether.
- ✓ The junction offers low resistance (called forward resistance, R_F) to current flow.
- ✓ Current flows in the circuit due to the establishment of low resistance path. The magnitude of current depends upon the applied forward voltage.

- ✓ **Reverse biasing:**
- ✓ When the external voltage applied to the junction is in such a direction that potential barrier is increased, this set-up is said to be in reverse biased condition.



- ✓ To apply reverse bias, connect negative terminal of the battery to p-type and positive terminal to n-type as shown in figure.
- ✓ It is clear that applied reverse voltage establishes an electric field which acts in the same direction as the field due to potential barrier. Therefore, the resultant field at the junction is strengthened and the barrier height is increased as shown in figure.
- ✓ The increased potential barrier prevents the flow of charge carriers across the junction. Thus, a high resistance path is established for the entire circuit and hence the current does not flow.

With reverse bias to p-n junction, the following points are worth noting:

- ✓ The potential barrier is increased.
- ✓ The junction offers very high resistance (called reverse resistance, R_r) to current flow.
- ✓ No current flows in the circuit due to the establishment of high resistance path.

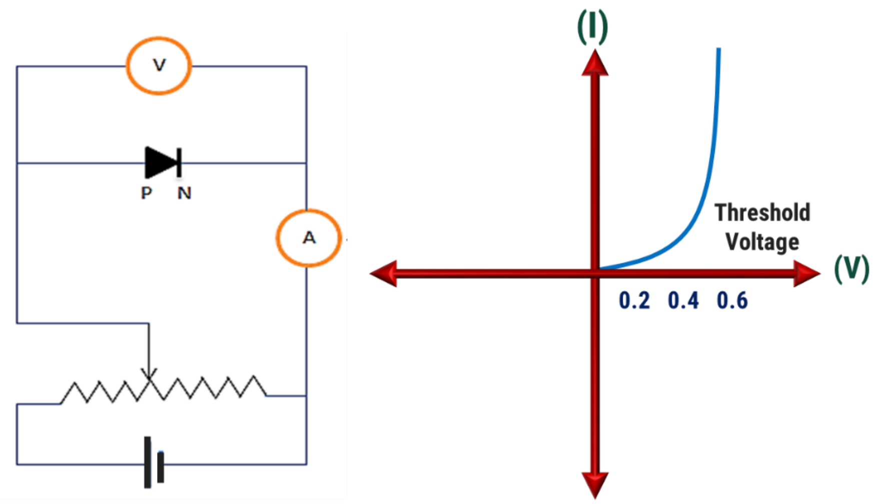
2.7.1 Curret – Voltage (I–V) characteristics of a P–N junction Diode:

- ✓ The behaviour of a diode can be obtained by means of graph known as volt-ampere or I – V characteristics.
- ✓ "It is a graph between voltage across the terminals of a pn junction diode and the current flowing through it."
- ✓ Characteristics of a diode can be studied under forward biasing and reverse biasing.

(a) Forward biasing of a diode:

- ✓ The circuit diagram for obtaining forward characteristics of a diode is shown in fig.
- ✓ When P–N junction diode is forward biased and if the applied voltage is gradually increases in steps, at some forward voltage (V_F), the potential barrier is altogether eliminated and current starts flowing.
- ✓ It is 0.3 V for Ge and 0.7 V for Si.

- ✓ “The voltage is known as threshold voltage (V_{th})“ (Also called knee voltage or cut-in voltage).



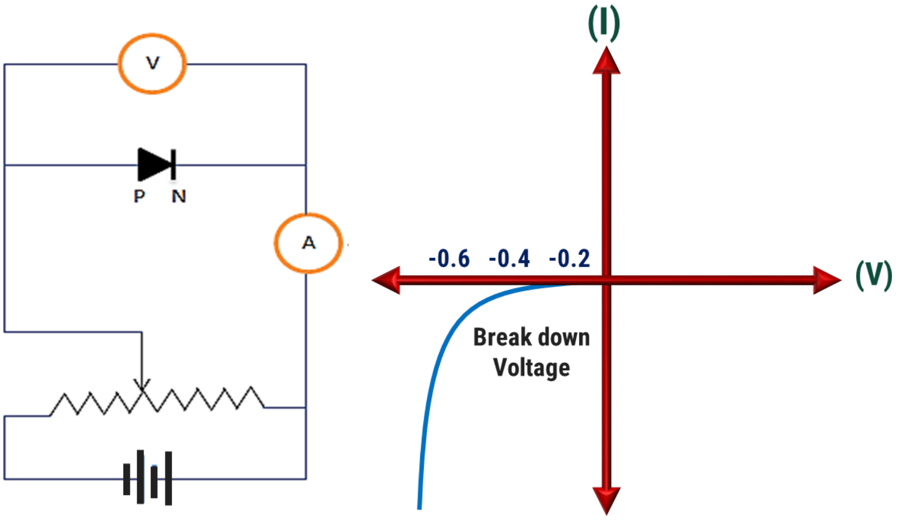
- ✓ Once the external voltage exceeds the barrier potential, the current increases exponentially as shown in graph. This is called the linear operating region of diode.
- ✓ $V_F = V_{th} = V_B$ (V_B = Barrier potential)
- ✓ Forward resistance can be calculated as:

$$R_F = \frac{\Delta V_F}{\Delta I_F}$$

- ✓ If the forward voltage is increased beyond the safe limit, damage of diode is likely to occure due to overheating.

(b) Reverse biasing of a diode:

- ✓ The circuit diagram for plotting reverse characteristics of a diode is as shown in fig.
- ✓ When a p-n junction is reverse biased, majority carriers are blocked and only a small current due to minority carriers flows through the diode.
- ✓ As the reverse voltage is increased in suitable steps, reverse current reaches its maximum or saturation value. This is called reverse saturation current or leakeg current.
- ✓ The diode current is recorded at each step and graph is plotted as shown in fig.
- ✓ When the breakdown voltage is more than the applied voltage, diode current is very small and almost constant.

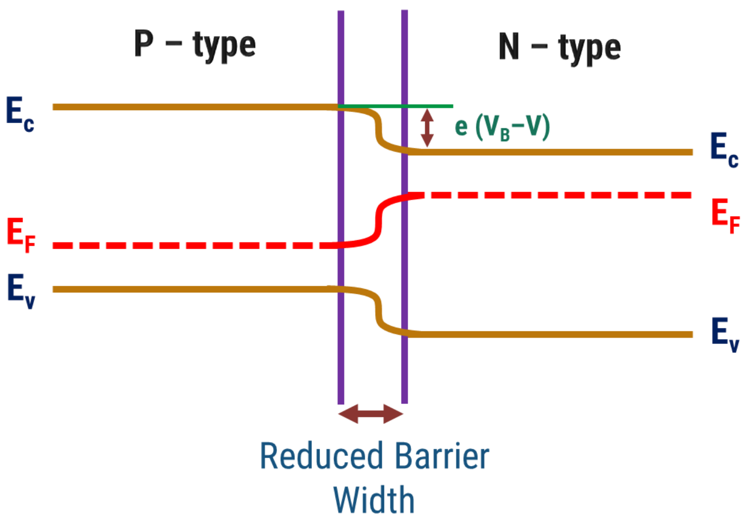


- ✓ When external voltage exceeds the breakdown voltage, current sharply exceeds, this curve is called the zero resistance path.
- ✓ Reverse current is of an order of (μA) for Ge and (nA) for Si.
- ✓ Resistance of diode from the curve is:

$$R_R = \frac{\Delta V_R}{\Delta I_R}$$

2.7.2 Energy band diagram of P – N junction:

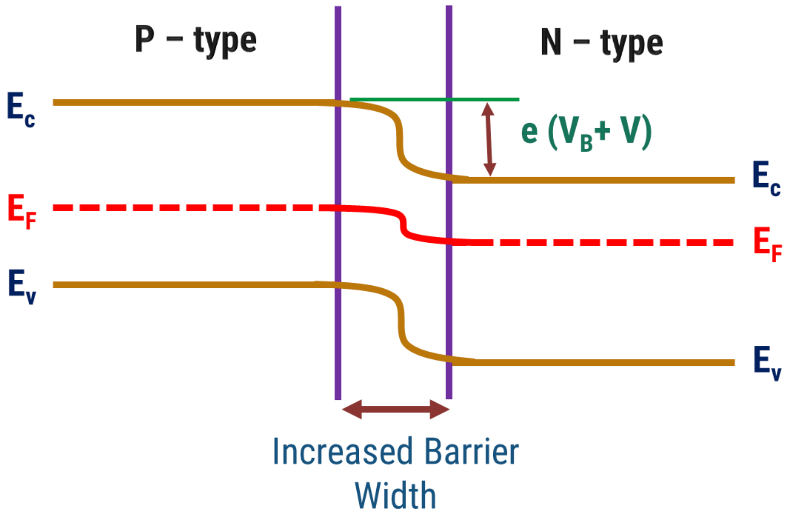
(a) Forward biasing of a diode:



- ✓ An external battery of voltage V, with its positive terminal connected to p-typeand negative terminal is connected to n-type.

