

# JOIN



Telegram  
@PuneEngineers

For more Subjects

<https://www.studymedia.in/fe/notes>



SCAN ME



# Unit 4

## Semiconductor Physics

**Prof. G. V. Khandekar**





# Syllabus

Band theory in solids, free electron theory (qualitative), electrical conductivity in conductor and semiconductor, influence of external factors on conductivity (temperature, light and impurity), Fermi energy, density state (qualitative), concept of effective mass, electrons and holes, Fermi-Dirac probability distribution function (effect of temperature on Fermi level with graph), Position of Fermi level in intrinsic semiconductor (with derivation) and extrinsic semiconductors, Dependence of Fermi level on temperature and doping concentration (qualitative), diffusion and drift current (qualitative), band structure of PN junction diode under i) zero bias, ii) forward bias, iii) reverse bias, Working of transistor (NPN only) on the basis of Band diagram, Hall effect (with derivation), photovoltaic effect working of solar cell on the basis of band diagram and its applications.

## **Unit Objectives: On completion of this unit students will be able to**

- Understand free electron theory and band theory in solids
- Know factors affecting electrical conductivity
- Understand phenomena involved in semiconductors
- Elaborate position of Fermi level in intrinsic and extrinsic semiconductors
- Understand band diagram of PN junction diode under different biasing conditions
- Familiarize with the working of NPN on the basis of band diagram
- Understand Hall effect
- Get acquainted with the working of solar cell

# Valence Band, Conduction Band & Forbidden Band

All types of solids consists three types of bands,

## 1. Valence Band:

It is an energy band which contains the **outermost valence electrons**.

## 2. Conduction Band:

It is an allowed energy band next to the valence band which contains **free electrons that take part in conduction**.

## 3. Forbidden Band:

It is an energy band between the valence and conduction band. The energies in this band are forbidden i.e. not allowed for the electron.

To raise the electron from valence band to conduction band, energy equivalent to the forbidden energy gap has to be supplied to the electron.

# Classification of Solids on the basis of band theory

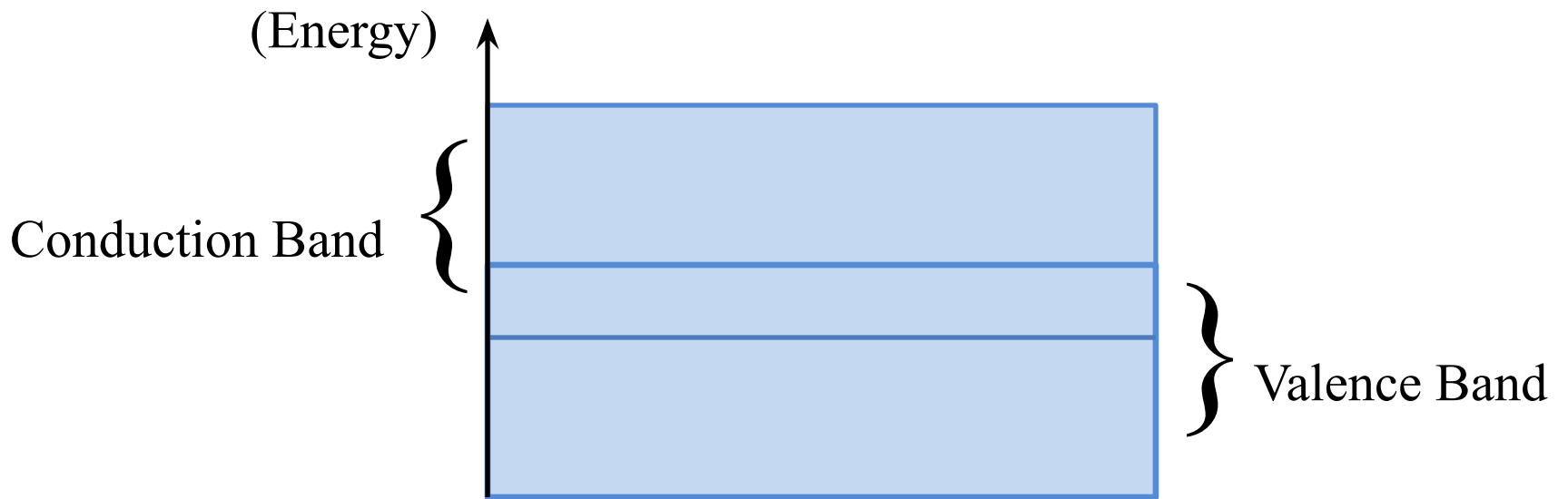
## 1. Conductors:

In conductors, the valence band & conduction band overlap. There is no forbidden band. The electrons can be made to move and constitute a current by applying a small potential difference.

The resistance of conductor is very low & it increases with temperature. Hence the conductors are said to be positive temperature coefficient of resistance.

The energy band structure of conductor is shown in figure.

Metals like copper, gold, silver, aluminium are good conductors.



Energy bands structure in conductors.



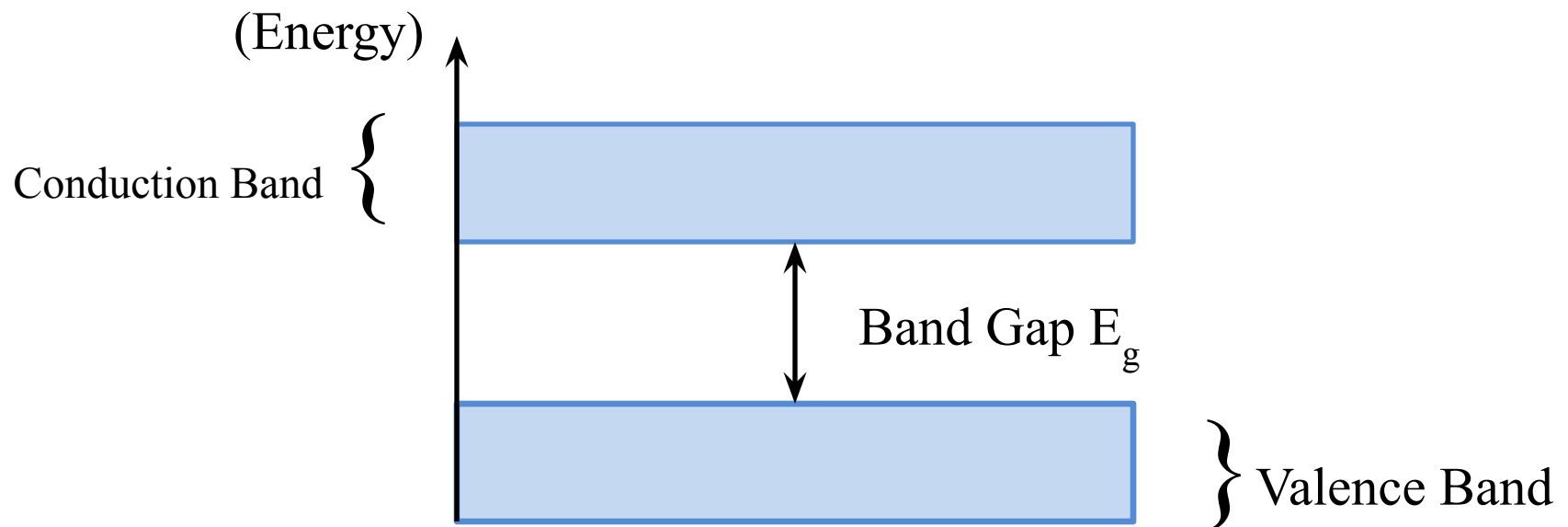
## 2. Insulators:

Insulators have completely filled valence band & an empty conduction band which are separated by a large forbidden gap.

The band gap energy is about 5 eV . Hence large amount of energy is required to transfer electrons from valence band to conduction band.

Insulators have low conductivity & high resistance. Diamond, glass are insulators.

The band structure of insulator is shown in figure.



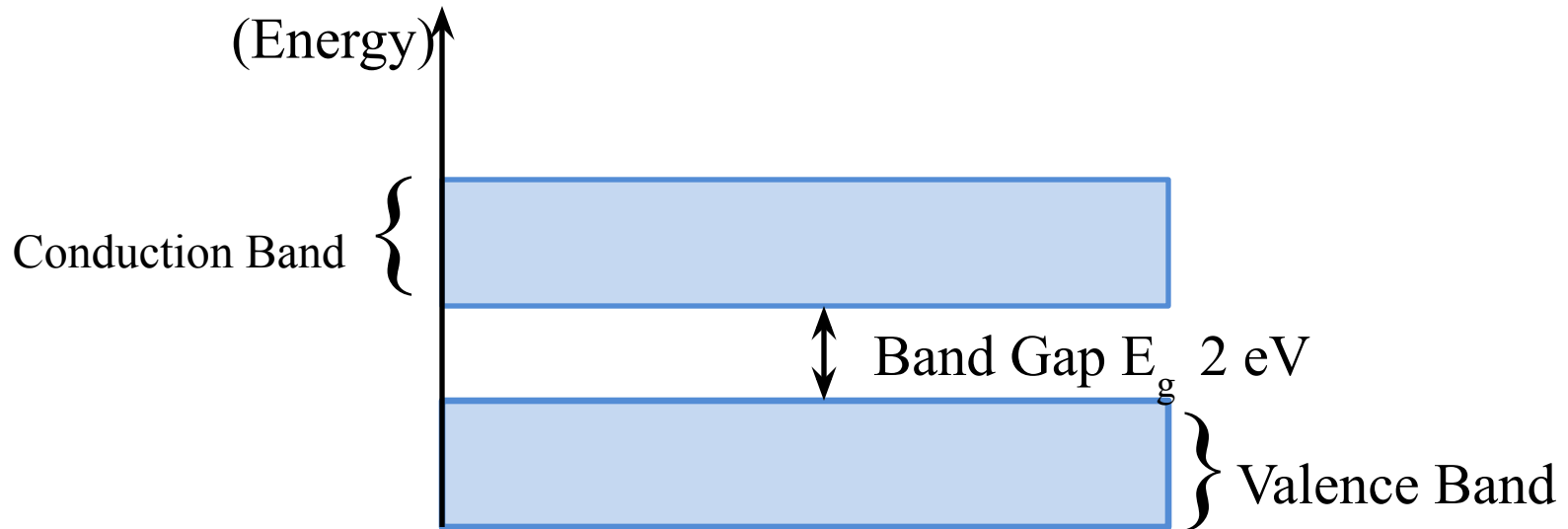
## Semiconductors:

In semiconductors valence band is completely filled and the conduction band is empty at absolute zero temperature.

The valence band and conduction band are separated by a small forbidden band of the order 2 eV.

Hence compared to insulator small energy is required to transfer the electrons from valence band to conduction band.

In semiconductors conductivity is better than the insulators but not as good as the conductors. Examples Si, Ge.



As temperature increases, the electron from valence band will move to conduction band leaving a vacancy in valence band which is known as hole.

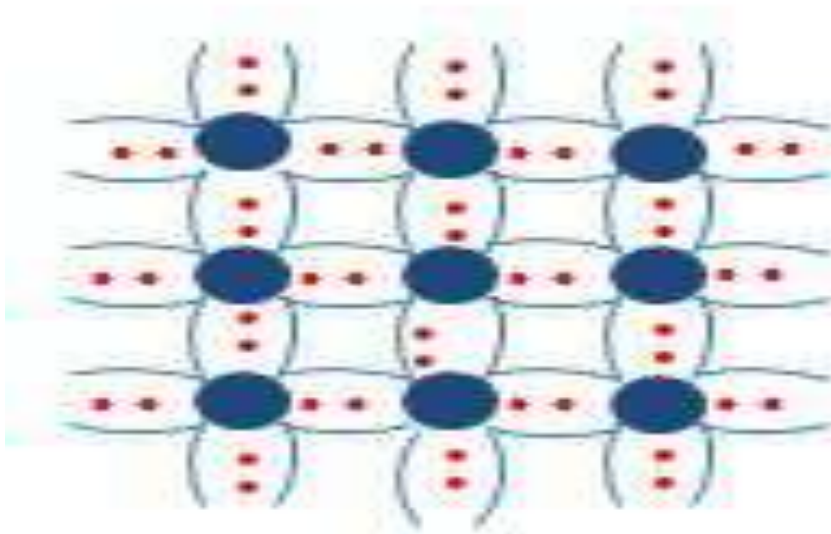
Hence conductivity increases with increase in temperature, therefore semiconductors are said to have negative temperature coefficient.

# Types of Semiconductors

The semiconductors are classified into two types

1. Intrinsic Semiconductor (Pure Semiconductor)
2. Extrinsic Semiconductor (Impure semiconductor)

1) Intrinsic Semiconductor (Pure Semiconductor):



Silicon covalent bonding structure

## II) Extrinsic Semiconductors:

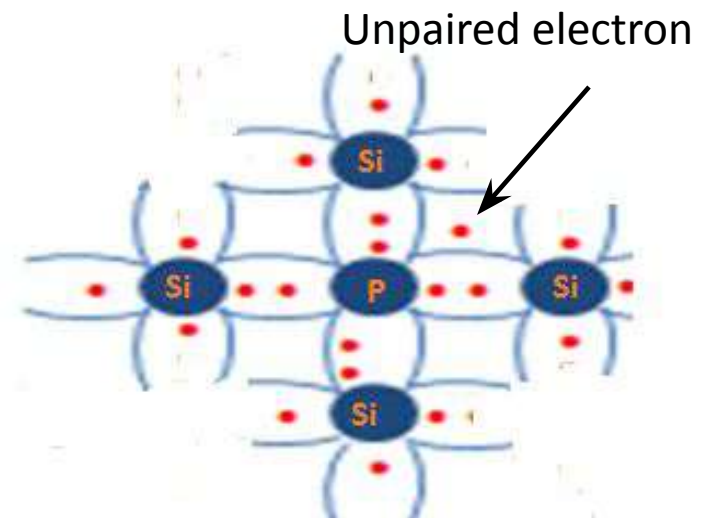
Extrinsic semiconductors are of two types.

1. n-type semiconductor
2. p- type semiconductor

### n-Type Semiconductor:

n-type semiconductors are obtained by adding group V<sup>th</sup> elements (pentavalents) like phosphorus, arsenic, antimony to the pure semiconductors.

When a pentavalent atom like phosphorus replaces a silicon atom in the silicon crystal, four electrons participate in the formation of covalent bonds & one electron is left unpaired which is free electron.

