# Semiconductor Physics

**Dr. Jagadish Naik**

# Contents

- Introduction to semiconductor physics

- Fermi Dirac statistics

- Fermi level in  intrinsic and extrinsic semiconductors

- Fermi level and energy band diagram in P and N type of semiconductors

- Hall effect and its applications

- PN junction diode on the basis of energy band diagram

- NPN Transistor

-  Solar cell

# Lecture Plan

| |
|---|
| Introduction, **importance of semiconductor physics in engineering and technology, b**and theory of solids, energy bands in metals, insulators and semiconductors, <br> How energy bands are formed? ( with examples of Li, Be), |
| Semiconductors and their useful properties, Fermi Dirac statistics, Fermi Dirac formula, concept of Fermi level and its physical significance |
| Discussion of intrinsic and extrinsic semiconductors on the basis of Fermi level, Fermi level in intrinsic semiconductors at T = 0 K and T > 0 K (mathematical and graphical description) |
| Fermi level and energy band diagram in P and N type of semiconductors at T = 0 K and T > 0 K, effect of impurity concentration (doping level) |
| Quantitative description of semiconductors (I, J, V, E, R, $\rho$, $\sigma$, $v_d$, $\mu$ etc). **without derivation** |
| Hall effect and its applications |
| PN junction diode on the basis of energy band diagram |
| NPN Transistor (basics and energy band diagram) and **solar cell (to be taught in lab)** |

The properties and applications of any solid are governed by it's two characteristics,

its atom and the inter-atomic interaction

| Property ⇒ Material ⇓ | Type | Density of charge carriers $n$ (m$^{-3}$) | Resistivity $\rho$ $\Omega$-m | Temperature coefficient of resistivity (K$^{-1}$) |
|---|---|---|---|---|
| Copper | Metal (conductor) | $9 \times 10^{28}$ | $2 \times 10^{-8}$ | $+4 \times 10^{-3}$ |
| Silicon | Semiconductor | $1 \times 10^{16}$ | $3 \times 10^{-3}$ | $-70 \times 10^{-3}$ |
| Diamond | Insulator | | $10^{16}$ | |

Significant difference in the electrical properties of conductors, semiconductors and insulators

A quantum mechanical theory called as band theory of solids which explains reason for this variation

This theory explains the behavior of electronic devices such as diodes, BJT, FET, LED, Photodiodes, solar cells, etc
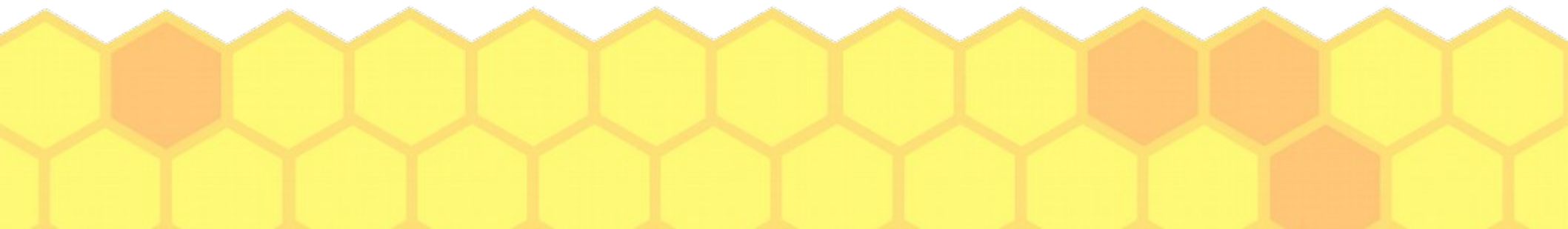
**Transistor invented in 1947**

Transforming old vacuum tube electronics to solid state electronics.

PN junction diode, NPN or PNP transistor, FET, photodiode, LED, solar cells etc.

Several advantages
compact size, fast action, requirement of less power etc.

# BAND THEORY OF SOLIDS

- The energy levels of atoms become energy bands when a solid is formed

- Explained on two approaches

    - Felix Bloch : Restrictions on the allowed energy levels of the electrons due to the periodicity of the crystal

    - Walter Heitler and Fritz London: Splitting of the energy levels of the electrons due to their interaction
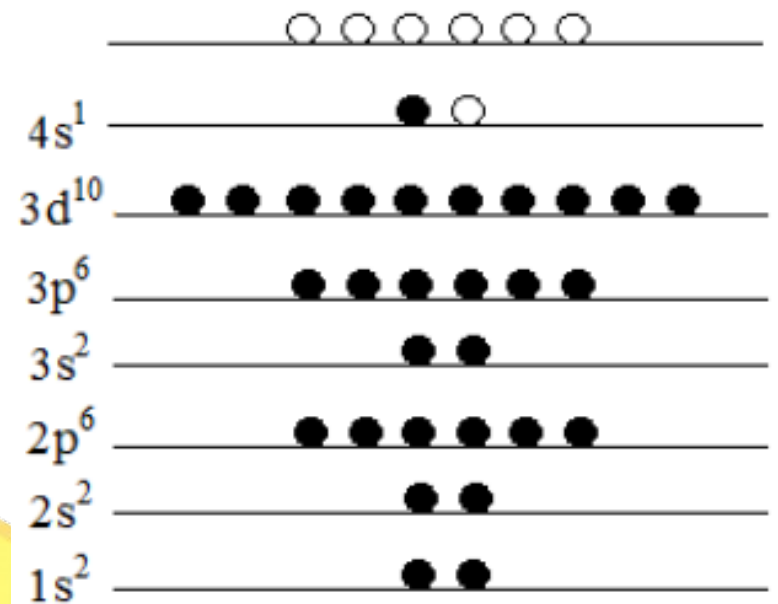
- Ex: **Copper – 29 Electrons**

   According to **Pauli's exclusion principle**, these electrons are distributed in to 29 exclusively different quantum states characterized by a group of four quantum numbers ($n$, $l$, $m_l$, $m_s$)