- ✓ The energy of electrons in N – region, increases by eV (As N-type is connected to –ve terminal).
- ✓ Nowthefermilevelisrisesbyafactore V andhencepotentialbarrierisreducedtoe(V_B – V) and the barrier width is reduced.
- ✓ V_B is the potential barrier across junction
- ✓ Theelectronthusfacea reduced potentialand can crossthejunction.
- ✓ Forthecurrentflow,theappliedpotentialshouldbegraterthanbarrierpotential.

(b) Reverse biasing of a diode:



- ✓ Anexternalbatterywithvoltage Visconnected, withitspositiveterminalconnectedtoN – region and negative terminal is connected to P – region.
- ✓ TheenergyofelectronsisnowreducedbyeV.Sothefermilevelshifteddownbyafactor eVandpotential barrierincreasestoe(V_B+V),therebyincreasingbarrierwidth.
- ✓ Itnowbecomesdifficultforelectronstocrossthejunction,sothereisnocurrentflow.
- ✓ However, a very small current can flow due to the minority charge carriers (μA for Ge and nA forSi).

Application:

- ✓ P-N junction diodes are used in clamping circuits for dc restoration.
- ✓ They are used in clamping circuits for wave shaping.
- ✓ They are used in voltage multipliers.
- ✓ They are used as switch in digital logic circuits.
- ✓ They are used in demodulation circuits and optical communications.

2.7.3 Zener Diode (P – N Junction)

- ✓ It is named after Clarence Zener who discovered Zener effect.
- ✓ "A Zener diode is a type of p-n junction diode that allows current flow not only from its anode to cathode, but also in reverse direction when Zener voltage is achieved."
- ✓ The Zener diode's operation depends on the heavy doping of its p-n junction.
- ✓ The Zener diode is designed to operate in the breakdown region without damage.

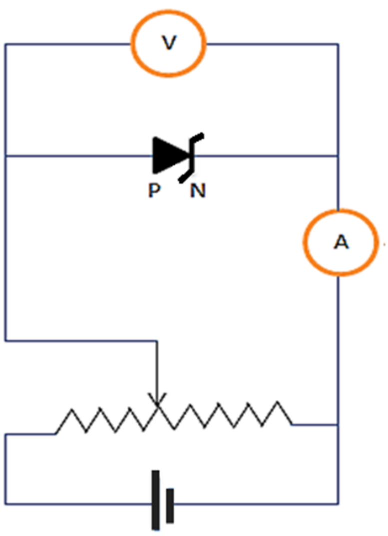
Working Principle:

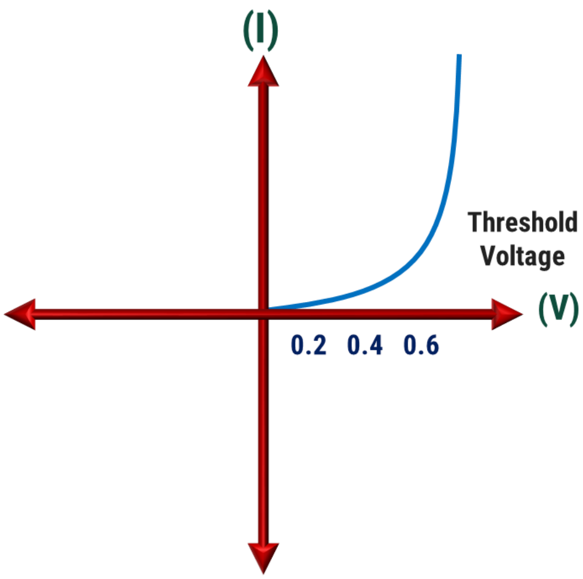
- ✓ "It is a type of electrical breakdown that occurs in reversed biased p-n junctions when the electrical field enables tunneling of electrons from the valence band to conduction band of a semiconductor leading to a large number of free minority charge carriers, which suddenly increases the reverse current."

Working of Zener diode:

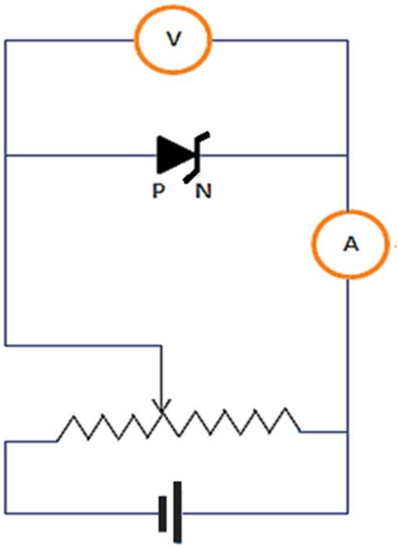
(a) Forward biasing of a diode:

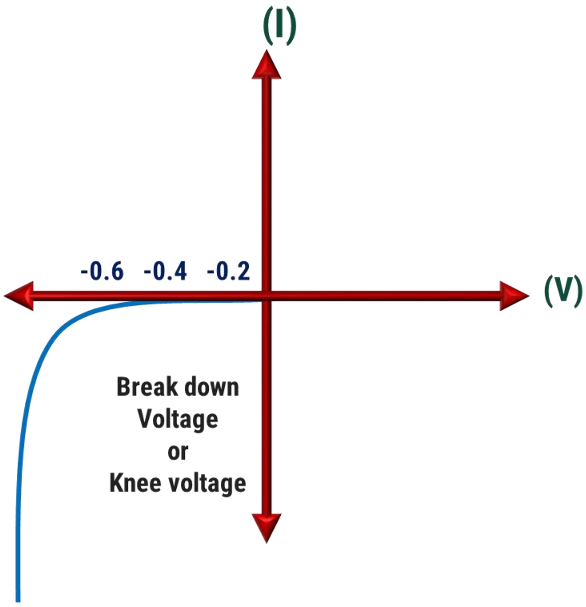
- ✓ When Zener diode is connected in forward bias, it will act like normal p-n junction diode, having a voltage drop of around 0.7 V.





(b) Reverse biasing of a diode:





- ✓ Under the reverse bias condition, the breakdown of a Zener diode occurs. The breakdown and hence the Zener voltage depends on the amount of doping.
- ✓ As the reverse voltage is increased, the reverse current remains negligible up to a point called the knee point.
- ✓ At this knee point voltage is very sharp as compared to the normal p-n junction diode.
- ✓ The reverse current increases sharply to a very high value after this point.
- ✓ The Zener diode will not burn as diode has entered breakdown. The external resistance connected to the circuit prevents the Zener diode from burning.
- ✓ The maximum permissible value of current is denoted by I_{max} and the minimum current sustain breakdown is called I_{min}.

Application:

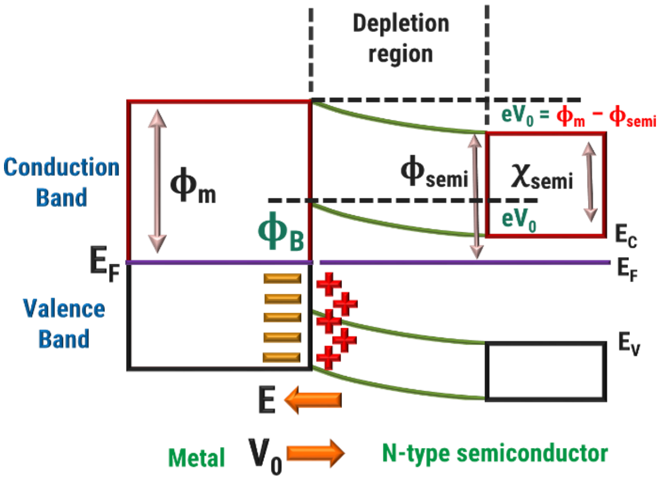
- ✓ Zener diodes are highly used as voltage regulator.
- ✓ They are used in wave shaping circuits as peak limiters or clippers.
- ✓ They are used for meter protection to prevent against damage from accidental overload.

2.8 Metal–Semiconductor Junction (Schottky and Ohmic)

- ✓ When metal and semiconductor are brought into contact, there are two types of junctions formed, depending on the work function (ϕ) of semiconductors and its relation with metal.
- ✓ Generally n-type semiconductor and metals like platinum, molybdenum, chromium, and tungsten are used.
- ✓ **Work function (ϕ)** is the minimum energy required to transfer an electron from a point within a solid to a point just outside its surface.
- ✓ **χ is the electron affinity** means amount of energy released or spent when an electron is added to any place.

1. **$\phi_m > \phi_{semi} \rightarrow$ Schottky junction**
2. **$\phi_m > \phi_{semi} \rightarrow$ Ohmic junction**