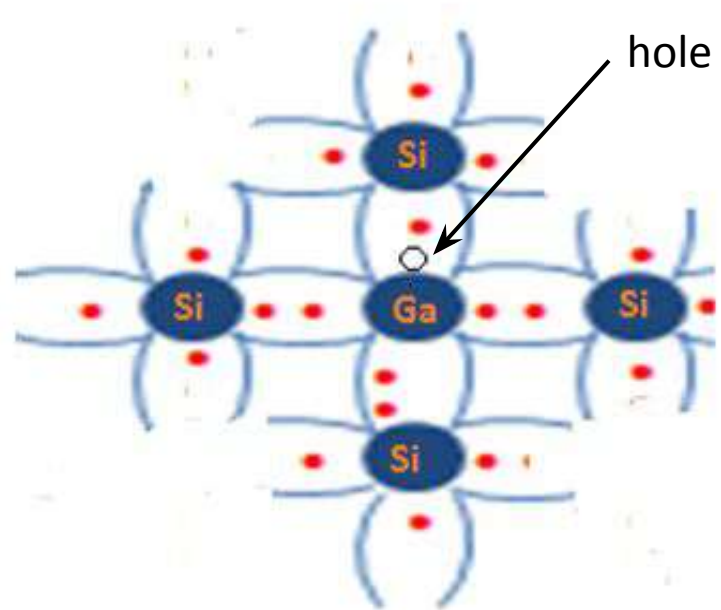


## p-type semiconductors:

p-type semiconductors are obtained by adding group-III elements like indium and gallium to pure semiconductors. These impurities are known as acceptors.

When a trivalent atom like gallium replaces a silicon atom in a silicon crystal, they produces allowable energy levels just above the valence band as shown in figure.

Hence the majority charge carriers in p-type semiconductors are holes





# Free Electron Models

Classical Model	Quantum Mechanical Model
Metal is an array of positive ions with electrons that are free to roam through the ionic array	Electrons are in a potential well with infinite barriers: They do not leave metal, but free to roam inside
Electrons are treated as an ideal neutral gas, and their total energy depends on the temperature and applied field	Electron energy levels are discrete (quantized) and well defined, so average energy of electron is not equal to $(3/2) k_B T$
In the absence of an electrical field, electrons move with randomly distributed thermal velocities	Electrons occupy energy levels according to Pauli's exclusion principle
When an electric field is applied, electrons acquire a net drift velocity in the direction opposite to the field	Electrons acquire additional energy when electric field is applied
Other Subjects: <a href="https://www.studymedia.in/fe/notes">https://www.studymedia.in/fe/notes</a>	

# The Classical Free Electron Theory (Drude-Lorentz Theory)

- The metal atoms have a core, which consist of a nucleus surrounded by the inner electrons and the valence electrons. The valence electrons are free to move throughout the volume of the sample.
- The electrostatic forces of attraction between the free electrons and the ion cores are negligible.
- The electrons cannot escape from the metal due to potential barrier at the surface. Inside the metal potential is constant.
- The free electrons are equivalents to gas molecules and hence the kinetic theory of gases is applicable to them. In absence of electric field, they have random thermal motion. Their energies are distributed according to the Maxwell-Boltzmann distribution.

# Success of classical free electron theory

- It is used to verify ohm's law.
- It is used to explain the electrical and thermal conductivities of metals.
- It is used to explain the optical properties of metals.
- Ductility and malleability of metals can be explained by this model.

# Drawbacks of classical free electron theory

- From the classical free electron theory the value of specific heat of metals is given by  $4.5R$ , where ' $R$ ' is called the universal gas constant. But the experimental value of specific heat is nearly equal to  $3R$ .
- With help of this model we can't explain the electrical conductivity of semiconductors and insulators.
- The theoretical value of paramagnetic susceptibility is greater than the experimental value.
- Ferromagnetism cannot be explained by this theory.

- At low temperature, the electrical conductivity and the thermal conductivity vary in different ways. Therefore  $K/\sigma T$  is not a constant. But in classical free electron theory, it is a constant in all temperature.
- The photoelectric effect, Compton effect and the black body radiation cannot be explained by the classical free electron theory.

# The salient features of quantum free electron theory

- *Sommerfeld* proposed this theory in 1928 retaining the concept of free electrons moving in a uniform potential within the metal as in the classical theory, but treated the electrons as obeying the laws of quantum mechanics.
- Based on the *DeBroglie wave concept*, he assumed that a moving electron behaves as if it were a system of waves. (called matter waves-waves associated with a moving particle).
- According to quantum mechanics, the energy of an electron in a metal is quantized. The electrons are filled in a given energy level according to Pauli's exclusion principle. (i.e. No two electrons will have the same set of four quantum numbers.)



- Each Energy level can provide only two states namely, one with spin up and other with spin down and hence only two electrons can be occupied in a given energy level.
- So, it is assumed that the permissible energy levels of a free electron are determined.
- It is assumed that the valence electrons travel in constant potential inside the metal but they are prevented from escaping the crystal by very high potential barriers at the ends of the crystal.
- In this theory, though the energy levels of the electrons are discrete, the spacing between consecutive energy levels is very less and thus the distribution of energy levels seems to be continuous.

# Success of quantum free electron theory

- According to classical theory, which follows Maxwell-Boltzmann statistics, all the free electrons gain energy. So it leads to much larger predicted quantities than that is actually observed. But according to quantum mechanics only one percent of the free electrons can absorb energy. So the resulting specific heat and paramagnetic susceptibility values are in much better agreement with experimental values.
- According to quantum free electron theory, both experimental and theoretical values of Lorentz number are in good agreement with each other.

# Drawbacks of quantum free electron theory

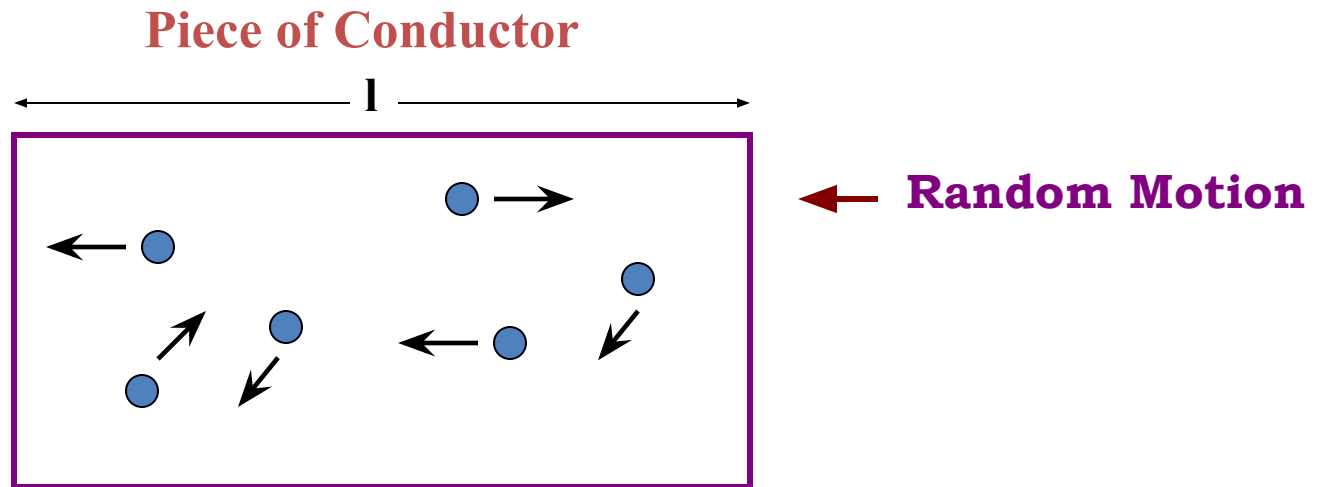
- It is incapable of explaining why some crystals have metallic properties and others do not have.
- It fails to explain why the atomic arrays in crystals including metals should prefer certain structures and not others.

# Conductivity of Conductors

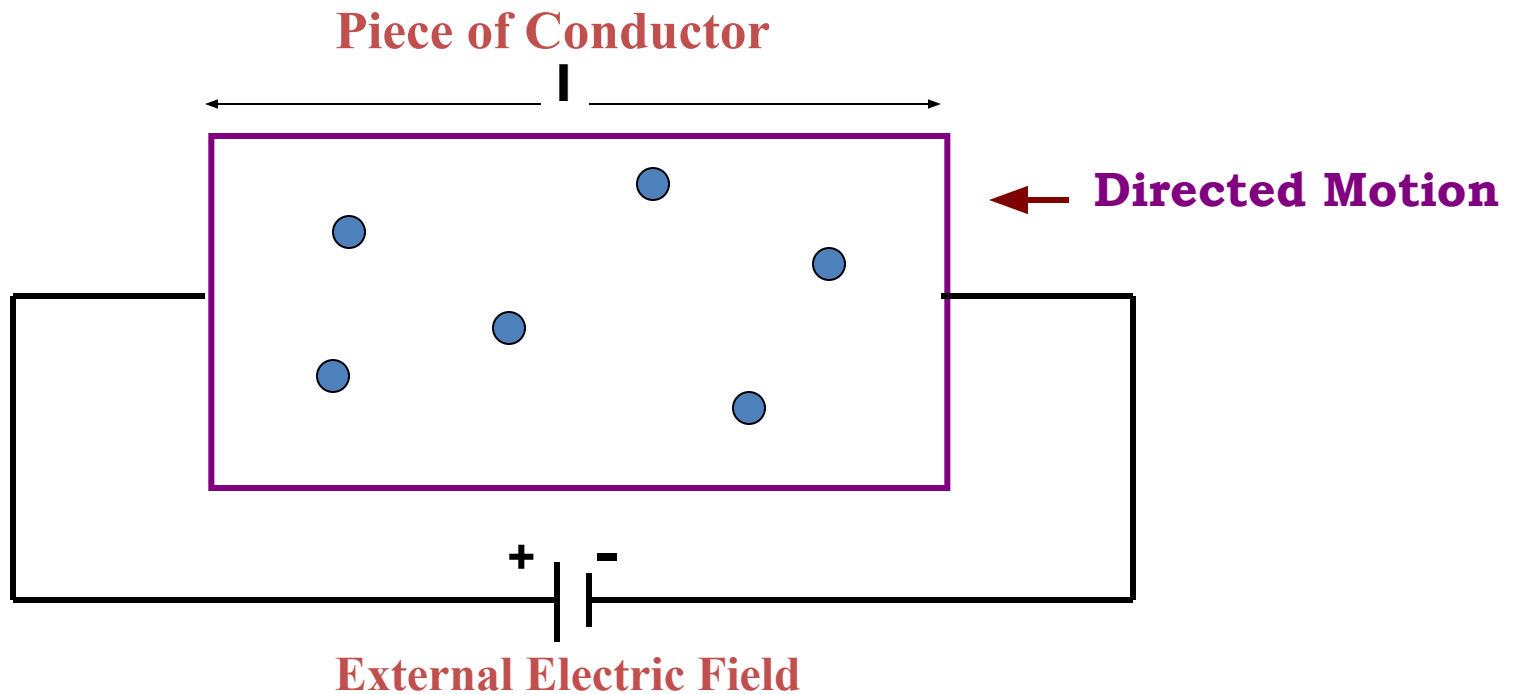
According to the free electron theory,

- Free electrons are called as conduction electrons & they form the “free electron cloud”

In absence of an external electric field the electron moves randomly in all directions.



When an electric field is applied to the metal, the random motion becomes directed. **This directed motion is known as drift & the velocity gained by the electron is called as drift velocity.**



The drift velocity 'v' of the electrons depends upon the electron mobility  $\mu_e$  & the applied electric field E.

The drift velocity 'v' is given by,

$$v = \mu_e E \text{----- 1)}$$

Let, A = conductor cross-section area

n = electron density (number of electron per unit volume of the conductor)

l = length of conductor

V = voltage across the two ends of the conductor

E = electric field applied

The charge crossing the cross-section 'A' of the conductor in unit time is equal to  $n \times (v \times A) \times e$ . This rate of flow of charge constitute the current.

$$I = n v A e \text{---- -2)}$$

Substituting for v from equation 1)

$$I = n \mu_e E A e \text{-----3)}$$



Now substituting for  $E = V/l$  in equation 3)

$$I = n \mu_e \frac{V}{l} A e \text{ ----- 4)}$$

$$\frac{V}{I} = \frac{l}{A n \mu_e e} \text{ ----- 5)}$$

By Ohm's law, we have,  $R = \frac{V}{I}$

$$R = \frac{l}{A n \mu_e e} \text{ ----- 6)}$$

$$\text{But, } R = \rho \frac{l}{A} \text{ -----7)}$$

where  $\rho$  is the resistivity of the conductor

Compare equation 6) & 7), we get

$$\rho = \frac{1}{n \mu_e e} \text{ ----- 8)}$$

The unit is ohm-m.

Conductivity ' $\sigma$ ' is defined as the reciprocal of resistivity.

$$\sigma = \frac{1}{\rho} = n e \mu_e \text{ -----9)}$$

The unit is mho/m

●The current density 'J' is defined as the current flowing across the unit cross section.

From equation 3)

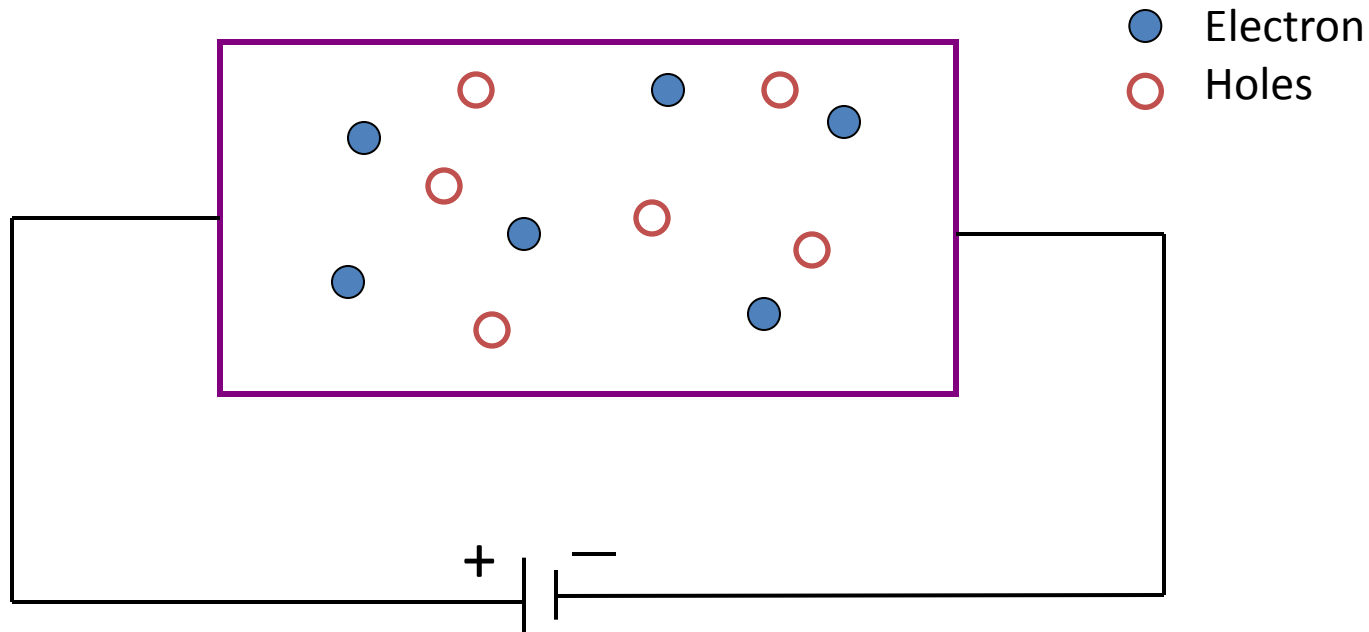
$$J = \frac{I}{A} = n e \mu_e E \text{ ----- 10)}$$

From equation 9) & 10)

$$J = \sigma E \quad OR \quad \sigma = \frac{J}{E}$$

# Conductivity of Semiconductors

Figure shows the total current flowing in a semiconductor is a sum of current flowing due to electrons & holes.