   Electronic configuration of copper

   $1s^2 \; 2s^2 \; 2p^6 \; 3s^2 \; 3p^6 \; 3d^{10} \; 4s^1$
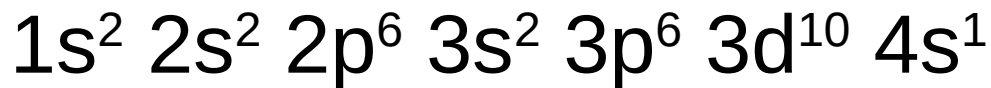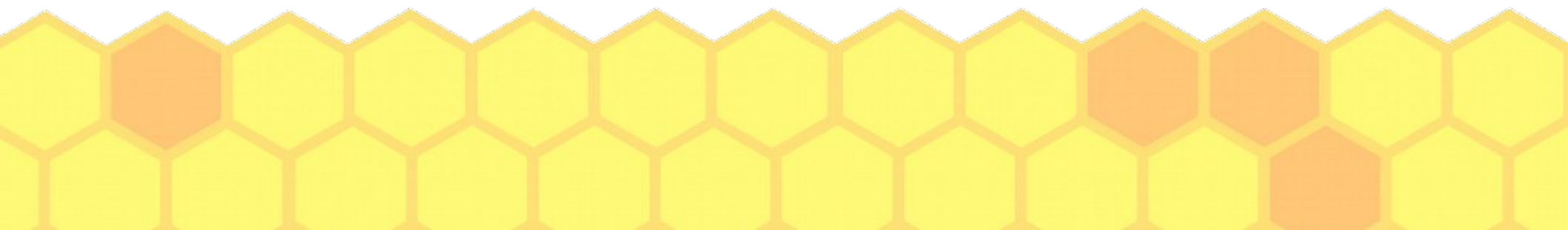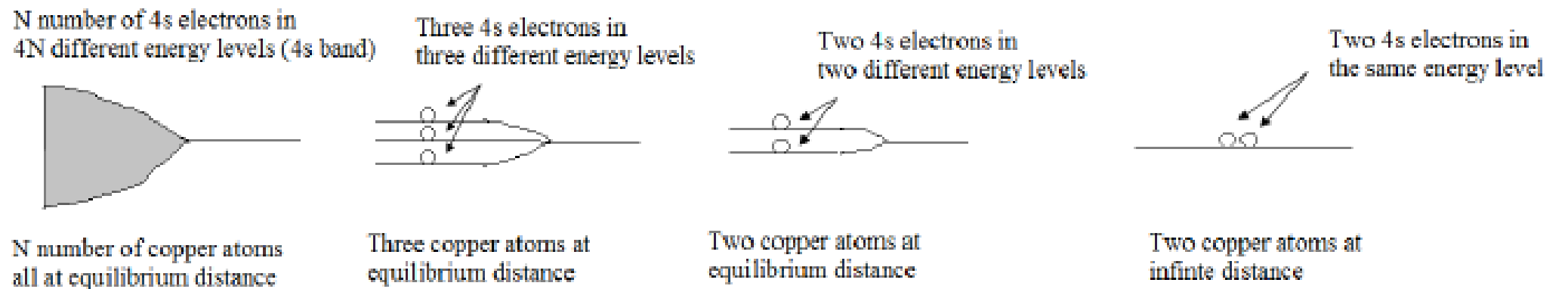
- Discrete energy levels

**N copper atoms at infinite distance, then such atoms do not interact with each other**

At equilibrium, the **inter-atomic distance** of the copper atoms in the solid form is **2.6Å**.

If the atoms come close to each other at such distance, the valance electrons will start strongly **interacting with each other**.
In such case the electrons cannot be accommodated in the same energy levels.
For ex. the two 4s electrons cannot be accommodated in the same 4s level.
The 4s level splits in to two closely spaced 4s sublevels.

N number of 4s electrons in 4N different energy levels (4s band)

Three 4s electrons in three different energy levels

Two 4s electrons in two different energy levels

Two 4s electrons in the same energy level

N number of copper atoms all at equilibrium distance

Three copper atoms at equilibrium distance

Two copper atoms at equilibrium distance

Two copper atoms at infinte distance

The electrons undergo a strong electrostatic interaction hence their energies change

According to **Quantum Mechanics, the electrons behave like waves**. Thus when electrons come in the proximity, their **wavefunctions overlap**. As a result, **symmetric and anti-symmetric wavefunctions, which correspond to two distinct energy levels, are formed**.

when an **Avagadro number of atoms come close and form bonds** becomes a single system and thus **Pauli's exclusion principle** applies to the pair.

Accordingly, **there have to be N different quantum states with different energies for the N 4s electrons**.

Thus when **N atoms come together, there will be N number of energy levels, all belonging to 4s category**.

The **wavefunctions of these electrons also overlap and the levels split and form bands**

The number of quantum states in the band is the product of occupancy of the corresponding level and the number of atoms.
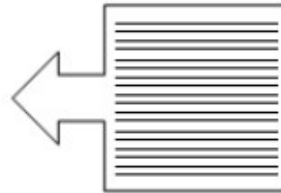
**s band consists of 2N states, p band contains 6N states, d band contains 10N states**
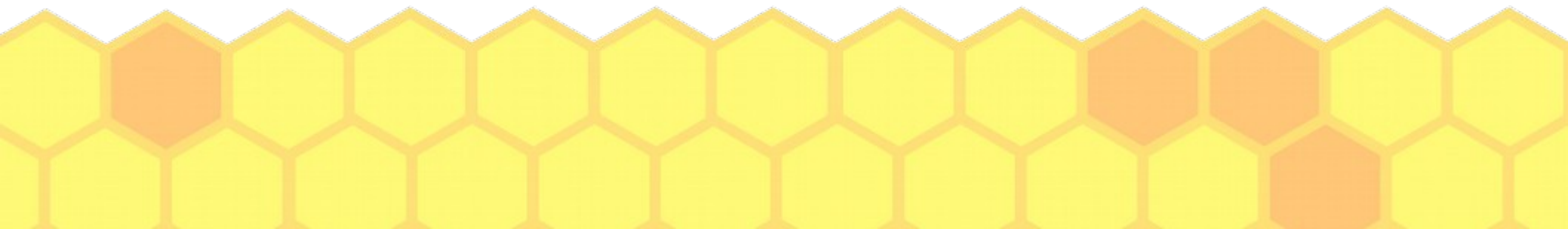
4s band 2N states N electrons

d band 10N states 10N electrons

3p band 6N states 6N electrons

3s band 2N states 2N electrons

2p band 6N states 6N electrons

2s band 2N states 2N electrons
1s band 2N states 2N electrons

Inbetween any two allowed energy bands, there are **forbidden bands,** which consist of forbidden energy levels

The **energy band diagram** is **characterized** by the **total number of bands** which it involves, their **occupancy**, **size** and the **forbidden gap** between them

4s band has an occupancy of 2N states, however, it contains only N number of electrons occupying the lower levels. 4s band is thus partially (half) filled

the **higher band have greater width as compared to the lower bands**
the upper bands are due to **stronger interaction of valance electrons**. As we move down, the **lower level electrons interact weakly due to greater distance and screening effect** of the upper level electrons.
Due to larger distance, the **wavefunctions of these electrons overlap to a lesser extent**.
As a result the splitting effect is weak and therefore the bands are narrower

# Valance band, conduction band and forbidden gap

The electrons in the outermost orbit of any element are called as **valance electrons**

**The group of energy levels of the valance electrons constitutes a valance band**

topmost or highest occupied band

**All the bands above the valance bands are empty**

In the group of unoccupied bands, the **lowest unoccupied band** is called as **conduction band**

When the electrons in the valance band are bound to their parent atoms, but when these electrons are excited to conduction band, they become free and thus take part in conduction

**Between the valance band & conduction band, there is a group of forbidden energy levels.**

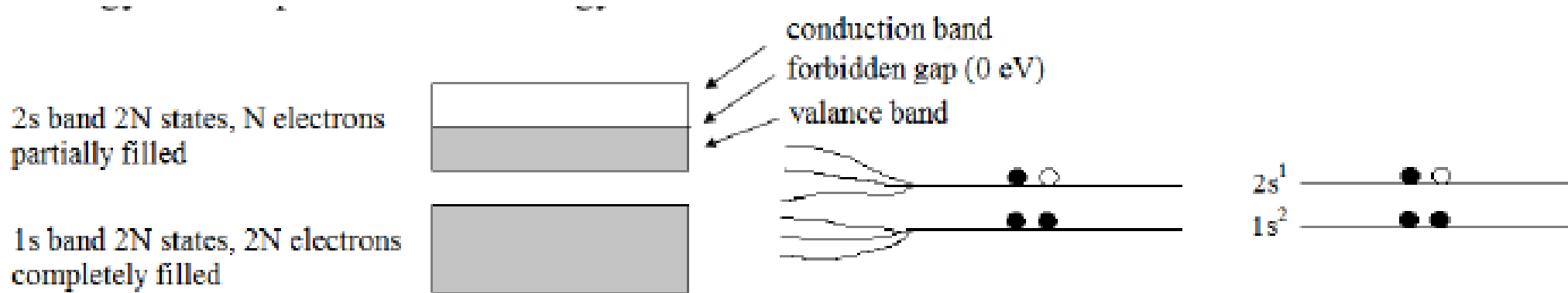Quantum mechanically these levels are not allowed to the electrons.