1. Schottky Contact ($\phi_m > \phi_{semi}$):



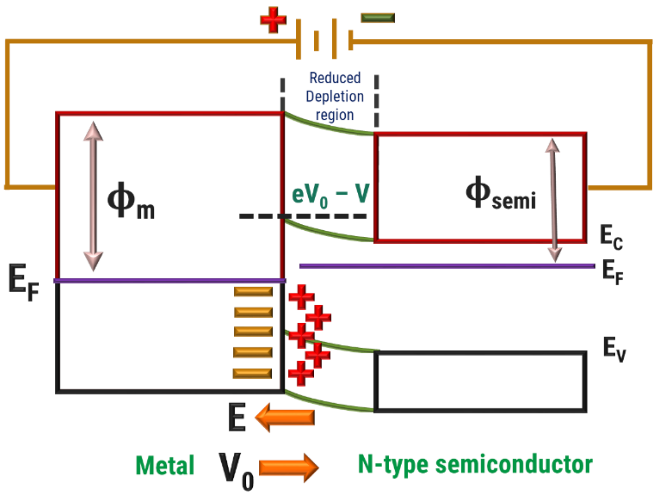
- ✓ When contact is made the fermi level should line up at equilibrium.
- ✓ The fermi level lines up and a positive potential is created on semiconductor side and a negative potential on metal side.

- ✓ When the contact is formed, due to low charge carrier density on semiconductor side, electrons are removed not only from the surface, but also from certain depth of semiconductor.
- ✓ This leads to formation of depletion region on the semiconductor side.
- ✓ The fermi level lines up and a positive potential is created on semiconductor side and a negative potential on metal side.
- ✓ So, the bends (V.B. and C.B.) bends up in the direction of electric field.
- ✓ There is built in potential in Schottky junction, given as difference of work function. $\phi_m - \phi_{semi} = eV_0$
- ✓ This contact potential acts as a barrier for electrons to move from semiconductor to metal. When the contact was made, electrons moved to metal side and formed a depletion region on semiconductor side which prevents further motion of electrons.
- ✓ This is the Schottky barrier, denoted by $\Phi_B =$

  $(\phi_m - \phi_{semi}) + (E_c - E_F)$

  $\Phi_B = (\phi_m - \chi_{semi})$ (χ_{semi} is the electron affinity of semiconductor).

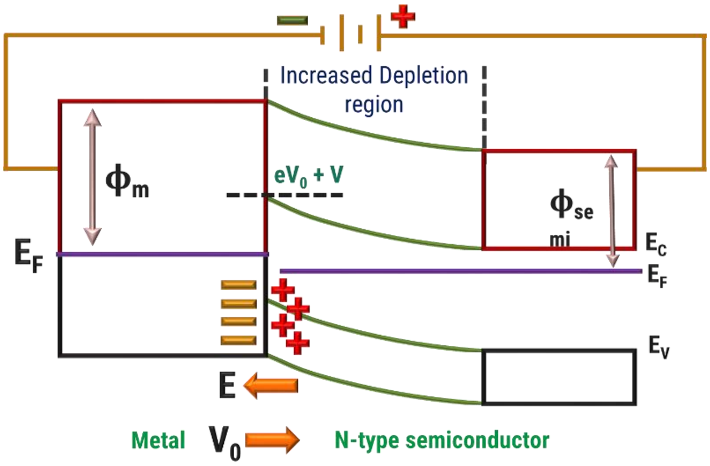
(a) Forward Bias



- ✓ The external voltage is applied in such a way that it opposes the built-in potential.

- The fermi levels no longer line up, but are shifted. The magnitude of the shift depends on the applied voltage. The depletion layer is thus narrowed and electrons move from semiconductor to metal.
- A large current, exponentially related to 'V' now starts flowing
- $I = I_0 [e^{(eV/kBT)} - 1]$, I_0 is a constant and depends on ϕ_B (Schottky barrier).

(b) Reverse Bias



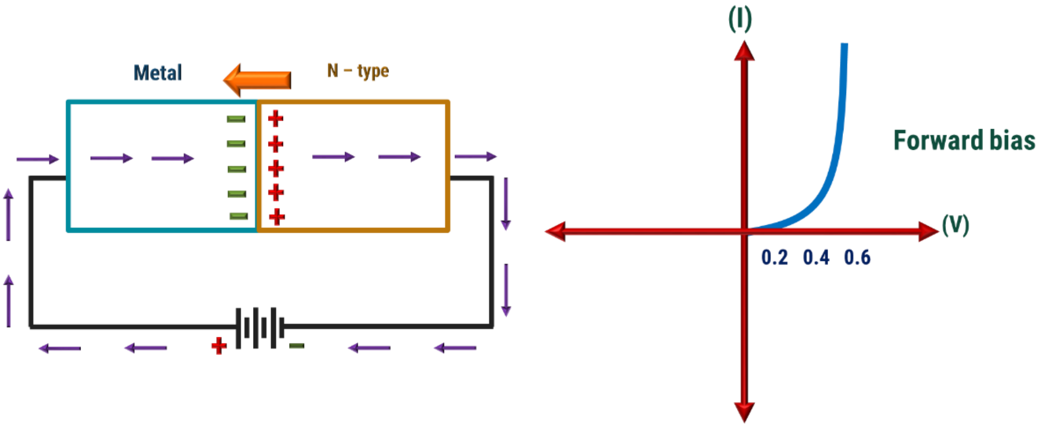
- In this case, the external potential, applied is in the same direction as built-in potential. Again, the fermi levels do not line up, but the barrier for electron motion from n-type to metal becomes higher.
- The applied voltage adds on to the built-in potential and depletion region gets wider.