In a semiconductor, Let

$n_e$  = electron density in conduction band

$n_p$  = hole density in valence band

$\mu_e$  = electron mobility

$\mu_p$  = hole mobility

$v_e$  = drift velocity of electron

$v_p$  = drift velocity of hole

$A$  = cross section area of semiconductor

$V$  = voltage applied across the semiconductor length

The current due to electrons is given by,

$$I_e = n_e v_e A e \text{ -----1)}$$

And the current due to hole is given by

$$I_p = n_p v_p A e \text{ ----- 2)}$$

● Therefore the total current flowing through the semiconductor will be,

$$\text{Total current, } I = I_e + I_p$$

$$I = n_e v_e A e + n_p v_p A e$$

$$I = A e (n_e v_e + n_p v_p) \text{ ----- 3)}$$

The drift velocity of a charged particle in electric field is given as,

$$v = \mu E$$

$$\text{For electrons, } v_e = \mu_e E$$

$$\text{For holes, } v_p = \mu_p E$$

$$\text{But } E = \frac{V}{l}$$

$$\text{Hence, } v_e = \mu_e \frac{V}{l} \text{ ----- 4)}$$

$$v_p = \mu_p \frac{V}{l} \text{ ----- 5)}$$

Substituting equation 4) and 5) in equation 3), we get

$$I = A e (n_e \mu_e \frac{V}{l} + n_p \mu_p \frac{V}{l})$$

$$I = \frac{A e V}{l} (n_e \mu_e + n_p \mu_p) \text{ ----- 6)}$$

$$R = \frac{V}{I} = \frac{l}{A e (n_e \mu_e + n_p \mu_p)} \text{ ----- 7)}$$

$$\text{But } R = \rho \frac{l}{A} \text{ ----- 8)}$$

From equation 7) & 8)

$$\rho = \frac{1}{e (n_e \mu_e + n_p \mu_p)} \text{ ----- 9)}$$

$$\text{The conductivity is, } \sigma = \frac{1}{\rho} = e (n_e \mu_e + n_p \mu_p) \text{ ----- 10)}$$

Hence the conductivity in a semiconductor is a sum of conductivity due to electrons and holes.



Hence,

$$\sigma_{sc} = \sigma_e + \sigma_p$$

From equation 3)

$$\frac{I}{A} = e (n_e \mu_e + n_p \mu_p) E$$

Hence current density is,

$$J = \frac{I}{A} = e (n_e \mu_e + n_p \mu_p) E \text{ ----- 11)}$$

From equation 10) & 11)

$$J = \sigma E$$

**In case of Intrinsic semiconductor,**

$$n_e = n_p = n_i$$

∴ Conductivity of an intrinsic semiconductor is,

$$\sigma_i = e n_i (\mu_e + \mu_p)$$

## Extrinsic semiconductor

### 1. n-type semiconductor

In case of n-type semiconductor, electron concentration is much more greater than the hole concentration.

$$\therefore n_e \gg n_p \quad \text{or} \quad n_e \mu_e \gg n_p \mu_p$$

Hence, 
$$\sigma_n = e n_e \mu_e$$

If  $n_d$  is electron concentration or concentration of donor atoms,

then, 
$$\sigma_n = e n_d \mu_e \quad (\text{as } n_e = n_d)$$

### 2. p-type semiconductor

In p-type semiconductor, electron concentration is negligibly small in comparison to hole concentration.

$$\therefore n_p \gg n_e \quad \text{or} \quad n_p \mu_p \gg n_e \mu_e$$

Hence, 
$$\sigma_p = e n_p \mu_p$$

If  $n_a$  is concentration of acceptor atoms,

then, 
$$\sigma_p = e n_a \mu_p \quad (\text{as } n_p = n_a)$$

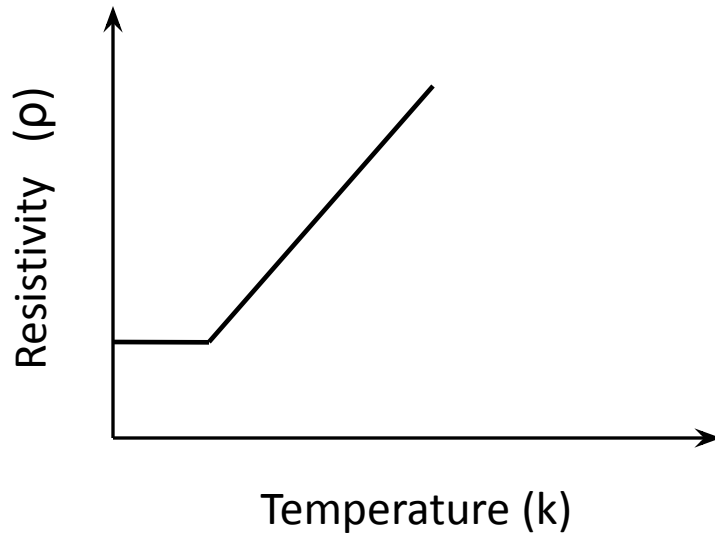
# Influence of external factors on conductivity

## 1. Temperature:

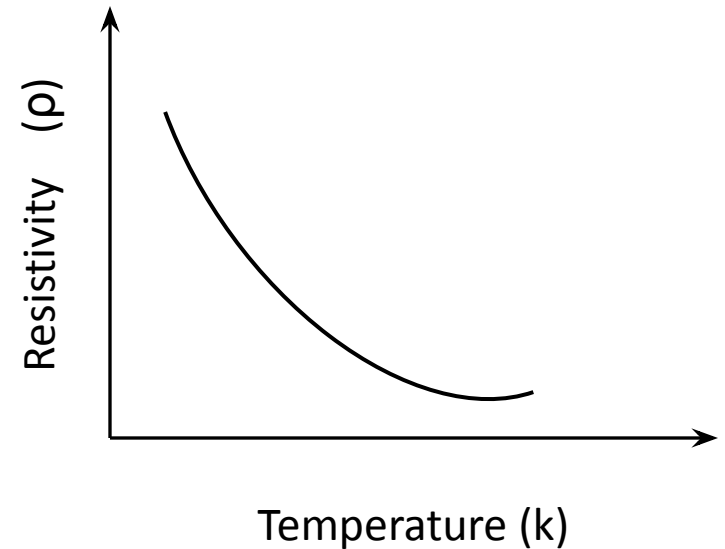
In case of metals, the increase in temperature increases the vibration of lattice points. As the amplitude of vibration is greater, chances of collision with electron increases. This decreases the drift velocity of the free electrons. Thus the conductivity decreases & resistivity increases with temperature in metals.

In case of semiconductors, as the energy gap between valence band & conduction band is small, a rise in temperature excites an electron from valence to conduction band. This creates electron hole pair & both will participate in conduction. Thus the conduction charge density increases with temperature. Therefore, in case of semiconductors the resistivity decreases with increase in temperature.

## Variation of resistivity with temperature



Conductors

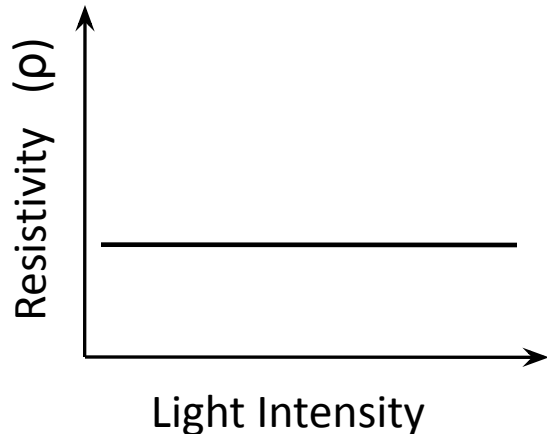


Semiconductors

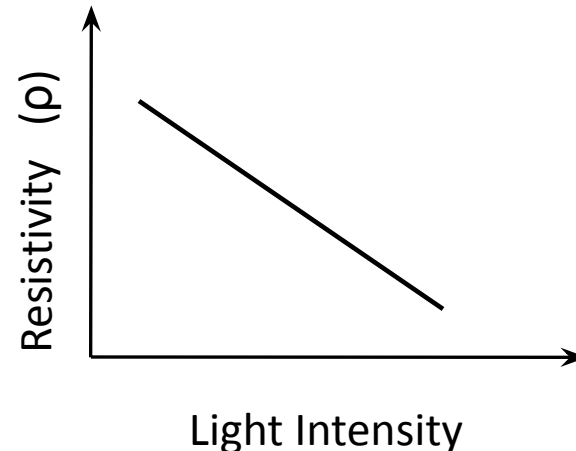
## 2. Light:

In case of metals, whenever a light is incident & energy of photon is more than a critical value, an electron is ejected from a metal surface. But this does not affect the overall resistivity of the metal. Therefore, the resistivity of metals do not depend on light.

In case of semiconductors, just like temperature, light affects the resistivity of semiconductors. When photon of energy equal to the band gap is incident on semiconductor, the photon will be absorbed & an electron will be excited to the conduction band. This increases the number of conduction charge carriers & results in increase in conductivity & decreases resistivity.



Conductors

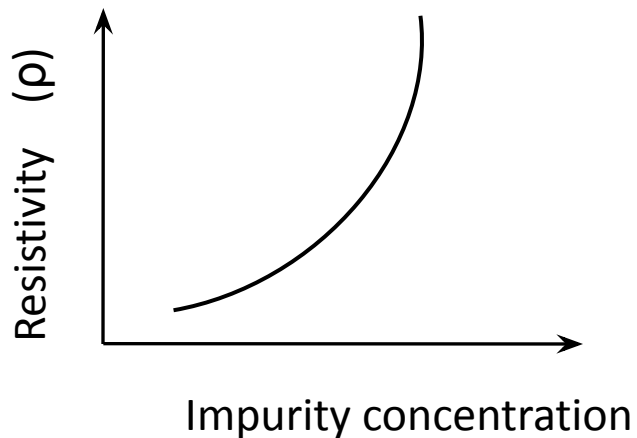


Semiconductors

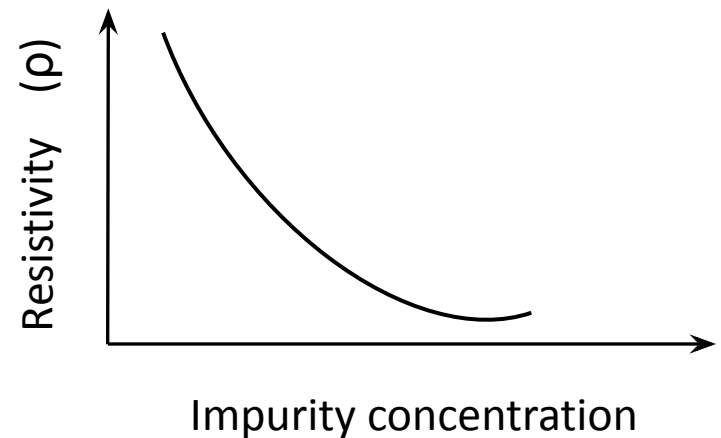
### 3. Impurity:

In metals, the presence of impurity increases the scattering of conduction electron at impurity atoms, thereby decreasing the drift velocity. The fall in drift velocity results in increase in resistivity & decrease in conductivity. As the chances of collision increases with impurity concentration, the resistivity also increases with impurity concentration.

On other hand, in semiconductors the addition of proper impurity (doping) increases the concentration of charge carriers. This increases the conductivity & decreases the resistivity with impurity concentration.



Metals



Semiconductors

## Fermi Energy:

The highest filled state in the highest energy band which contains electrons in a metal, at 0 K is called Fermi level & its corresponding energy is called the Fermi energy  $E_F$ .

Fermi level in **case of semiconductors** may be defined as the energy which corresponds to the centre of gravity of conduction electrons and holes when “weighted” according to their energies.

# Fermi-Dirac Probability Distribution Function

The result of statistical arrangement gives the distribution of electrons over a range of allowed energy levels at thermal equilibrium.

$$\text{i.e. } P(E) = \frac{1}{1 + e^{(E - E_F)/KT}} \text{ ----- 1)}$$

Where K is a Boltzmann's constant

The Fermi-Dirac distribution function  $P(E)$  gives the **probability** that an electron can occupy the energy state of energy  $E$  at absolute temperature  $T$ .

The term  $E_F$  is known as Fermi Energy

1. If the energy  $E$  is equal to Fermi energy ( $E = E_F$ ), the probability of occupation is given by,

$$P(E_F) = (1 + e^{(E_F - E_F)/KT})^{-1}$$

$$P(E_F) = 1/2$$

Thus, an energy state at the Fermi level has a probability  $1/2$  of being occupied by an electron for a temperature  $T > 0 \text{ K}$

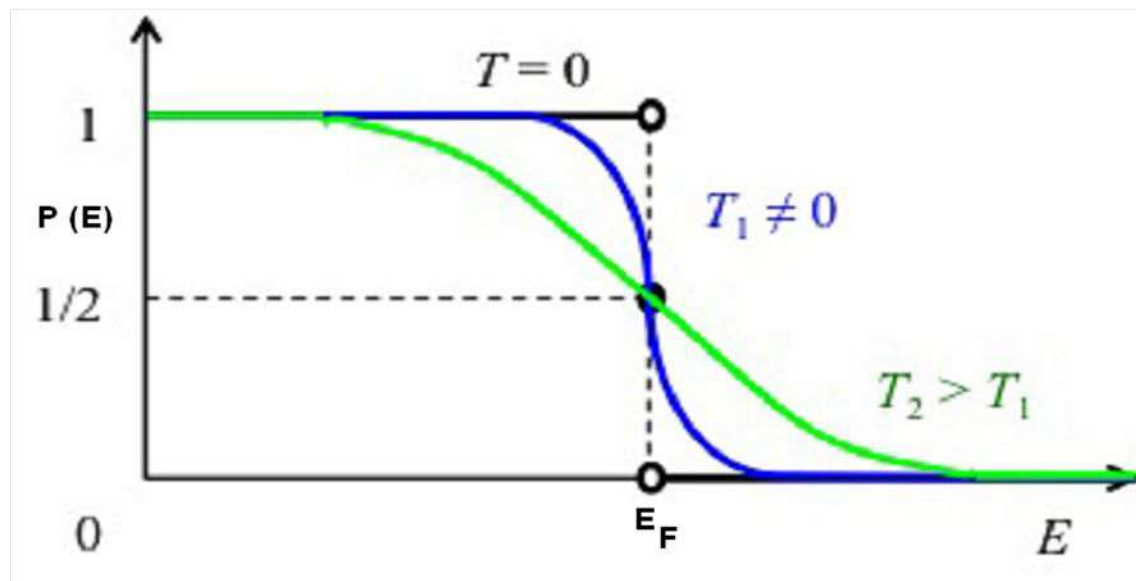


2. At  $T = 0$  K for  $E < E_F$ , the term  $e^{(E-E_F)/KT} = 0$ . So that the  $P(E) = 1$   
The probability of finding an electron with energy less than Fermi energy is one.