This group is called as a **forbidden gap or the band gap**

# Lithium (Z =3)

**1s² 2s¹**

Energy level diagram consists of **1s level having two electrons** and **2s level having 1 electron**. Lithium atoms come together and form bonds, the energy levels split and form energy bands

2s band 2N states, N electrons partially filled

1s band 2N states, 2N electrons completely filled

conduction band
forbidden gap (0 eV)
valance band

$2s^1$

$1s^2$

There are two bands, namely 1s band and 2s band.
1s band has 2N states filled by 2N electrons. Thus **1s band is completely filled**.

2s band has 2N available states, but as the 2s level for lithium atom contains only 1 electron, the 2s band contains only N number of electrons

According to **auf-bau rule**, **these electrons fill up the states in the increasing order of energy**. Thus the lower N states are filled with N electrons and upper N states remain unoccupied.

Thus **2s band of lithium is partially (half) filled**.

The lower filled part itself is the highest occupied band that it valance band, while in the same 2s band, the upper unfilled band is the lowest unoccupied band that is conduction band

the **gap between these two bands is almost 0 eV** (actually $10^{-28}$ eV)
According to kinetic theory, the thermal energy of the electrons is given by **(3/2)kT**.
At 0K, there is no energy available for the electrons to rise in the conduction band,

**at 300 K**, the thermal energy is **0.038 eV**, which is sufficient for the electrons to go in the conduction band.
It may be noted that there are no forbidden levels in between the valance and the conduction band.

The allowed but empty energy levels in the conduction band are in the vicinity of the filled level in the valance band.
When the electrons are excited to the conduction band, they become free.

As the valance electrons can be made free very easily, lithium, at room temperature, has plenty of electrons in conduction band, and consequently, **lithium behaves as conductor**.

Lithium belongs to **group I in the periodic table**.

The other elements in group I, such as sodium (Z= 11),  potassium etc. also have partially filled valance bands and thus are conductors.

The other examples of the elements with partially filled valance band are, aluminium (Z =13), copper(Z = 29), silver (Z = 47) and gold (Z = 79). As we know, all these elements are good conductors of electricity.

**Any element having partially filled valance band should behave like a conductor**

# Beryllium (Z = 4)

**1s² 2s² 2p···**

we expect that the 2s band of the beryllium should be completely filled and should behave like the valance band.

The next band should be 2p, it should be empty and should behave like a conduction band.

We expect that because of the existence of a finite gap (containing forbidden levels) between the valance and conduction band, beryllium **should behave like an insulator**.
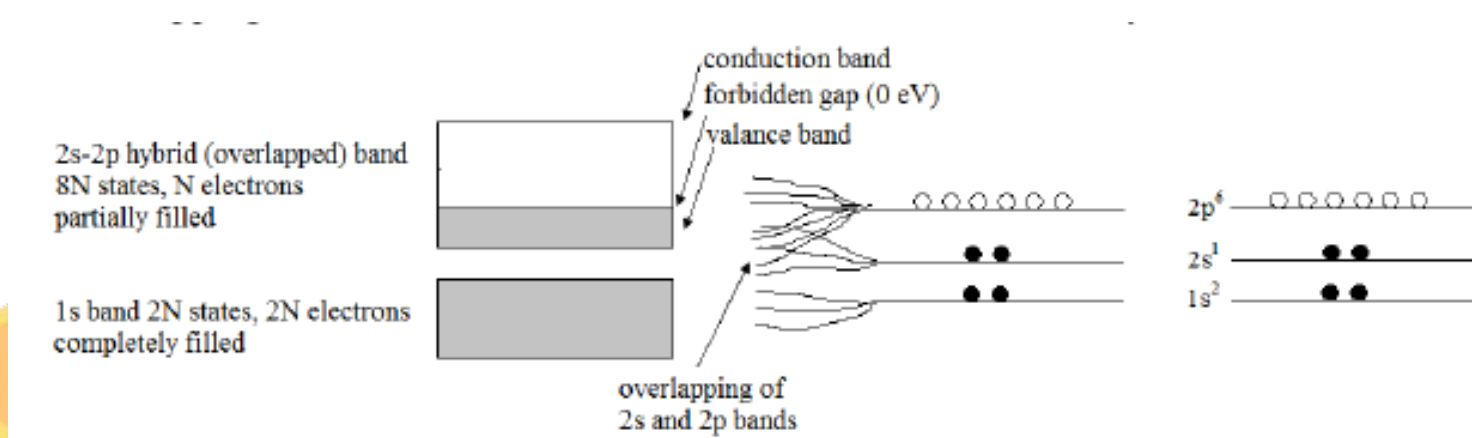
But **behaves like a conductor**.

**Beryllium atoms come close, the 2s and 2p bands split**.

As the distance approaches equilibrium separation, the 2s and 2p band expand and **at certain stage they merge (overlap) in to each other**.

Thus instead of separate 2s and 2p bands, we get **2s-2p hybrid band having 2N + 6N = 8N** available states. Out of these 8N states only lower 2N states are filled while the upper 6N states are unfilled.

Thus 2s-2p hybrid band is partially filled and thus beryllium behaves as a conductor.

Beryllium belongs to group II elements in the periodic table.



2s-2p hybrid (overlapped) band
8N states, N electrons
partially filled

1s band 2N states, 2N electrons
completely filled

conduction band
forbidden gap (0 eV)
valance band

2p⁶
2s¹
1s²

overlapping of
2s and 2p bands

# Insulators

ex: Diamond, band gap of **5.7 eV**.

The thermal energy of the valance electrons at 300 K is approximately **0.038 eV**

This is quite insufficient for the valance electrons to cross the band gap and enter in the conduction band

The electron cannot be excited to any energy level within the band gap, as these energy levels are forbidden.

Thus the concentration of the free electrons in diamond is extremely poor
it is an insulator

**Imparted any energy is immediately lost by the electron during it's collisions with the crystal imperfections**

**The band gap of diamond is 5.7 eV**
**The energies of the photons in the visible range is 1 to 3 eV.**
**Thus light cannot be absorbed in diamond**
**Therefore it is transparent to the light**

# Conductors

Due to either **partially filled valance band** or **overlapping of valance and conduction bands**, there is **no forbidden gap** in the conductors

At **absolute zero, the energy of electrons is not sufficient to enter the conduction band**

At room temperature, **due to thermal energy, the electrons just below the Fermi level can be easily excited to the conduction band**.