Schottky Diode:

- The Schottky diode named after Walter H Schottky is also called "Schottky barrier diode".
- It is a semiconductor diode formed by the junction between an n-type semiconductor and metals like molybdenum, chromium, platinum, tungsten, etc.
- It has a law forward voltage drop and a very fast switching action.
- Schottky barrier is a depletion layer formed at the junction of metal and n-type semiconductor.

- ✓ It is the potential energy barrier that electrons have to overcome in order to flow across the diode.
- ✓ One of the most important characteristics of a Schottky barrier is its height.
- ✓ As shown in the diagram, the atoms that lose electrons at the n-side become positive ions whereas the atoms that gain extra electrons at the metal side become negative ions. These positive and negative ions together from a depletion layer.
- ✓ The depletion layer formed is more on the n-side, so the free electrons need a great energy to overcome this barrier. Hence there is no conduction in an unbiased diode.

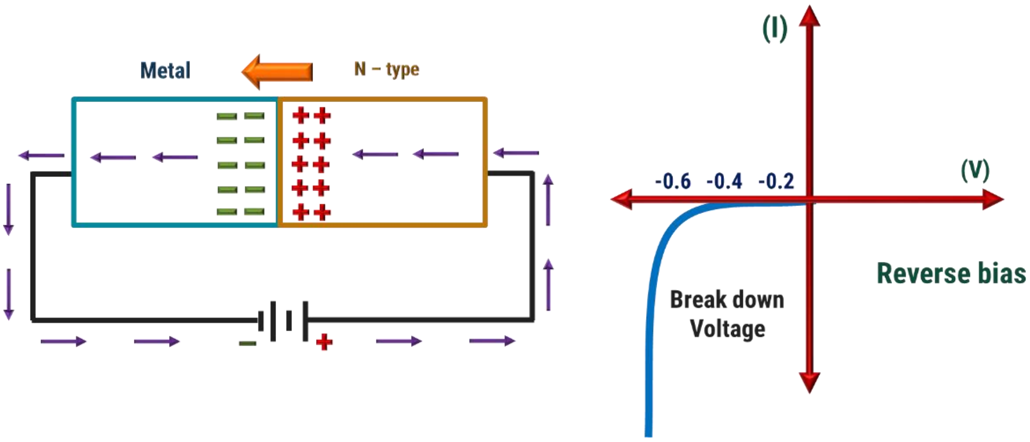
(a) Forward Bias



- ✓ If the positive terminal of battery is connected to the metal and negative terminal of battery is connected to the n-type the Schottky diode is said to be forward biased.
- ✓ When forward voltage is applied to Schottky diode, a large no. of free electrons are generated. When the barrier voltage or built-in voltage is overcome, these electrons cross the junction and a current starts flowing metal.
- ✓ The I–V characteristics are almost similar to PN junction diode.
- ✓ The forward voltage drop is around 0.2 to 0.3 V.

(b) Reverse Bias

- ✓ In the negative terminal of battery is connected to metal and positive terminal of battery is connected to n-type, the Schottky diode is said to be reversed biased.



- ✓ When reverse bias is applied, the depletion width increases and the electric current stops. A small leakage current flows due to thermally excited electrons in metal.
- ✓ Also, the reverse saturation current occurs at very low voltage as compared to silicon diode.

Advantages

- ✓ Low junction capacitance
- ✓ Fast recovery time
- ✓ High current density
- ✓ High efficiency