Hence at  $T = 0$  K, all the energy levels below Fermi levels are certainly occupied.

3. At  $T = 0$  K for  $E > E_F$ , the term  $e^{(E-E_F)/KT} = \infty$ .  $P(E) = 0$

Hence, at  $T = 0$ , the probability of occupying the energy states above  $E_F$  is zero hence they are empty.



# Position of Fermi Level in Intrinsic Semiconductors

The Fermi-Dirac distribution function is,

$$P(E) = \frac{1}{1 + e^{\frac{E - E_F}{KT}}} \text{ ----- 1)}$$

It gives the probability of an electron occupying a state of energy E  
To find the position of Fermi level in intrinsic semiconductor the following facts are assumed that,

1. The width of valence & conduction bands are small as compared to forbidden band  $E_g$ .
2. As band widths are small, all levels in the bands have same energy. The levels in the conduction band have energy  $E_c$  and levels in the valence band are  $E_v$ .
3. At 0 K, the solid is like insulator

At any other temperature T,

Let,  $n_c$  = number of electrons in conduction band

$n_v$  = number of electrons in valence band

∴ Total number of electrons in both the bands  $N = n_c + n_v$

From the probability theory,

$$P(E_c) = \frac{n_c}{N}$$

$$n_c = N P(E_c) \text{ ----- 2)}$$

Where,  $P(E_c)$  is the probability of an electron having an energy  $E_c$  in the conduction band.

So, according to Fermi-Dirac probability distribution function,

$$P(E_c) = \frac{1}{1 + e^{(E_c - E_F)/KT}} \text{ ----- 3)}$$

$$\text{From equation 2) \& 3), } n_c = \frac{N}{1 + e^{(E_c - E_F)/KT}} \text{ -----4)}$$

$$\text{Similarly, } n_v = \frac{N}{1 + e^{(E_v - E_F)/KT}} \text{ ----- 5)}$$

We know,  $N = n_c + n_v$

From equation 4) & 5)

$$N = \frac{N}{1+e^{(E_c-E_F)/KT}} + \frac{N}{1+e^{(E_v-E_F)/KT}}$$

Or,

$$(1+e^{(E_c-E_F)/KT}) (1+e^{(E_v-E_F)/KT}) = 1+e^{(E_c-E_F)/KT} + 1 + e^{(E_v-E_F)/KT}$$

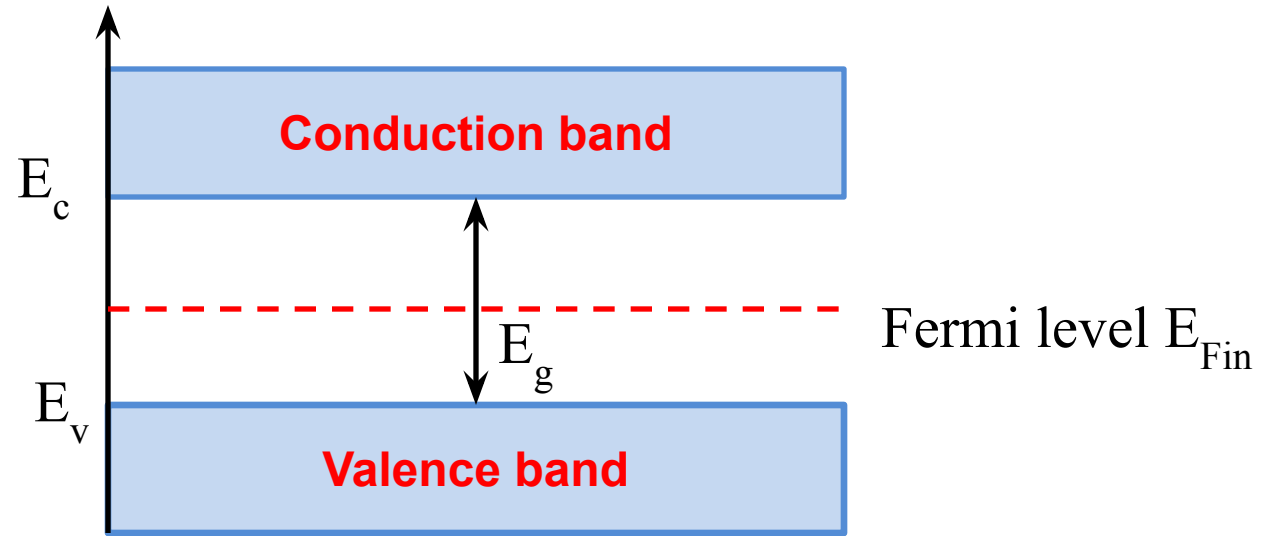
This gives,  $e^{(E_c+E_v-2E_F)/KT} = 1$

i.e.  $\frac{E_c+E_v-2E_F}{KT} = 0$

Hence,  $E_F = \frac{E_c+E_v}{2}$

Thus, Fermi level in intrinsic semiconductors is exactly in the middle of forbidden gap, as shown in figure.

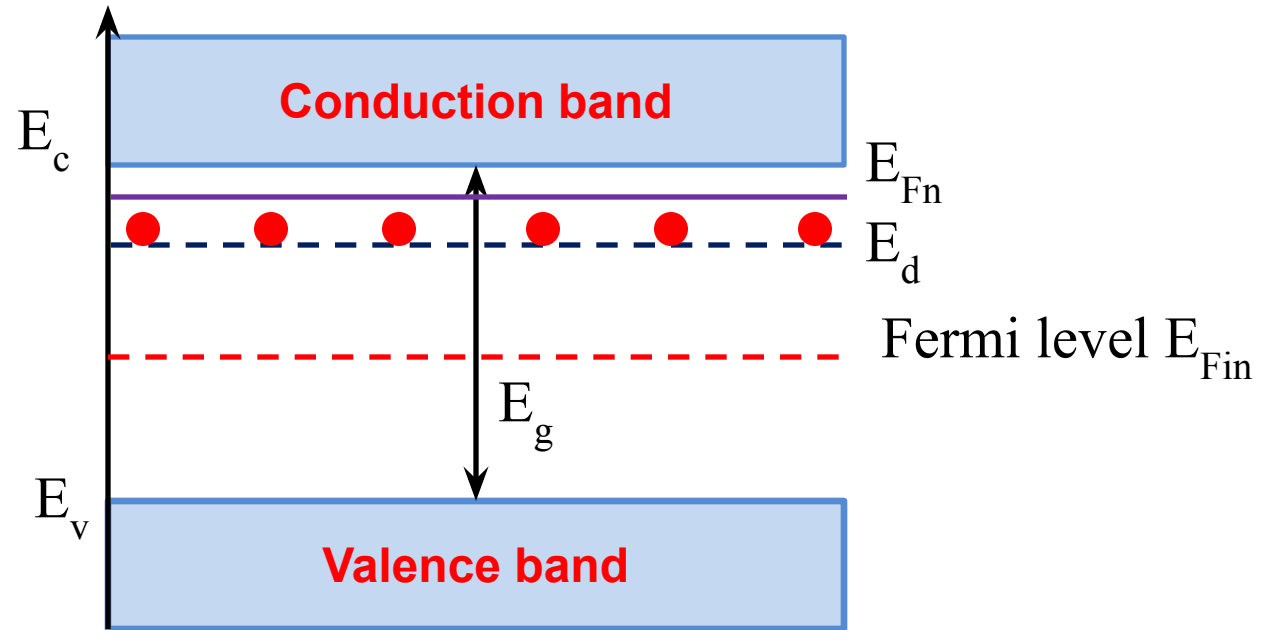
# Position of Fermi level in Intrinsic Semiconductor



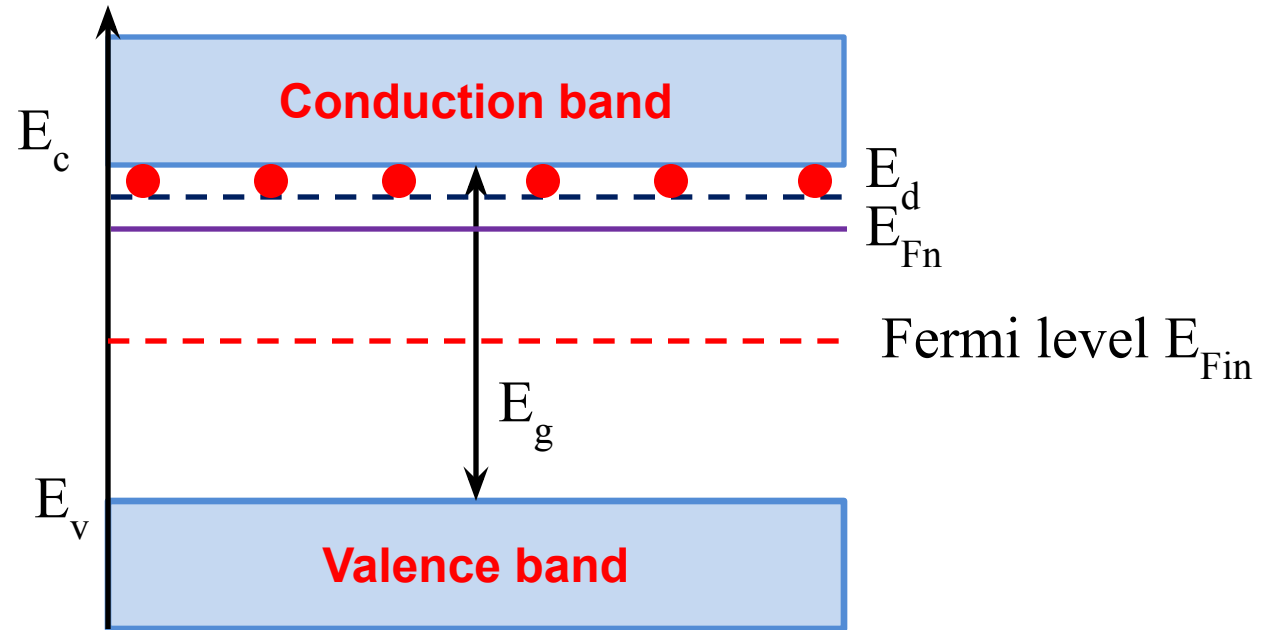
Position of Fermi level in intrinsic semiconductor