When electric field is applied, the electrons start moving an constitute the current.

The resistivity of the conductors (metals)

$$\rho = \frac{m}{ne^2\tau}$$

**n** - Number density of the electrons in the conduction band
**τ** - The relaxation time, that is the average time between the successive collisions.

Zero band gap, all valance electrons are set free at room temperature
When the **temperature is raised** further, this sea of electrons is thermally agitated offers resistance to the flow of conduction electron and increases with the temperature
Conductors thus have **Positive temperature coefficient** of resistance

# Semiconductors

Band gap of silicon --- 1.12 eV
Band gap of germanium --- 0.72 eV
**Band gap of insulator > Band gap of Semiconductor > Band gap of of conductor**

At room temperature, the thermal energy raises a small number of electrons in to conduction band

**free electron density**
silicon **$10^{16}$ /m³** < copper ($10^{28}$ /m³)

semiconductors exhibit a small conductivity better than insulators

the concentration of the charge carriers in the semiconductors can be increased significantly by adding impurities

**Semiconductors have two kinds of charge carriers**

When an electron is excited to the conduction band, it leaves a vacancy in the valance band. This vacancy is called **hole** (positive charge carrier).
Thus semiconductors have bipolar conduction (electrons and holes).

**Thermistors: (Temperature dependent resistors)**
When heat is applied, the electrons are thermally excited to the conduction band. Thus resistance of the semiconductors decreases with temperature.
Semiconductors are thus said to have N**egative temperature coefficient of resistance**

**Semiconductors can convert light in to electricity and vice versa**

| Name of the semiconductor | Symbol | Band gap (eV) | Wavelength corresponding to the band gap (A°) | Description |
|---|---|---|---|---|
| Silicon | Si | 1.12 | 11099 | Solar cells and other electronic components |
| Germanium | Ge | 0.67 | 18553 | Electronic devices |
| Silicon carbide | SiC | 2.3 | 5404 | Yellow LEDs |
| Gallium Nitride | GaN | 3.44 | 3613 | Electronics and spintronics, blue LEDs |
| Gallium Phosphide | GaP | 2.26 | 5500 | Red orange and green LEDs (after doping) |
| Gallium Arsenide | GaAs | 1.43 | 8693 | Next to silicon, IR LEDs, solar cells (after doping) |
| Cadmium sulphide | CdS | 2.42 | 5136 | Photoresistor, solar cells, quantum dots, lasers |
| Zinc Oxide | ZnO | 3.37 | 3689 | Laser diodes and conductive coatings |
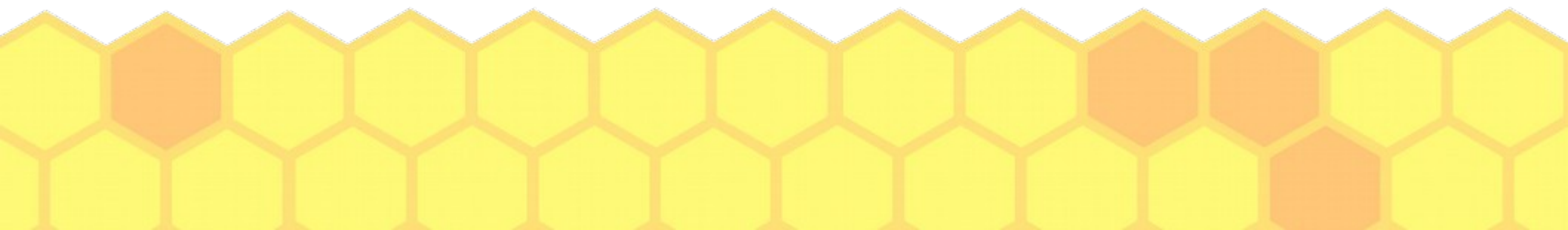
# FERMI DIRAC STATISTICS

It is the statistical description of an electrons in semiconductors

It gives the **probabilityof an electron to have an energy E**

It is a quantum statistics, which is **applicable to all particles having odd half integral spin** i.e. 1/2,3/2, 5/2..

Ex: Electron

In this statistics electrons are treated as wave, **which obeys Pauli's exclusion principle-- Fermions**

**Fermions** are **identicle but indistinguishable**, whose wave functions overlap considerably

The **wave functions of Fermions change the sign when electrons in any pair are exchanged** and thus are called as **antisymmetric wave functions**

The probability P(E) that fermion occupies a quantum state of energy E, at Temparature T is given by

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

k- Boltzman Constant

$E_F$- Fermi energy

**Probability of occupancy of higher energy levels increases with temperature**

# Fermi energy

The energy of the top most filled level in the ground state of the N-electron system

$$E_F = (\hbar^2/2m)(N\pi/2L)^2 = (\hbar^2/2m)(n_F\pi/L)^2$$

$N = 2n_F$

$n_F$ --- Uppermost filled Level

An electron of mass **m** confined to a length **L**

Fermi energy plays important role in determining properties of semiconductors

**Fermi Level**

The highest occupied energy level of the electrons in the valance band at $0^o$ K

At $0^oK$ all energy states upto $E_F$ are occupied and all states above $E_F$ are unoccupied (empty)

Probability P(E) that fermions occupies a quantum state of energy E, at Temparature T is given by

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

k- Boltzman Constant
$E_F$- Fermi energy

**At T=0K, there are two possibilities**

**E>$E_F$  or E<$E_F$**
**At T=0K and E>$E_F$ we have (E-$E_F$) >0 Positive, Thus**

$$P(E) = \frac{1}{1 + e^{\frac{(E - E_F)}{0}}} = \frac{1}{1 + e^{+\infty}} = 0$$

Thus at T = 0 K, **the probability of occupancy of all the levels above the Fermi level is zero.**
Thus at T = 0 K, **all the energy levels above the Fermi level are certainly unoccupied**

**At T=0K and E<E$_F$ we have (E-E$_F$) <0 Negative**, Thus

$$P(E) = \frac{1}{1 + e^{\frac{(E-E_F)}{0}}} = \frac{1}{1 + e^{-\infty}} = 1$$

Thus at T = 0 K, the **probability of occupancy of all the energy levels below the Fermi level is one**.
Thus at T = 0 K, **all the energy levels below the Fermi level are certainly occupied**.