Disadvantages

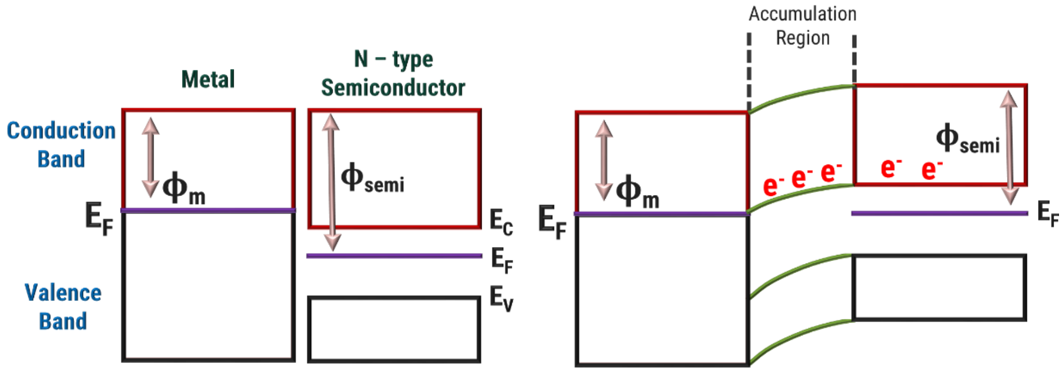
- ✓ Reverse saturation current is large

Applications

- ✓ Rectifiers
- ✓ Radio frequency applications
- ✓ Power supplies
- ✓ Logic circuits

2. Ohmic Contact ($\phi_m > \phi_{semi}$):

- ✓ When the semiconductor has a higher work function than metal, an Ohmic junction is formed.



- ✓ An Ohmic contact is defined as a metal – semiconductor contact that has a negligible contact resistance relative to the bulk or series resistance of the semiconductors.
- ✓ At equilibrium, the fermi levels line up. The electrons move from the metal to the semiconductor energy states of C.B, so that there is accumulation region near the interface of semiconductor.
- ✓ The accumulation region has a higher conductivity than bulk of the semi-conductor.
- ✓ Thus Ohmic junction behaves as a resistor conducting in both forward and reverse bias.
- ✓ For Ohmic junction, depending on the direction of current flow, heat can be generated or absorbed.
- ✓ This can be used as a practical cooling device.

2.9 Semiconductor materials of interest for optoelectronics

- ✓ When photons of energy equal to or greater than the band gap energy are incident on a semiconductor, electrons from the valence band are excited to conduction band, thereby creating electron-hole pair.

(a) Photoconductivity

"The increase in conductivity of a material due to EHP (electron hole pair) arising from optical excitation is called photoconductivity."

(b) Luminescence

"The property of light emission is called luminescence."

(c) Photoluminescence

When electrons are excited by the absorption of photons of suitable frequency and energy equal to or greater than bandgap the resulting radiation due to recombination of electron
– hole pairs is called photoluminescence.

2.10 LED's (Light emitting Diodes)

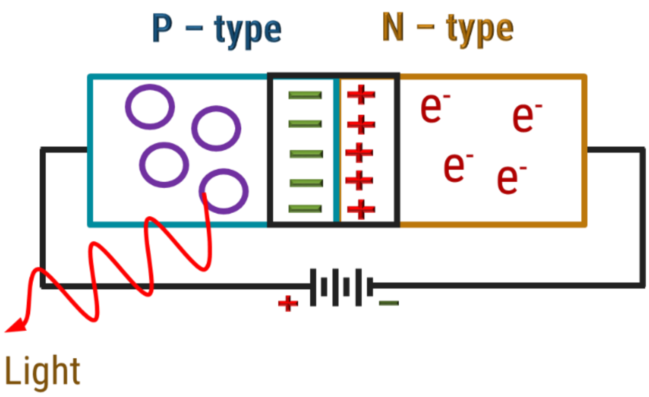
- ✓ "It is a two-lead semiconductor device which emits light, when electrons (from conduction band) recombine with holes (in valence band)."
- ✓ LED's are basically p-n junctions that are made from a very thin layer of fairly heavily doped semiconductor material and depending on the semiconductor material used, and the amount of doping, when forward biased, an LED emits light of a specific wavelength.

1	Ga As	Infrared (850 – 940 nm)
2	Ga As P	Red (630 – 660 nm)
3	Ga P	Yellow (585 – 595 nm)
4	Al Ga P	Green (550 – 570 nm)
5	Si C	Blue (430 – 505 nm)

Working of LED

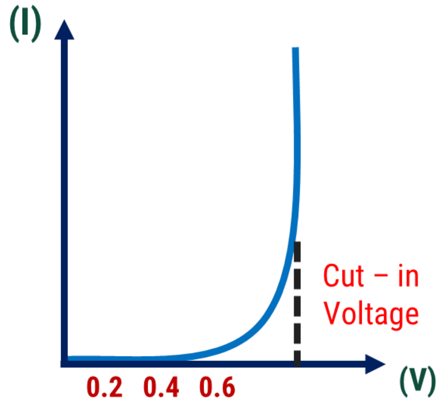
- ✓ As seen in the diagram, the fermi levels line up in equilibrium. There is built in potential due to which, electrons from n-side are not able to cross the junction.
- ✓ When an extra forward voltage is applied to an LED, the width of the depletion layer decreases on increasing applied voltage.