# Position of Fermi level in Extrinsic Semiconductor

## 1. n-type semiconductor:

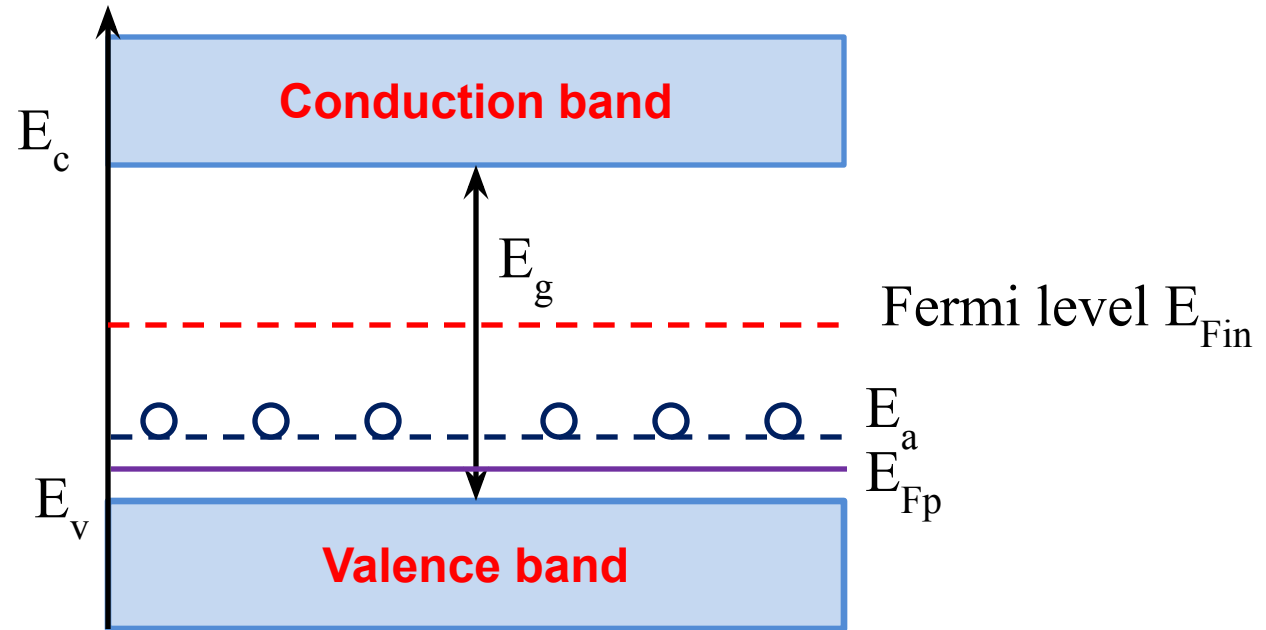


a)  $T = 0 \text{ K}$



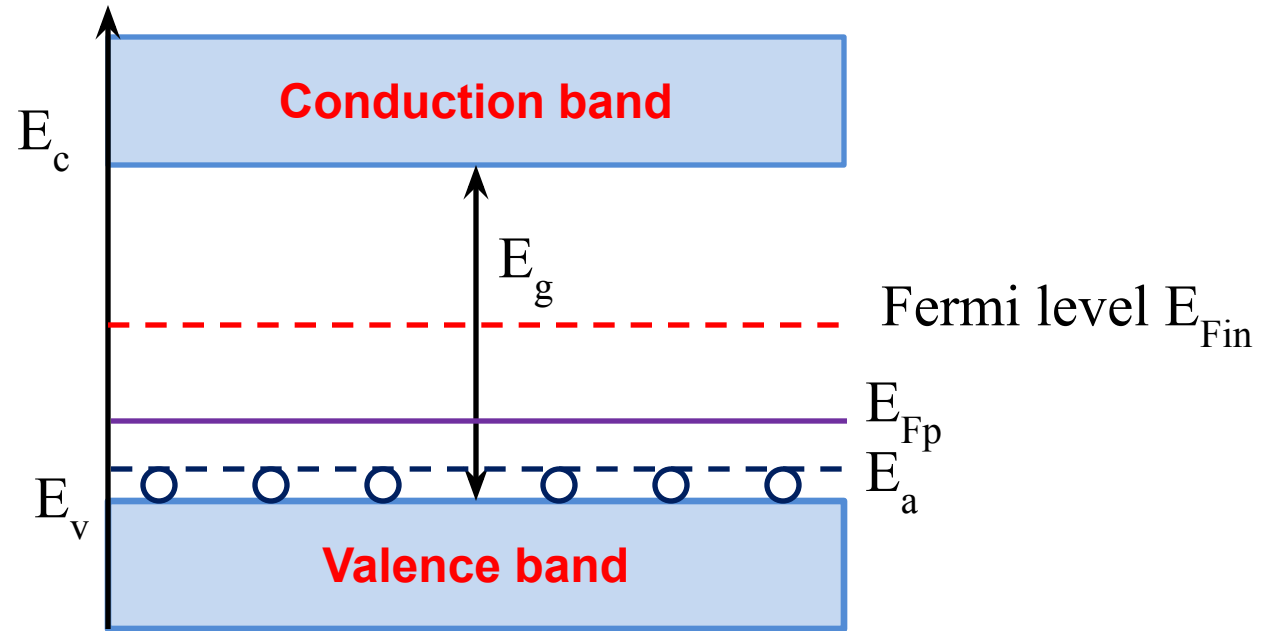
b)  $T > 0$  K

## 2. p-type semiconductor:



a)  $T = 0 \text{ K}$

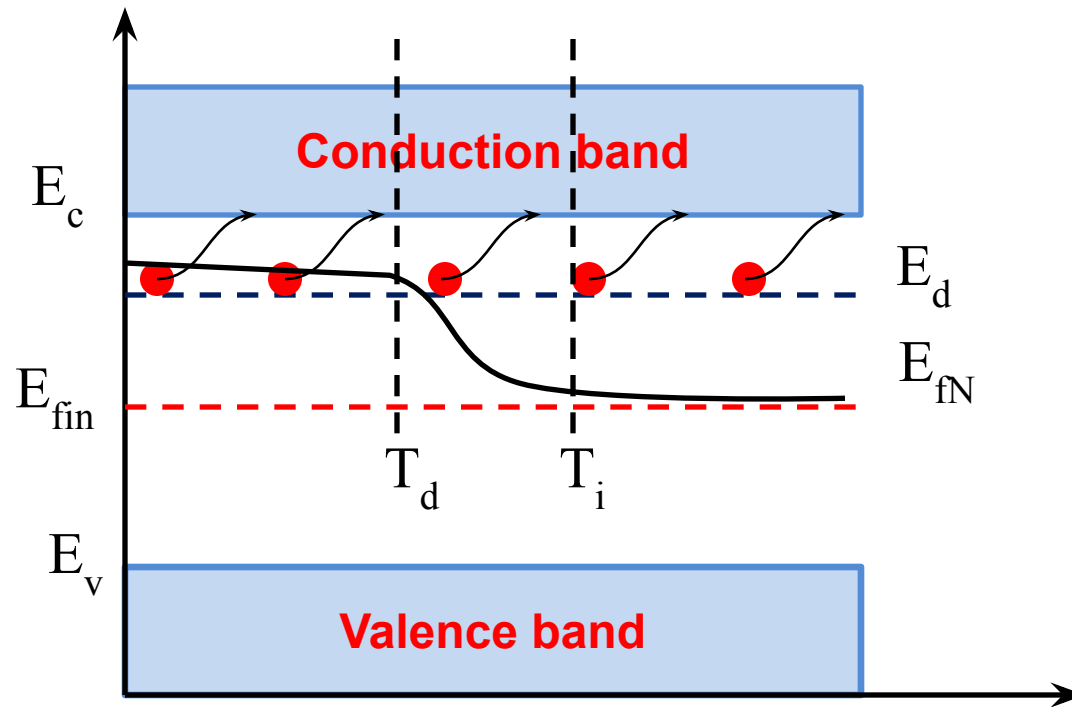




b)  $T > 0$  K

# Dependence of Fermi Level on temperature & doping concentration

## 1. Temperature:



Variation of Fermi Level with temperature in case of N-type semiconductor

1. In case of N-type semiconductor, at low temperature region, electrons in conduction band are only due to the transition of electrons from the donor level. Therefore the Fermi level  $E_{fN}$  lies between the donor level & bottom edge of the conduction band.

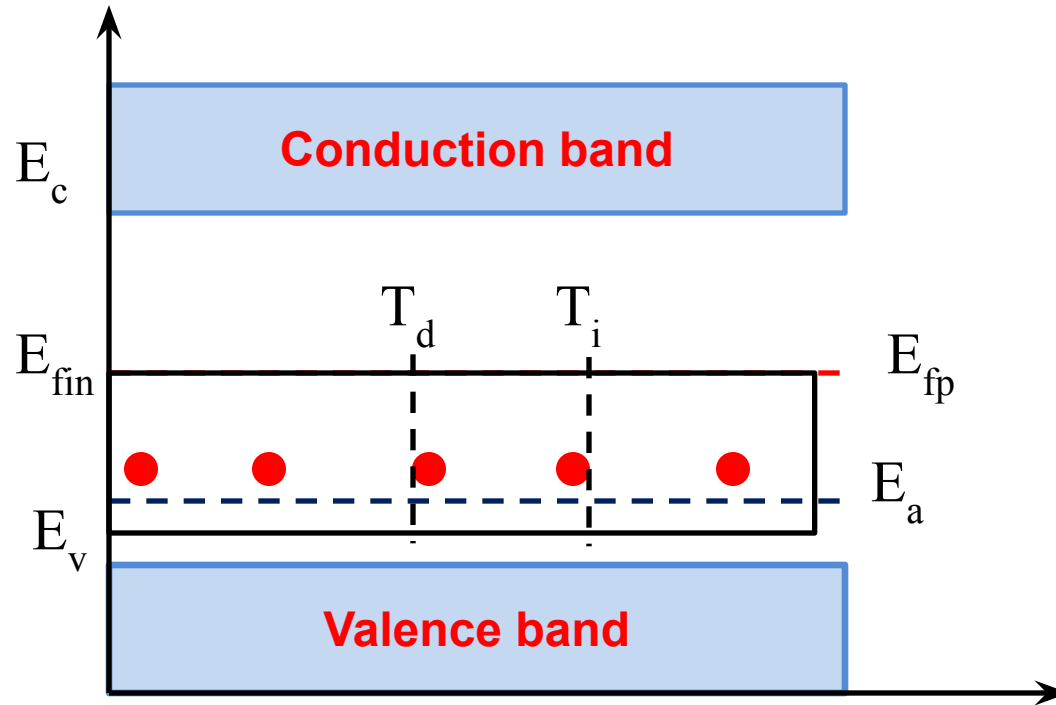
$$E_{fN} = \frac{E_c + E_d}{2} \text{ ----- Ionization Region}$$

2. As the temperature increases, the donor levels gradually gets depleted and the Fermi level shifts downwards. At the temperature of depletion  $T_d$ , the Fermi level coincides with the donor level  $E_d$ .

$$E_{fN} = E_d \text{ (at } T = T_d \text{)}$$

3. As the temperature goes above  $T_d$ , the Fermi level shifts downwards in an approximately linear fashion, though the electron concentration in conduction band remains constant. Fermi level approaches the value equal to intrinsic value.

4. With further increase in temperature, the behavior of extrinsic semiconductor transforms into that of an intrinsic type & Fermi level stays at  $E_{fin}$  i.e.  $E_{fN} = E_{fin} = \frac{E_g}{2}$  ----- Intrinsic region



Variation of Fermi Level with temperature in case of P-type semiconductor

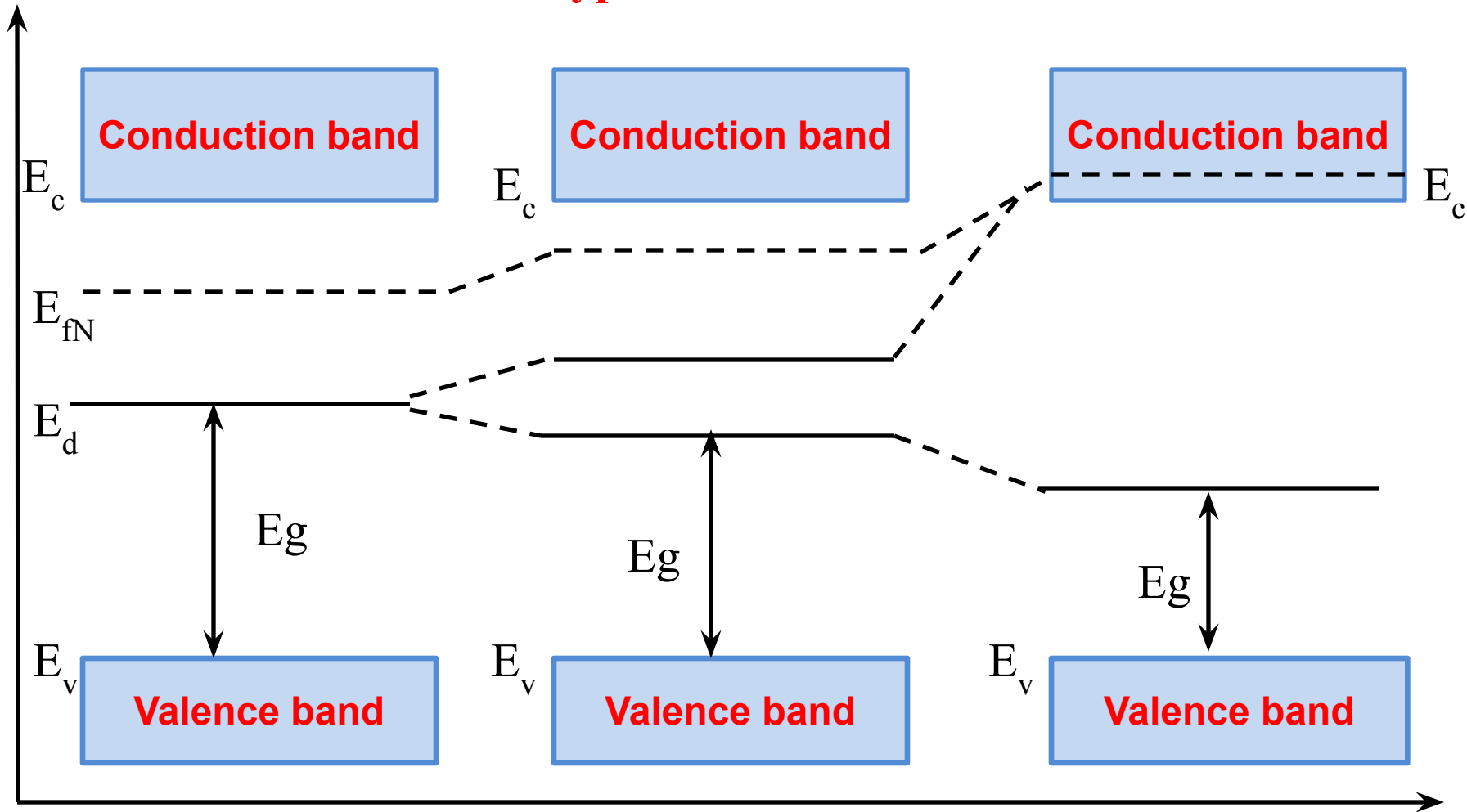
In case of P-type semiconductor, the Fermi level  $E_{fp}$  rises with increasing temperature from below the acceptor level to intrinsic level  $E_{fin}$ .

$$E_{fP} = \frac{E_a + E_v}{2} \text{ ---- Ionization region}$$

$$E_{fP} = E_a \text{ (at } T = T_d \text{)}$$

$$E_{fP} = \frac{E_g}{2} \text{ ---- } \textit{Intrinsic region}$$

**Effect of impurity concentration on Fermi level:  
N- type semiconductor**



**a) Low level doping**

**b) medium doping**

**c) heavy doping**

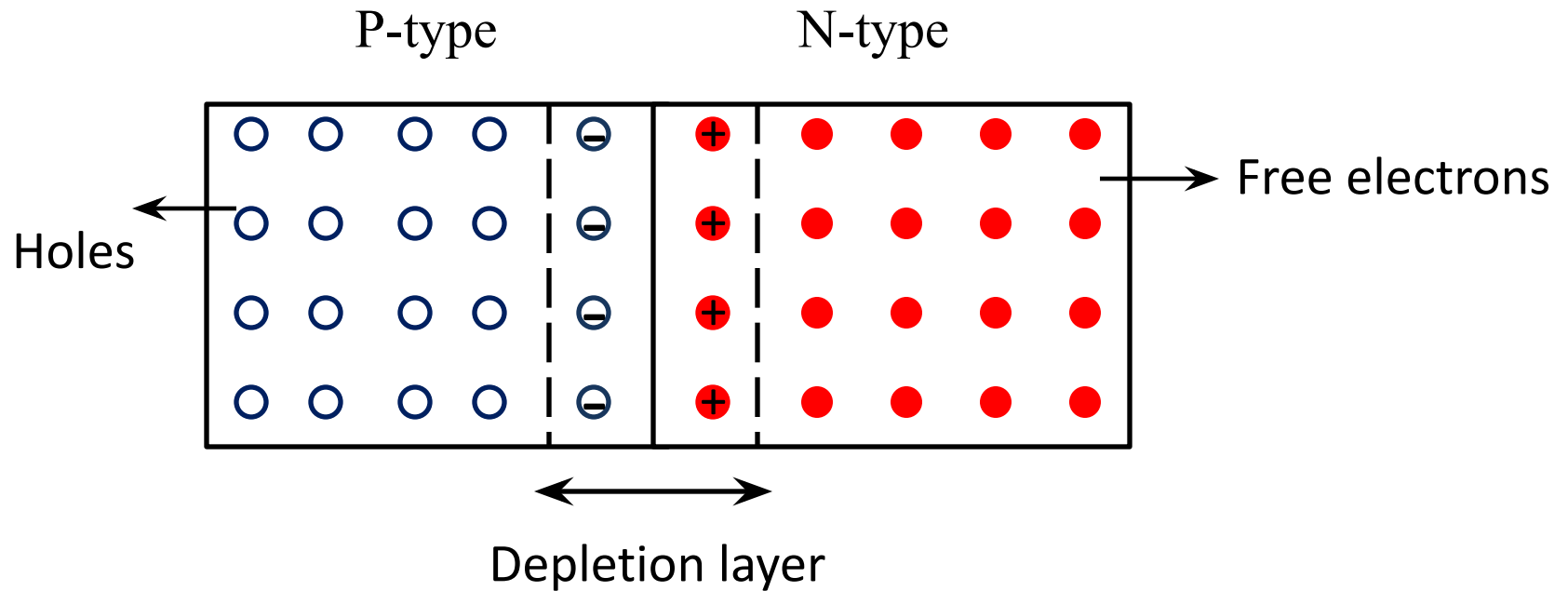
The addition of donor impurity to an intrinsic semiconductor leads to the formation of discrete levels below the bottom edge of the conduction band. At low impurity concentration, the impurity atoms are spaced far apart & do not interact with each other.

With increase in impurity concentration the separation tends to decrease & they interact. As a result the donor level splits & forms a energy band below the conduction band.

Larger doping concentration, broaden the impurity band & at one stage it overlap with conduction band. The broadening of donor levels into band is accompanied by decrease in the band gap and upward displacement of Fermi level. The Fermi level moves closer and closer to the conduction band and finally moves in to conduction band as donor band overlap the conduction band.