At **T=0K and E=E$_F$** we get

$$P(E) = \frac{1}{1 + e^{\frac{0}{0}}} = indeterminate$$
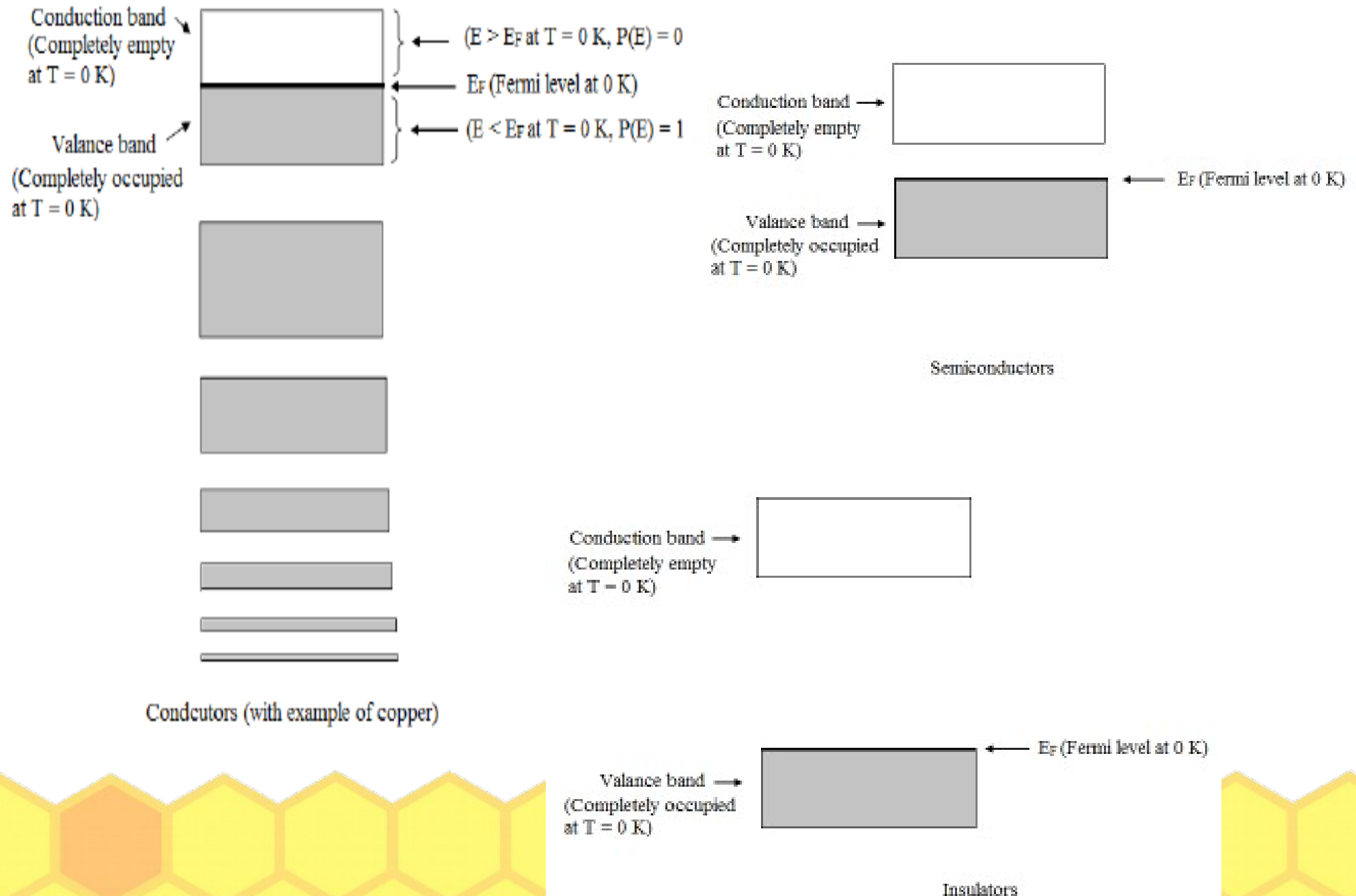
**This not possible**

At **T>0K and E=E$_F$** we get

$$P(E) = P(E_F) = \frac{1}{1 + e^{\frac{0}{T}}} = \frac{1}{1 + e^0} = \frac{1}{1 + 1} = \frac{1}{2} = 0.5 = 50\%$$

Thus the **probability of the occupancy of the Fermi level at any finite (nonzero) temperature is Always 50%**.
This is applicable to **metals, semiconductors as well as insulators**

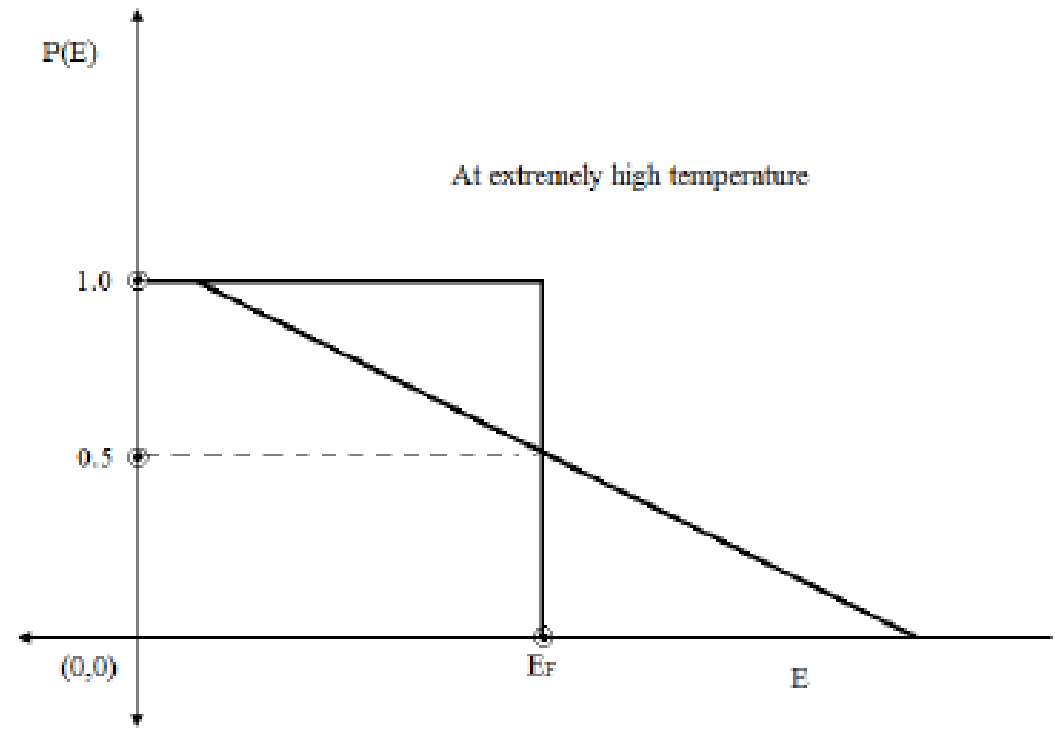# Physical significance of Fermi level Depending on temperatures