- ✓ The electrons now have sufficient energy to overcome the potential barrier. These electrons, on crossing the barrier, recombines with holes and releases the difference of energy ($E_c - E_v$) in the form of photon.



- ✓ Each recombination of carriers, emits some light.
- ✓ The energy of photons depends on the forbidden energy gap.
- ✓ When the forward bias is applied to the LED, the intensity of emitted light is small. As the forward current increases, the emitted light also increases.

Characteristics of LED



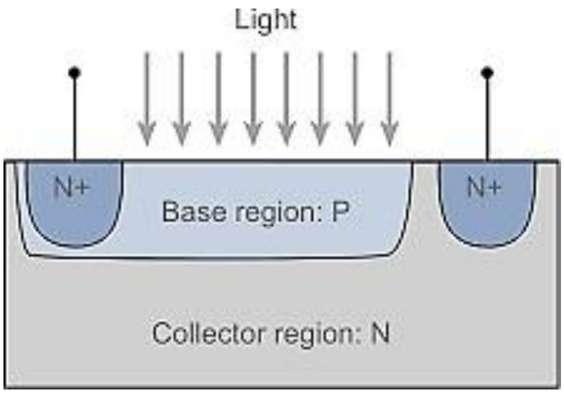
- ✓ From the graph, it is seen that current increases exponentially, after a certain voltage.
- ✓ Till then, due to potential barrier, current is almost zero.

Application

- ✓ Camera flashes
- ✓ Traffic signals
- ✓ General lighting
- ✓ Medical device

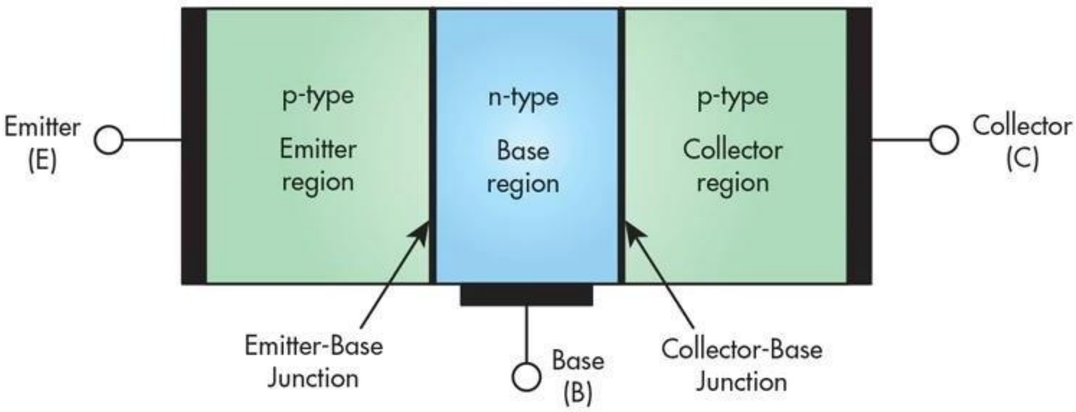
2.10.1 Photodiodes

- ✓ "Aphotodiodesisasemiconductordevicethatconvertslightintoelectriccurrent."
- ✓ Theworkingprinciple ofphotodiodes is "Photoelectric effect".



2.10.2 Phototransistor

- ✓ A phototransistor is a device that is able to sense light levels and alter the current flowing between emitter andcollectoraccordingtothelevel oflightitreceives.



IMP questions:

1) What are intrinsic and extrinsic semiconductors?
2) Difference between P-type and N-type semiconductor.
3) What is drift and diffusion current?
4) Define carrier generation and recombination.
5) Define work function and electron affinity.
6) Write a short note on Ohmic contacts.
7) Write a short note on Zener diode.

Descriptive questions:

1) Derive an expression for density of holes in valence band of an intrinsic semiconductor.
2) Derive an expression for density of electrons in conduction band of an intrinsic semiconductor.
3) Write a short note on direct and indirect recombination?
4) What changes takes place when a P–N junction is (1) Forward bias (2) Reverse bias.

Numericals:

1) The intrinsuc carrier density at room temperature in Germanium is $2.37 \times 10^{19}/m^3$. If electrons and hole mobility are 0.38 and 0.18 $m^2/V\cdot sec$ respectively, find out its resistivity.

   [Ans. $\rho = 0.471\ \Omega m$]

2) The electron and hole mobilities in intrinsic antimony are 6 and 0.2 $m^2/V\cdot sec$ respectively. At room temperature, resistivity is $2 \times 10^{-4}\ \Omega m$. Assuming the material is intrinsic, determine its intrinsic carrier density at room temperature.

   [Ans. $n_i = 5.04 \times 10^{21}/m^3$]