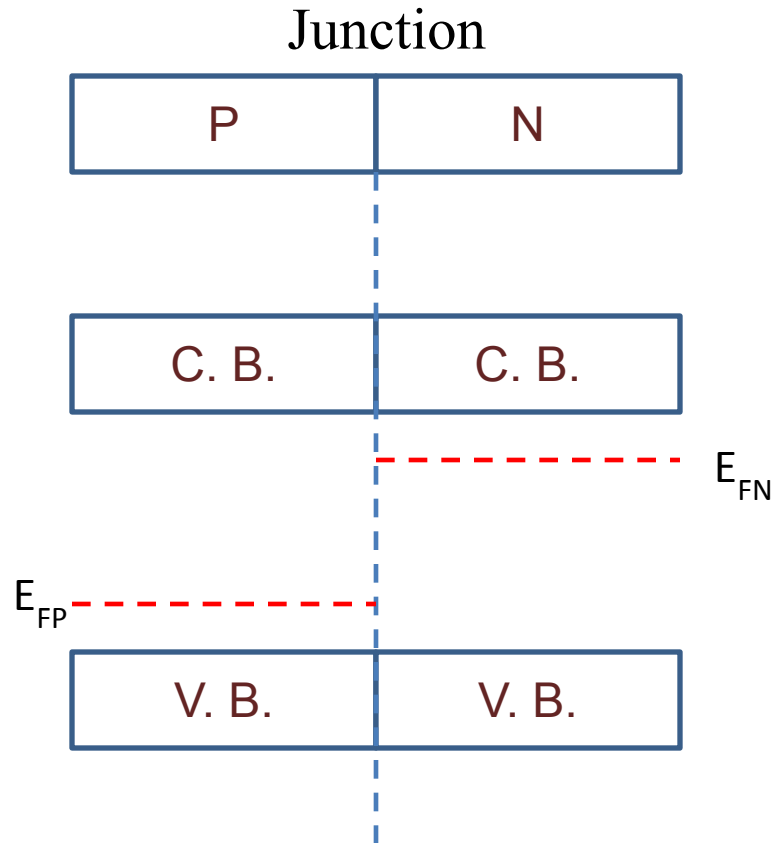
In a similar way in case of P- type semiconductor, the acceptor level broaden & forms into band with increase in impurity concentration which ultimately overlaps on the valence band. The Fermi level moves downwards closer to valence band & finally at very high impurity concentration it will shift in to valence band.

# P-N Junction Diode

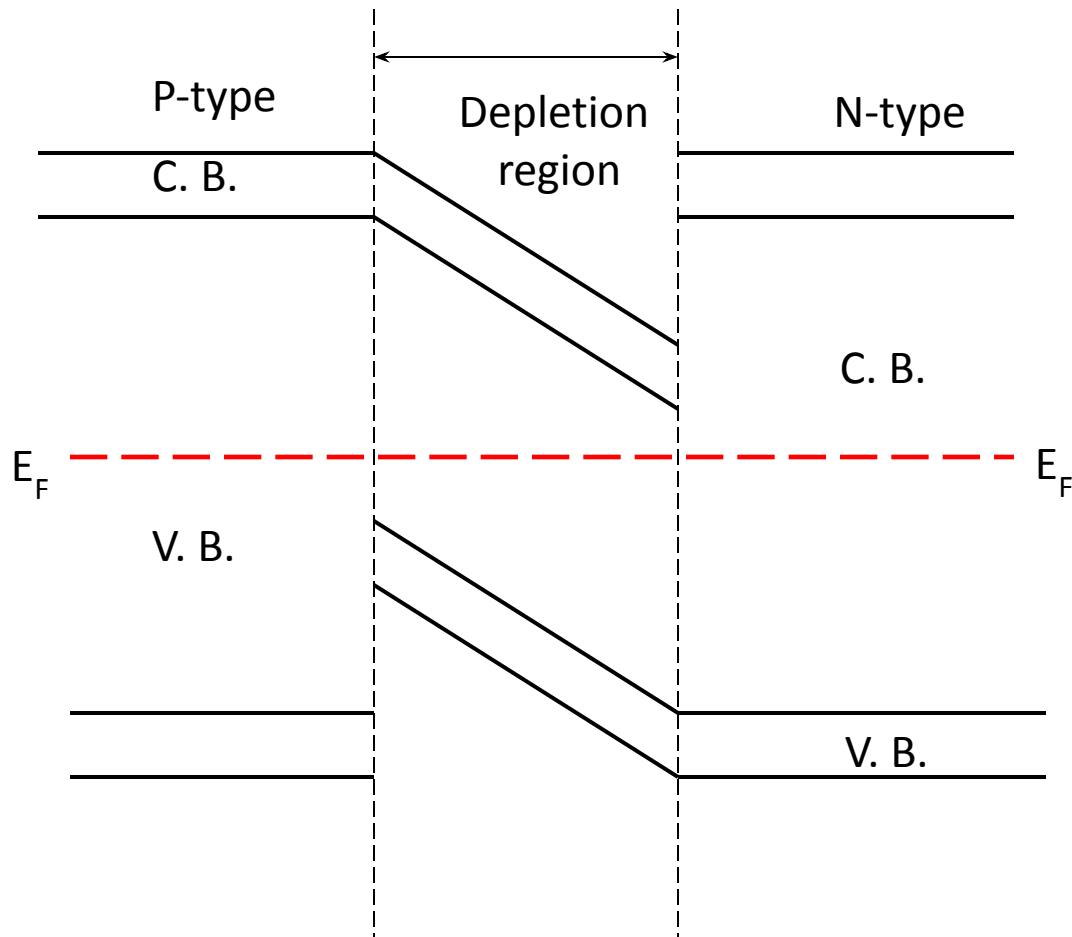




# 1. Open circuit P-N junction (Zero bias):

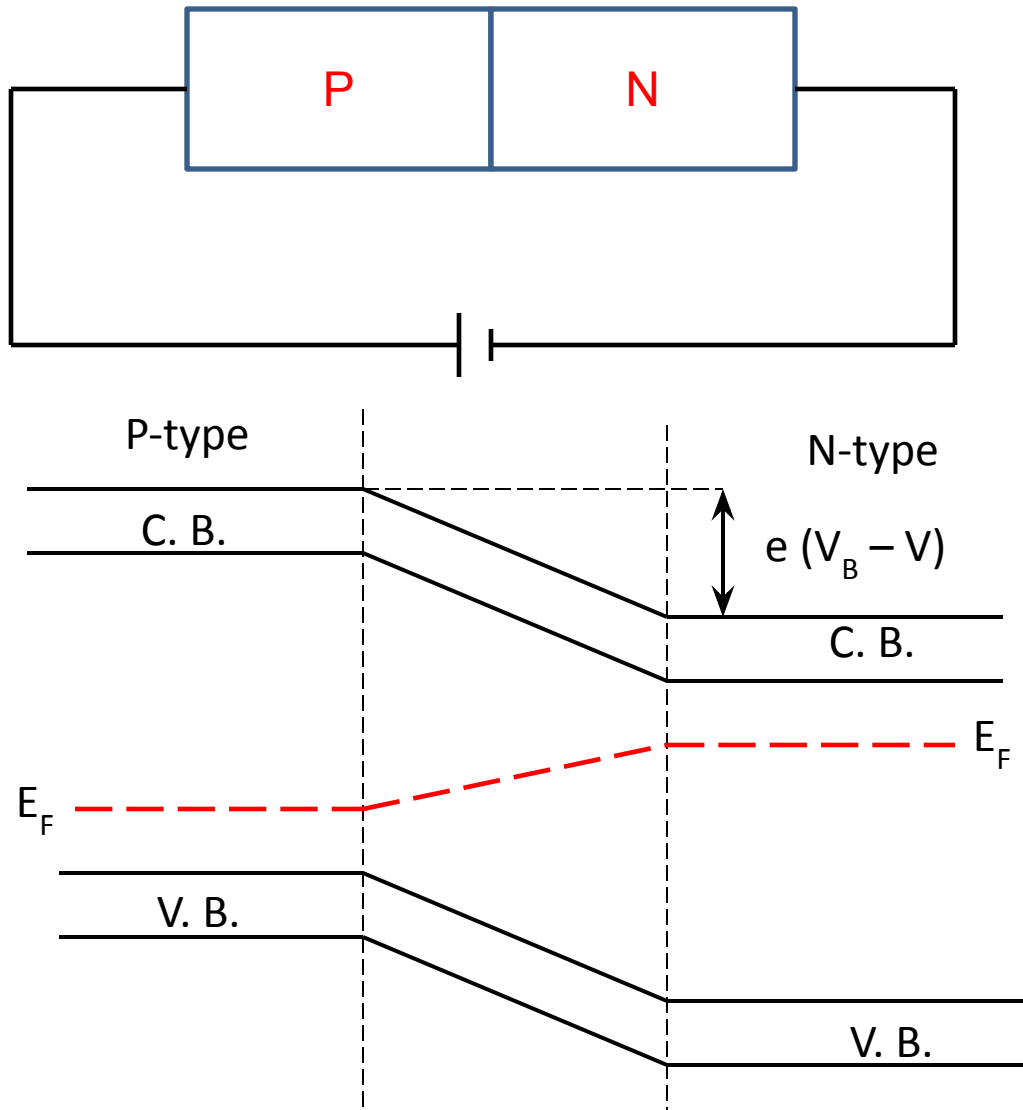


Non-equilibrium energy band picture of P-N junction

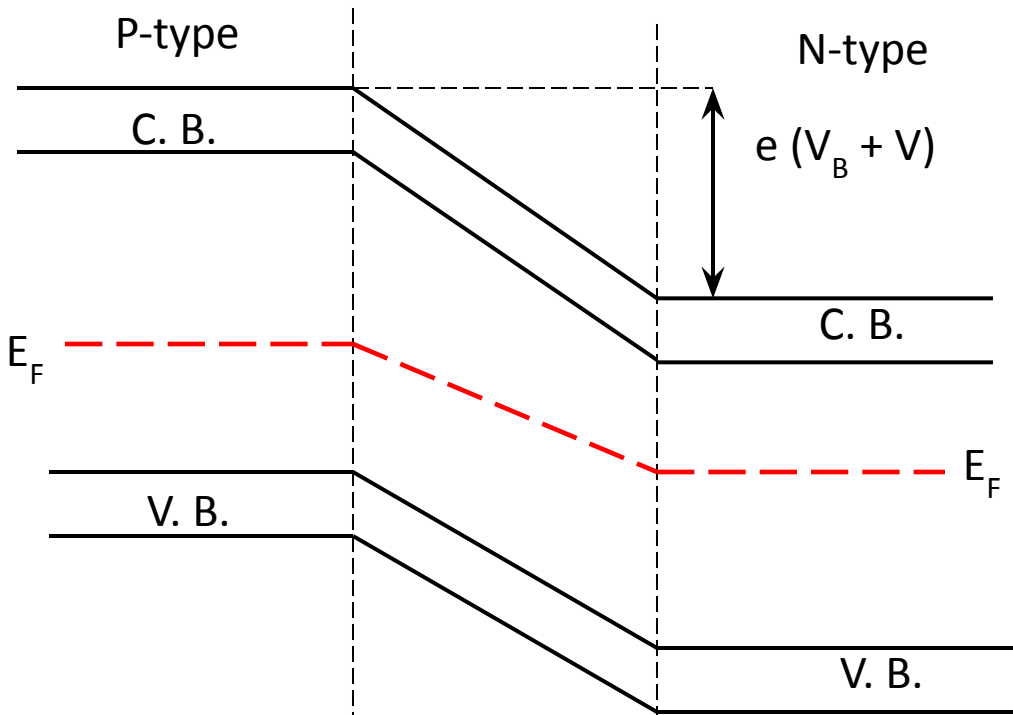
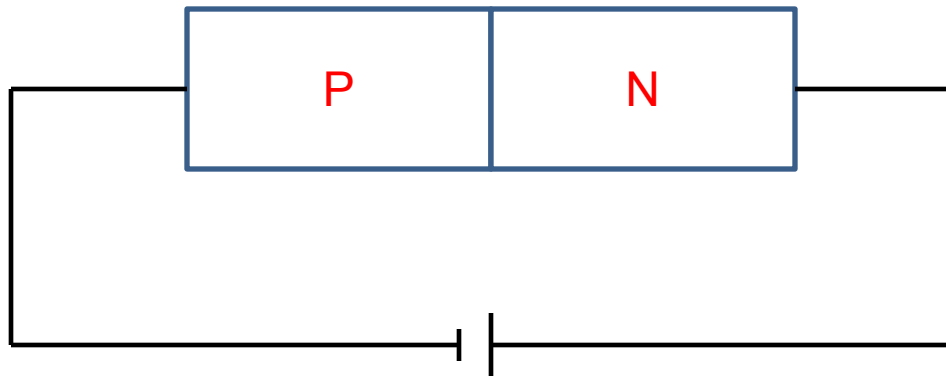


Shifting of bands in P & N type semiconductor

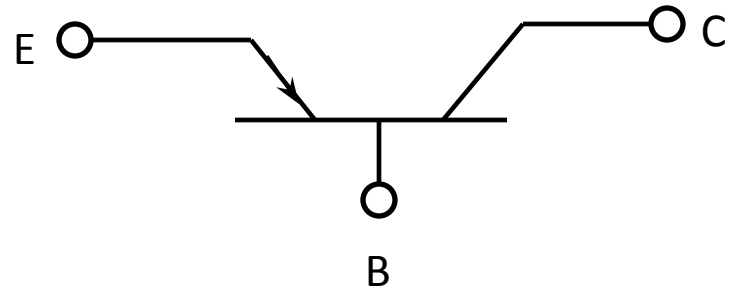
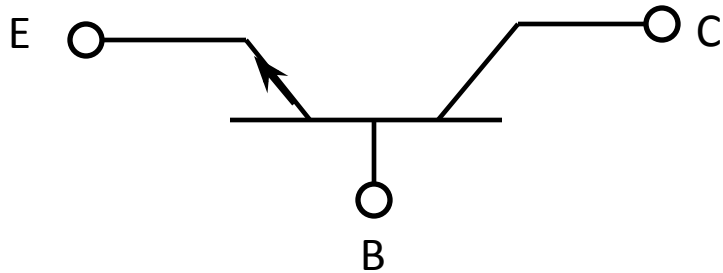
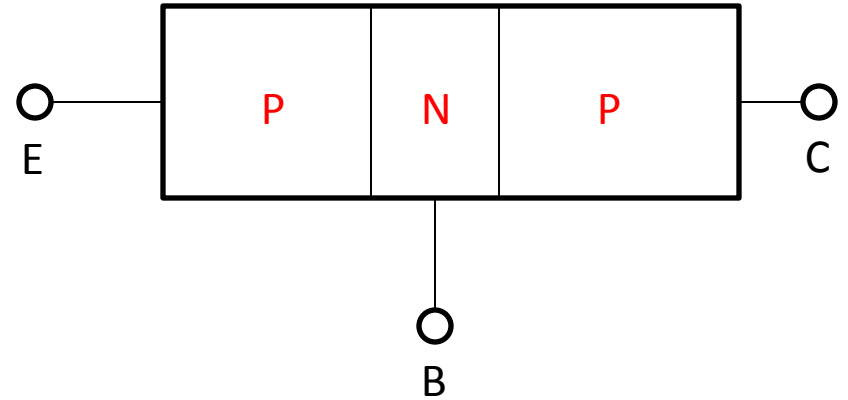
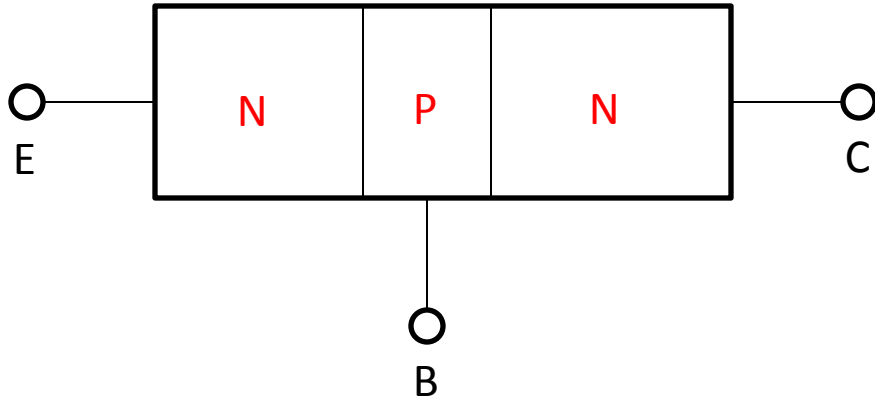
## 2. Forward Bias:



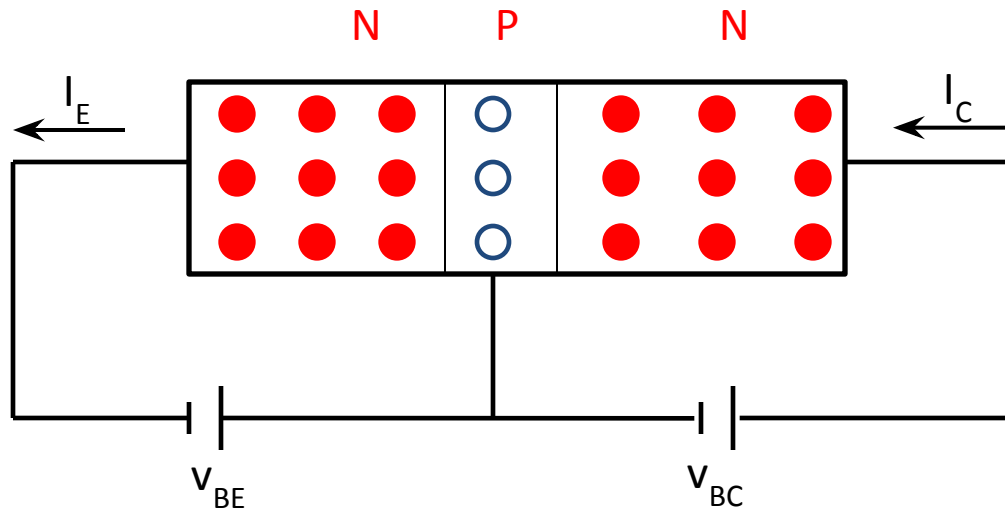
### 3. Reverse Bias:



## Junction transistor:

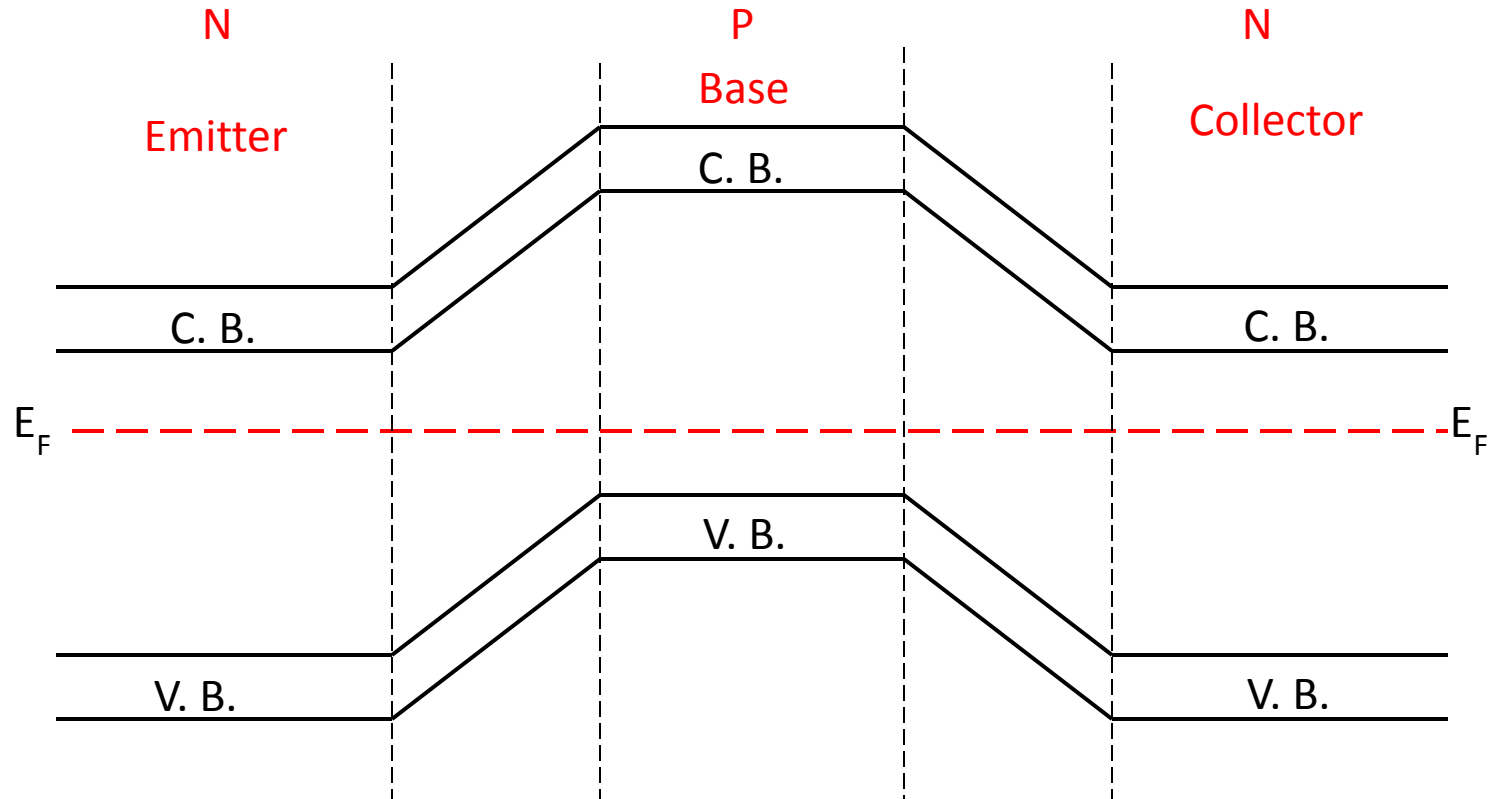


## Biasing of transistor:

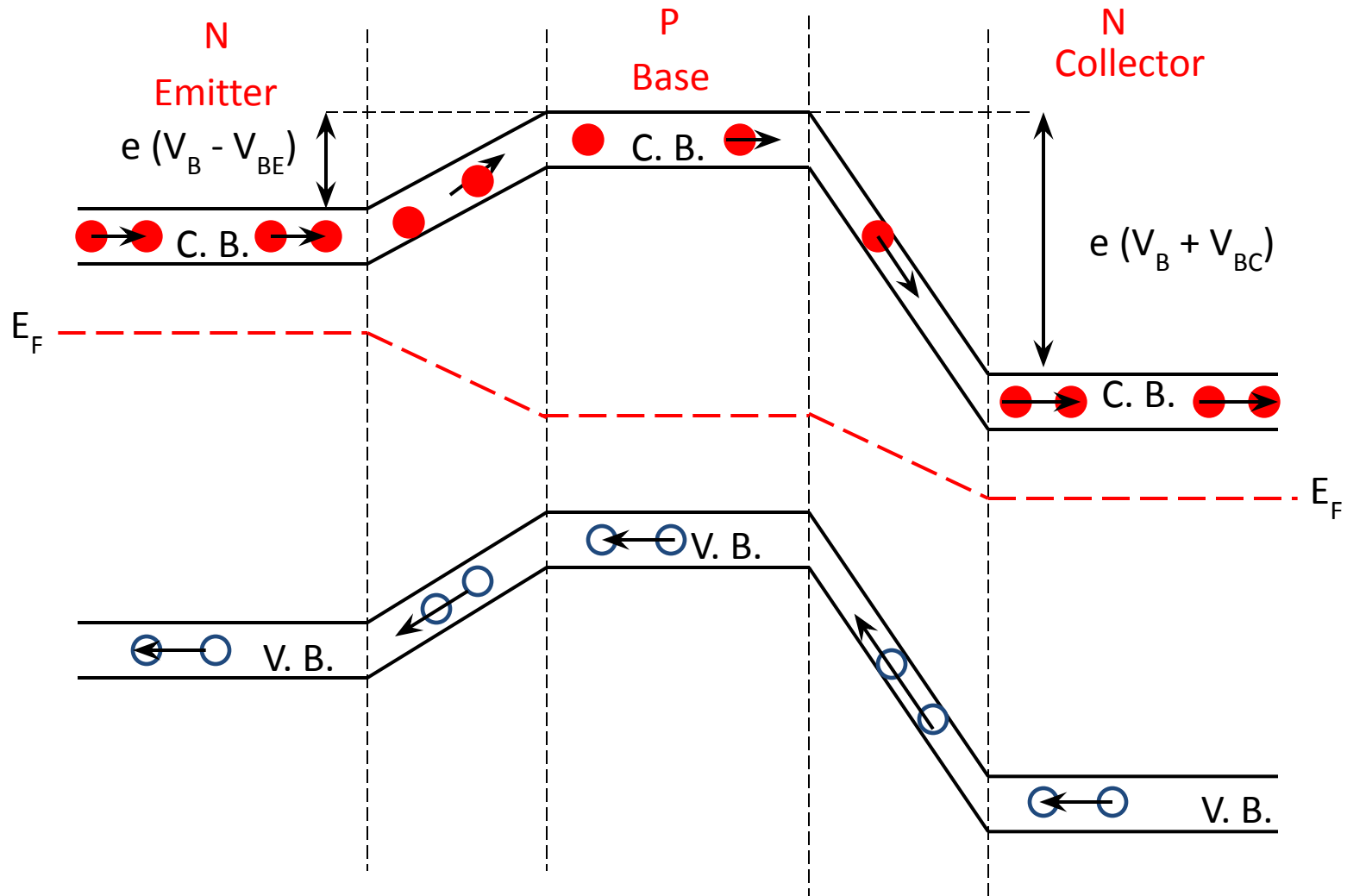


## Working of N-P-N transistor:

### 1. Unbiased N-P-N transistor:



## 2. Biased N-P-N transistor:

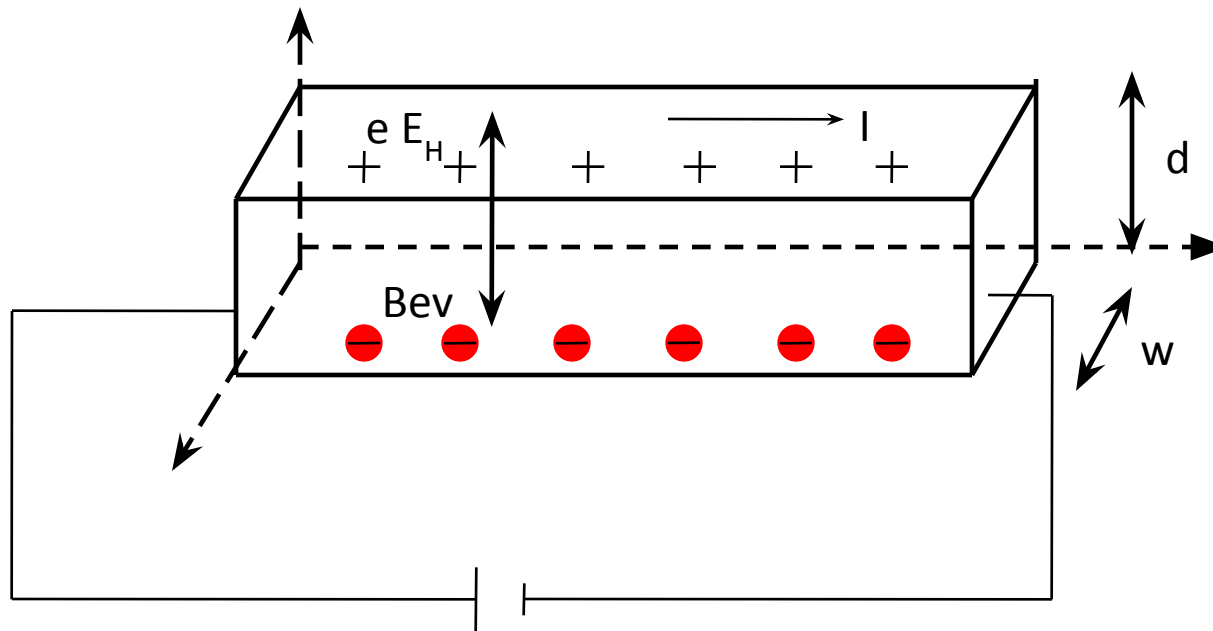




## Hall Effect:

When magnetic field is applied perpendicular to direction of current in a conductor (or semiconductor), a potential difference develops along an axis perpendicular to both current & magnetic field.

This effect is known as Hall effect and the potential difference developed is known as Hall voltage.



At equilibrium, the force on charge carriers because of magnetic field is balanced by force due to electric field.

$$e E_H = B e v$$

$$E_H = v B \text{ ----- 1)}$$

If I is the current in X-direction then,

$$I = n v A e$$

$$v = \frac{I}{n e A} \text{ ----- 2)}$$

Where n is the concentration of charge carriers.

$$E_H = \frac{B I}{n e A} \text{ ----- 3)}$$

Also,  $E_H = \frac{V_H}{d}$  where  $V_H$  is the Hall voltage

$$V_H = E_H d \text{ ----- 4)}$$

From equation 3) & 4)

$$V_H = \frac{B I d}{n e A} \text{ ----- 5)}$$

$$V_H = R_H \frac{B I d}{A} \text{ ----- 6)}$$

Where  $R_H = \frac{1}{n e}$  is the Hall coefficient for charge “e”.