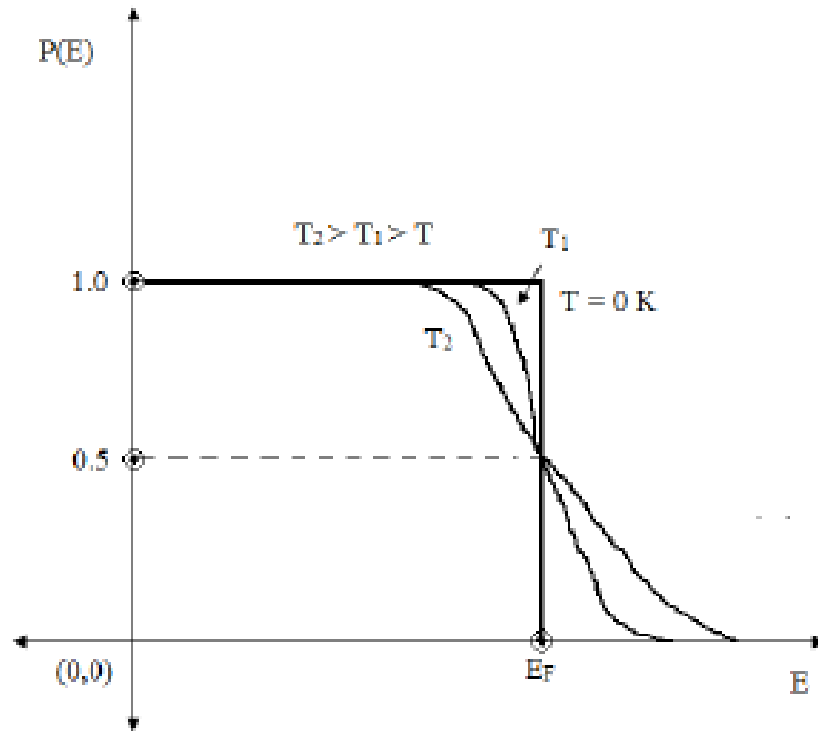Conduction band (Completely empty at T = 0 K)

Valance band (Completely occupied at T = 0 K)

(E > E_F at T = 0 K, P(E) = 0

E_F (Fermi level at 0 K)

(E < E_F at T = 0 K, P(E) = 1

Conduction band → (Completely empty at T = 0 K)

E_F (Fermi level at 0 K)

Valance band → (Completely occupied at T = 0 K)

Semiconductors

Condcutors (with example of copper)

Conduction band → (Completely empty at T = 0 K)

Valance band → (Completely occupied at T = 0 K)

E_F (Fermi level at 0 K)

Insulators

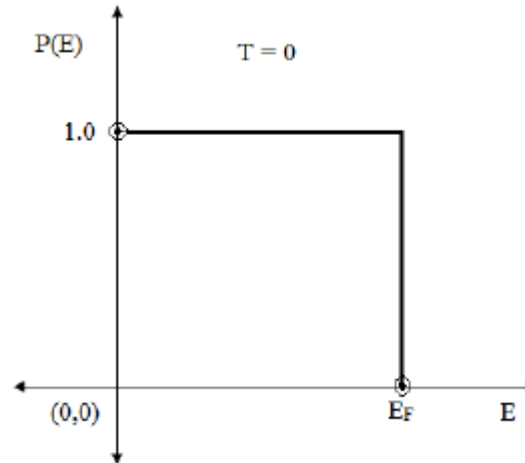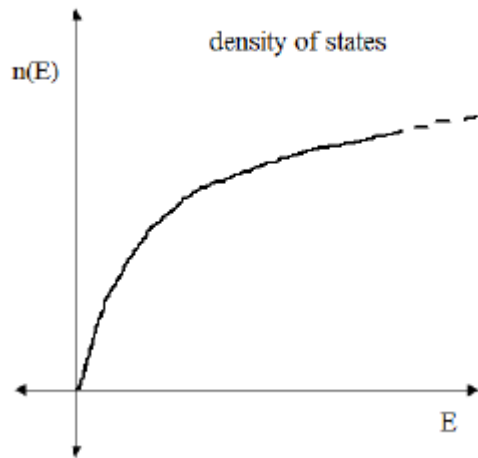# The significance of Fermi level in conductors (metals) at T = 0 K
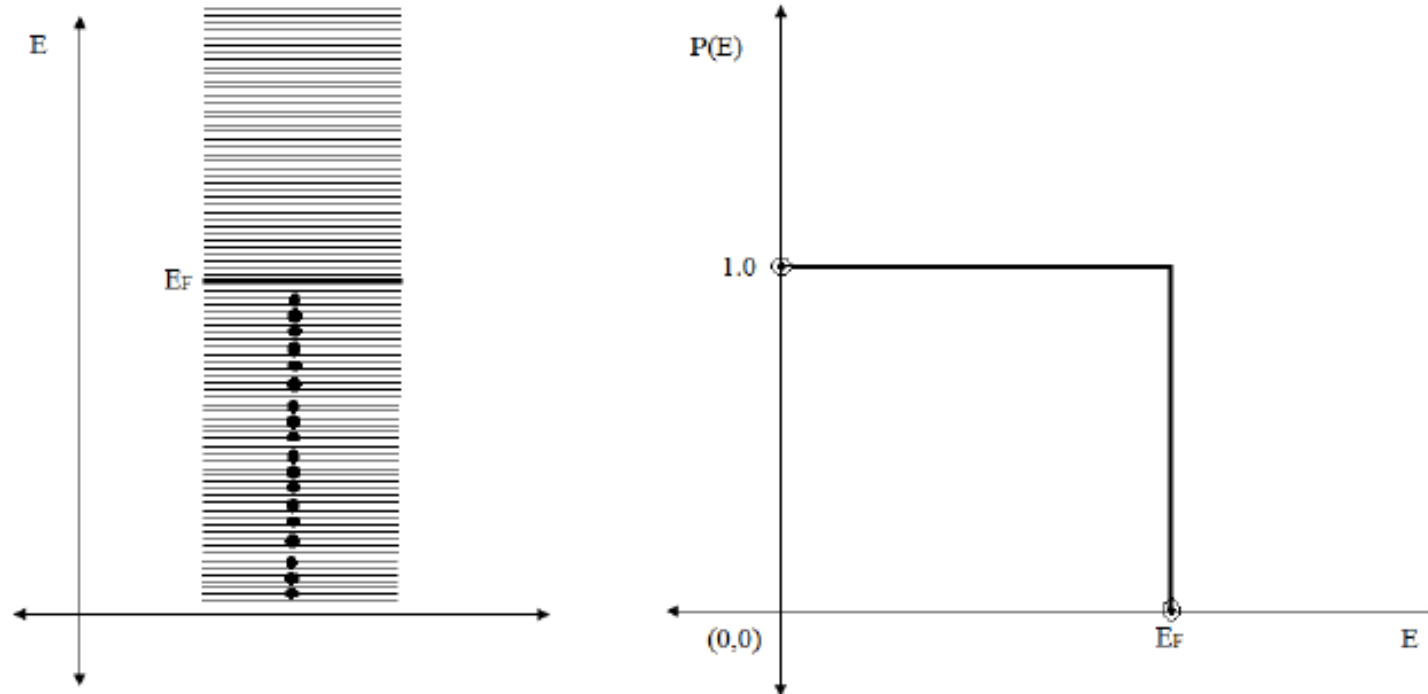
# The significance of Fermi level in conductors (metals) at T > 0 K
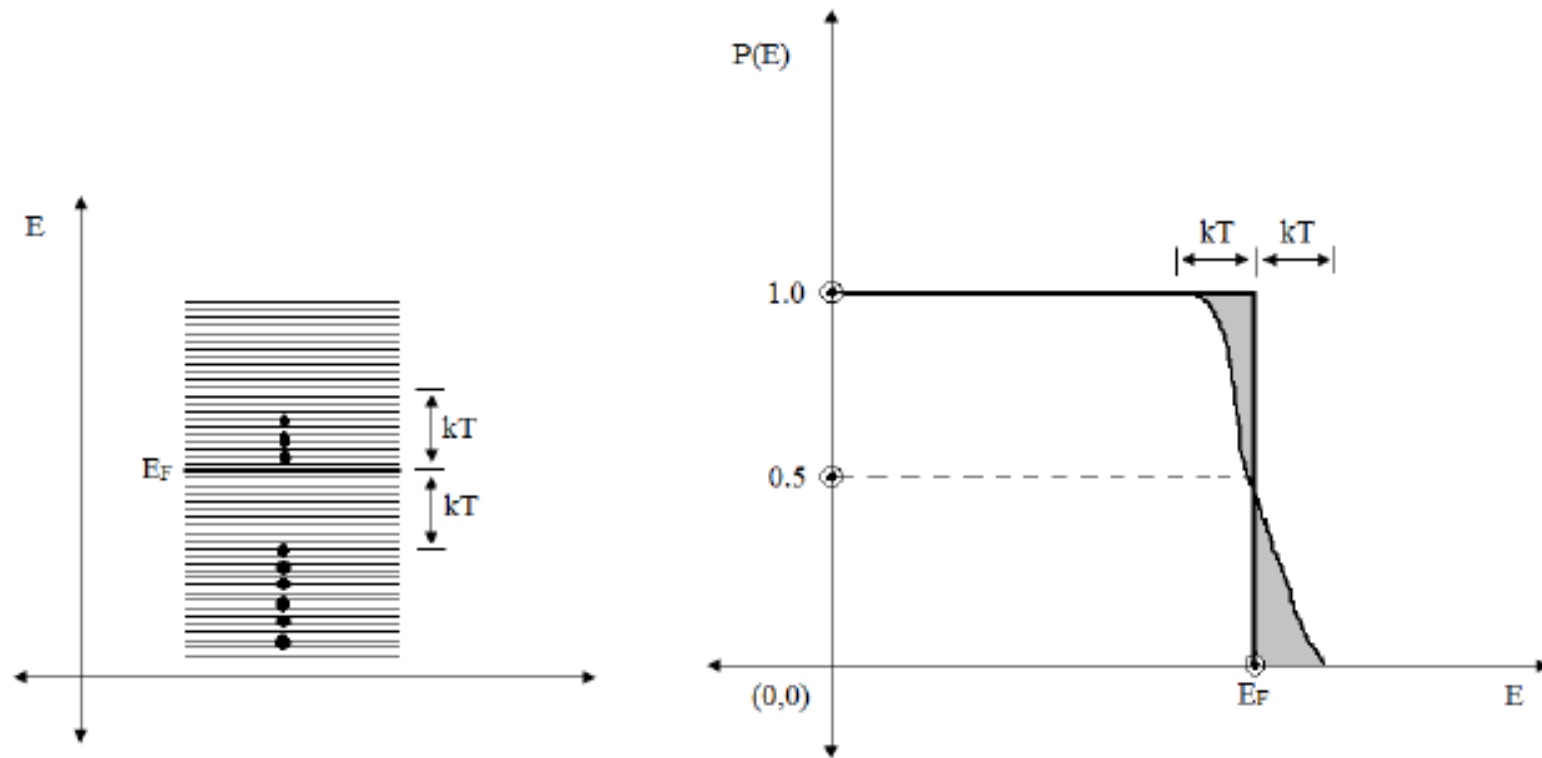
# Graphical representation of Fermi Dirac statistics. Physical significance of the Fermi level

# Density of states at T = 0 K

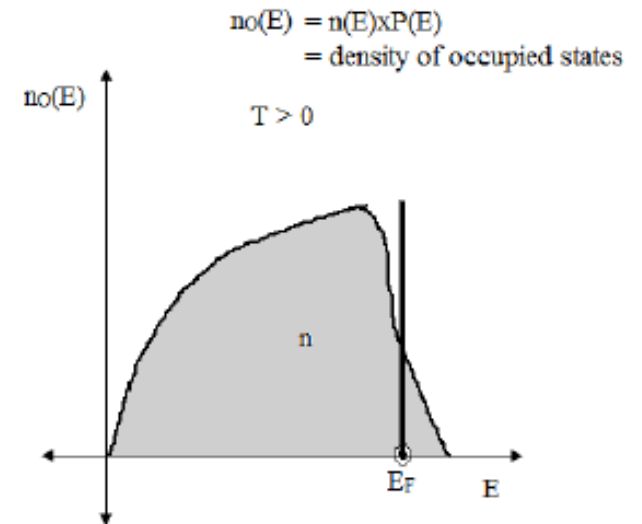density of states

n(E)

E

P(E)   T = 0

1.0

(0,0)   $E_F$   E

$n_0(E) = n(E) \times P(E)$
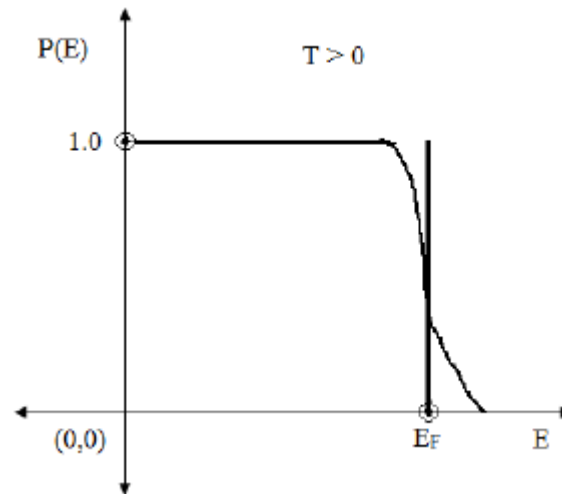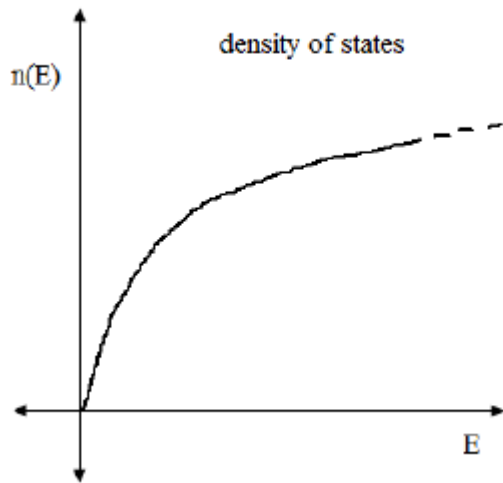= density of occupied states

$n_0(E)$   T = 0

n

$E_F$   E
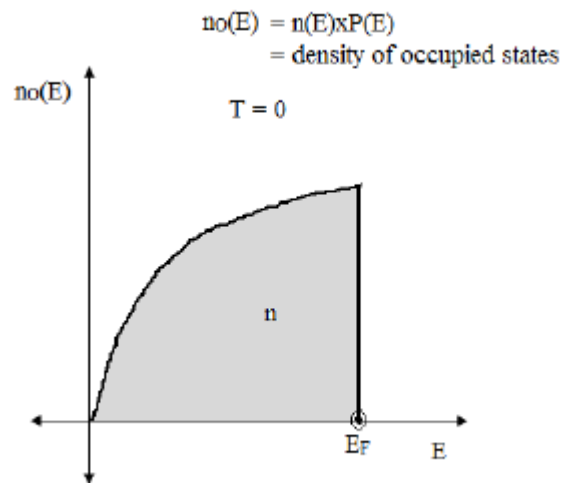
$$n(E) = \frac{8\sqrt{2}\pi m^{\frac{3}{2}}}{h^3} E^{\frac{1}{2}}$$