If  $J_x$  is the current density along X-direction then,

$$V_H = \frac{B J d}{n e} \text{ ----- 7)}$$

If the specimen is of dominating charge carriers electrons then,

$$V_H = - \frac{B J d}{n e}$$

### Hall Coefficient:

The Hall coefficient  $R_H$  is determined by measuring the Hall voltage that generates the Hall field. If  $V_H$  is the Hall voltage across the sample of thickness ‘d’ then,

$$V_H = E_H d \text{ ----- 1)}$$

Also Hall Voltage is given as,  $V_H = R_H \frac{B I d}{A} \text{ -----2)}$

If ‘w’ is the width of sample then its cross section will be d x w

$$V_H = R_H \frac{B I d}{d w} = R_H \frac{B I}{w} \text{ ---- 3)}$$

$$R_H = V_H \frac{w}{B I} = \frac{1}{n e}$$

## Applications of Hall Effect:

1. Determination of type of semiconductor
2. Calculation of charge carrier concentration

$$n = \frac{B I d}{e A V_H}$$

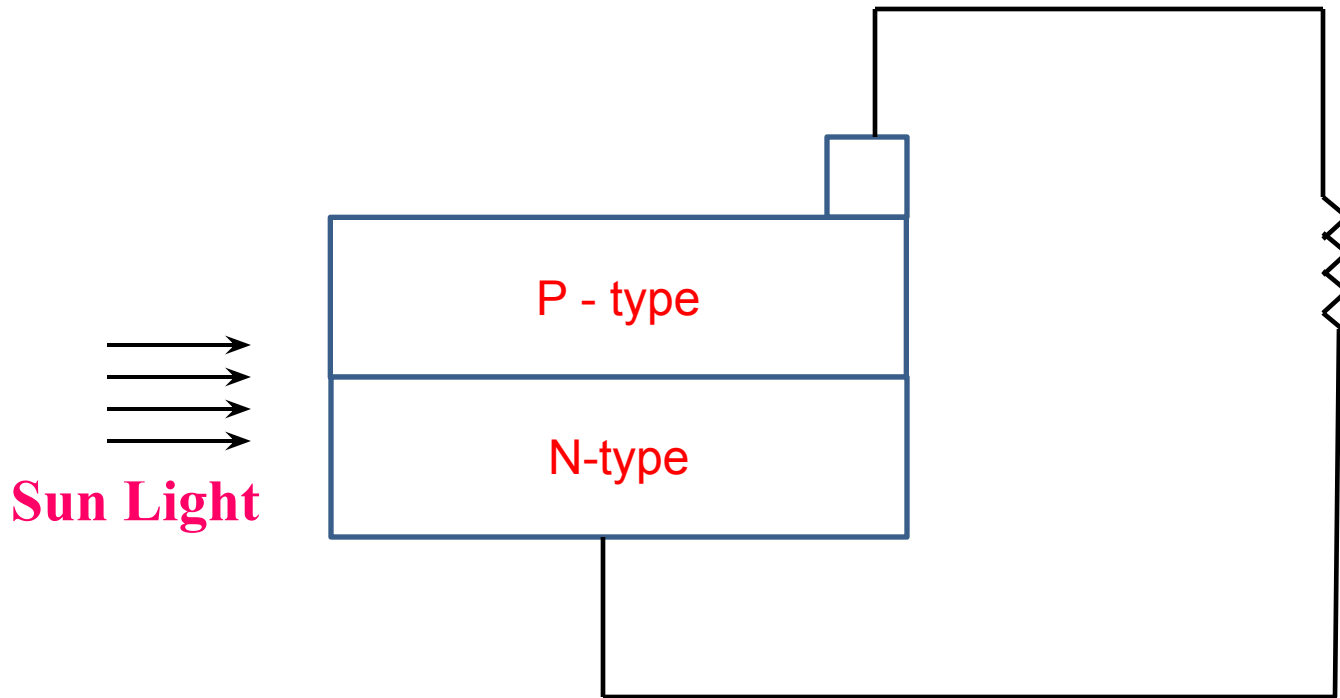
3. Determination of mobility

$$\sigma = n e \mu_e$$

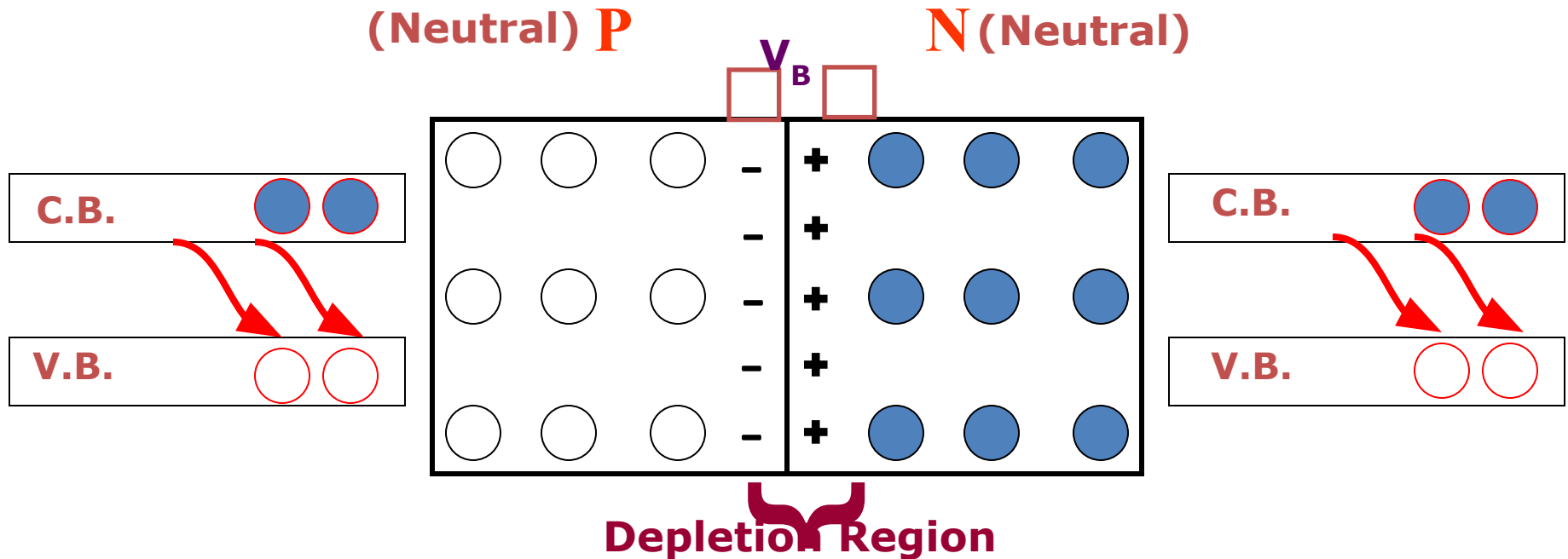
$$\mu_e = \frac{\sigma}{n e} = \sigma R_H$$

# Solar Cell

**Solar cell is a device which converts light energy into electrical energy.**

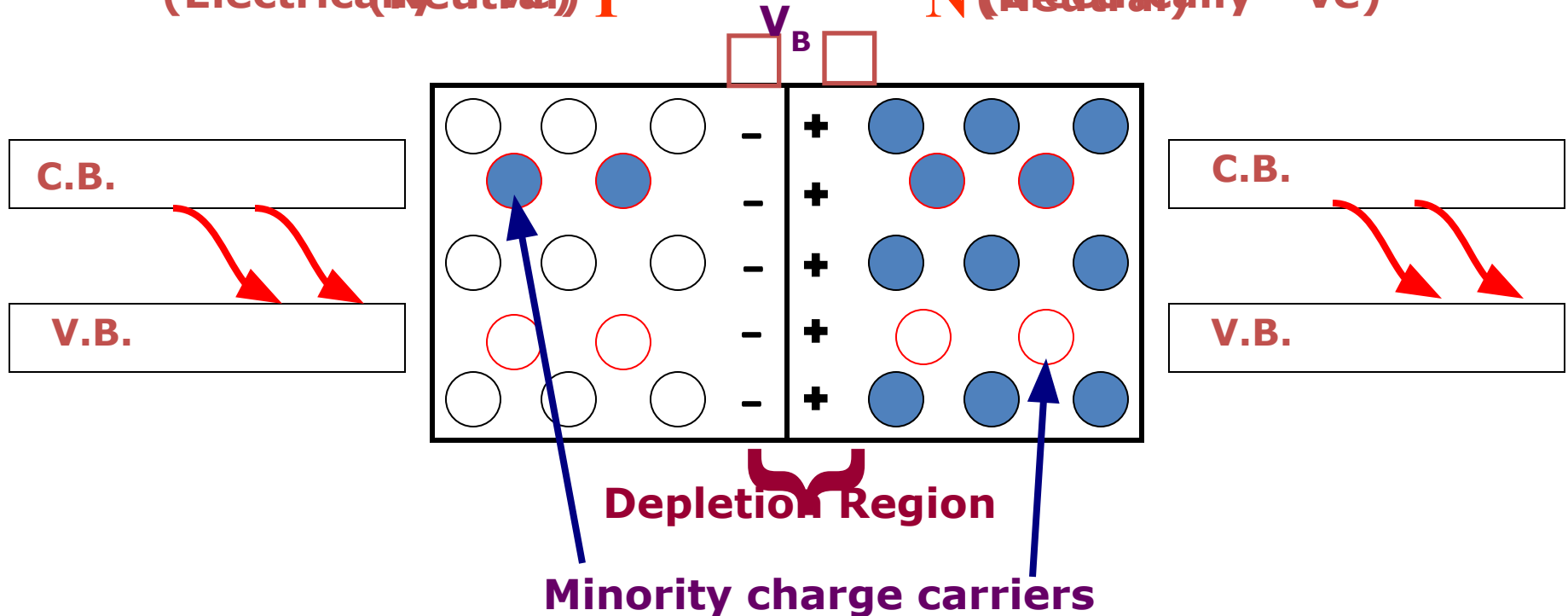


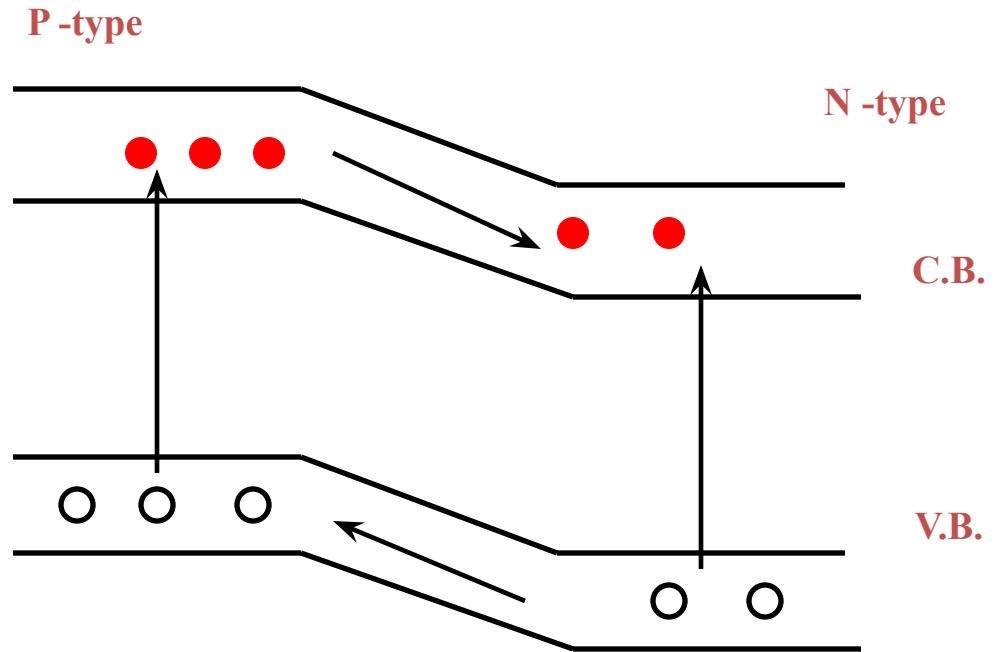
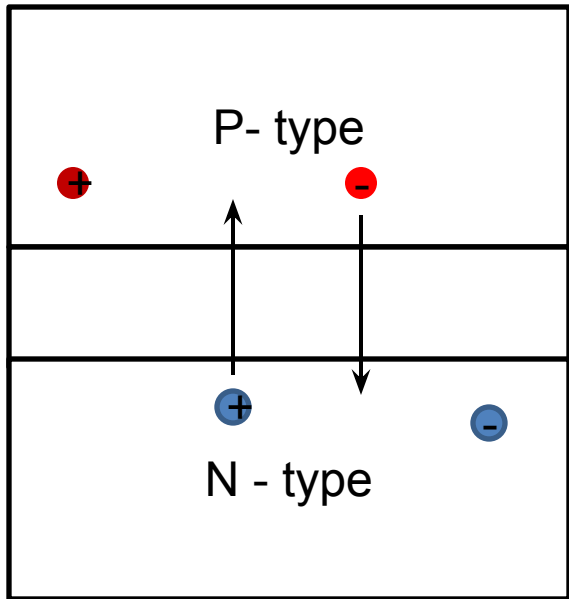
# Working of solar Cell



# Working of solar Cell

(Electrically Neutral) P N (Electrically -ve)



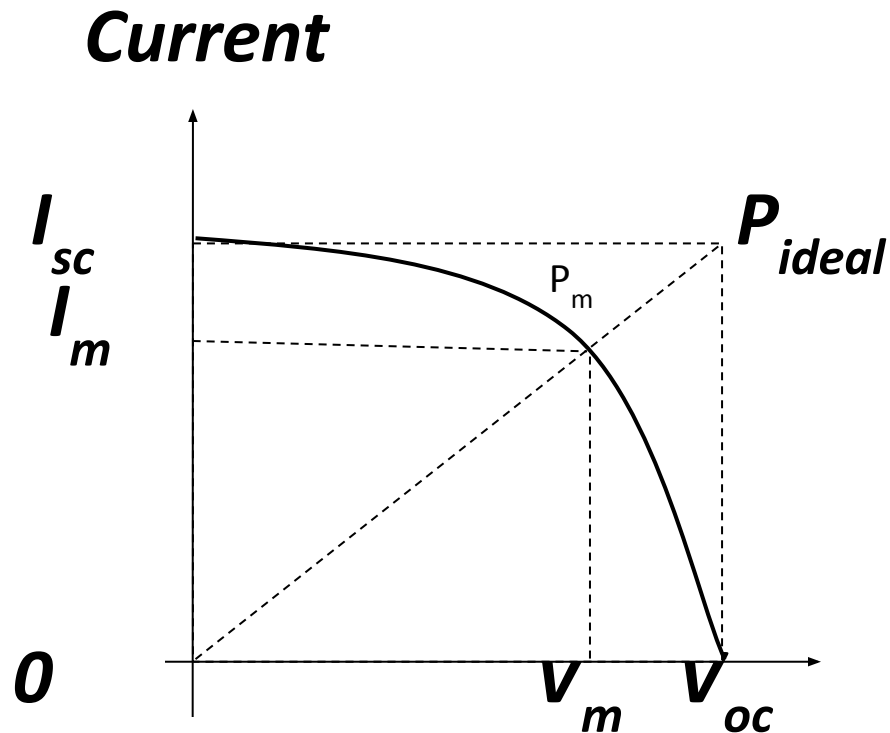


**Diffusion of electrons & holes and energy band diagram corresponding to diffusion of electrons & holes**



# Solar cell characteristics:

- Open circuit voltage ( $V_{oc}$ )
- Short circuit Current ( $I_{sc}$ )



- Fill Factor =  $\frac{V_m I_m}{V_{oc} I_{sc}}$

## Advantages of solar cell:

- It is pollution free source of energy.
- It is not harmful to human life.
- Input energy (i.e., solar energy ) is available adequately.
- Input energy is free of cost.
- It can be used in remote area.

## Disadvantages of solar cell:

- Solar cells are expensive (high production cost).
- They have very low efficiency.



**Thank You**

Other Subjects: <https://www.studymedia.in/fe/notes>