Density of states = number of quantum states n(E), per unit energy interval
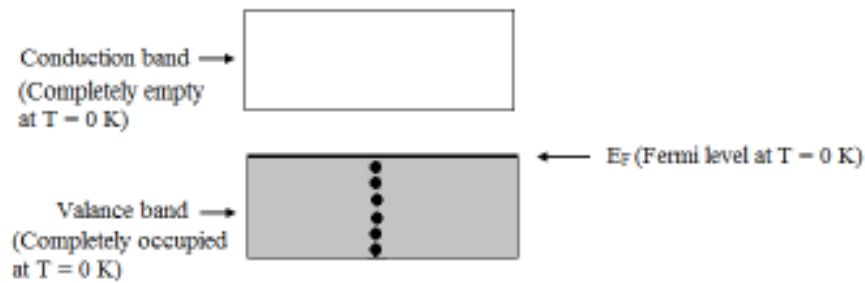
# Density of states at T > 0 K



The probability of the occupancy of the levels above the fermi level increases at the cost of energy levels below $E_F$.

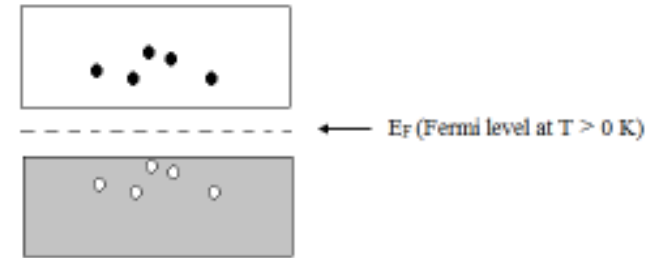Thus density of the occupied states above $E_F$ increases at the cost of density of occupied states below $E_F$

The graphs at T>0K are almost similar to the graphs of T=0K indicates that **even at higher temperatures, modifications take place only in the closet vicinity of Fermi level**.

# Fermi Level in Intrinsic Semiconductors



Conduction band →
(Completely empty
at T = 0 K)

Valance band →
(Completely occupied
at T = 0 K)

$E_F$ (Fermi level at T = 0 K)

Intrinsic semiconductor at T = 0 K

$E_F$ (Fermi level at T > 0 K)

Intrinsic semiconductor at T > 0 K

At 0°K highest occupied level is fermi level

At any non-zero temperature, Fermi level is an average level whose probability of occupancy is 50%

$$E_F = \frac{E_V + E_C}{2}$$

$E_V$ and $E_C$ are the average energies of the electrons in valance and conduction bands

**Intrinsic semiconductors, the Fermi level is situated in the middle of the band gap**

# Fermi Level in N-Type Semiconductors

There are donor energy levels just below the conduction band.

At 0°K, these levels are occupied by unshared electrons of pentavalent impurity.

Majority of the electrons in the conduction band come from these donor levels.
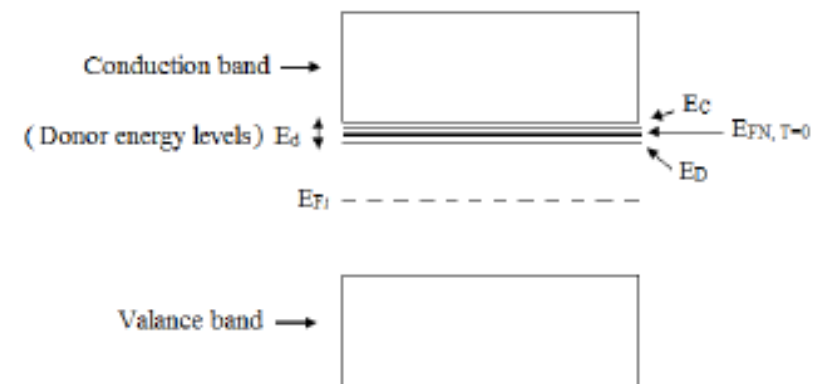
At 0 K, all these electrons exist in donor levels only. Therefore the Fermi level of N type of semiconductor at 0 K is situated in the middle of the donor levels

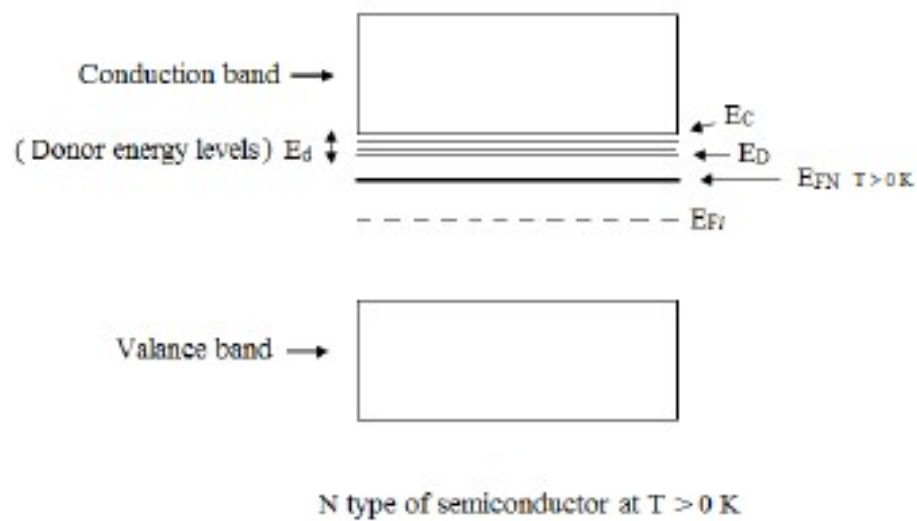$$E_C \geq E_{FNT=0K} \geq E_D$$

$$E_{FN\ T=0K} = \frac{E_C + E_D}{2}$$

$E_C$ --- lowest energy level in the conduction band

$E_D$ --- lowest energy level amongst the donor levels

Conduction band ⟶

(Donor energy levels) $E_d$

$E_C$

$E_{FN,\ T=0}$

$E_D$

$E_{Fi}$

Valance band ⟶

N type of semiconductor at T = 0 K

As every phosphorous atom 'donates' one free electron, it is called as 'donor impurity'. Unlike the 4 shared electrons, the energy levels of unshared electrons cannot be represented in the valance band, as it would mean that their energy gap is 1.1 eV. The negligible energy required to detach the unshared electrons indicates that the energy levels of these electrons be shown just below the conduction band. These energy levels are called **donor levels**

Conduction band ⟶

( Donor energy levels) $E_d$ ↕

Valance band ⟶

$E_C$
$E_D$
$E_{FN\ T>0K}$
$E_{Fi}$

$$E_D \geq E_{FN\ T > 0K} \geq E_{Fi}$$

N type of semiconductor at T > 0 K

**Temperature is raised**, the electrons in the donor levels start gaining thermal energy and they move to conduction band.
Thus the **donor levels are gradually depleted**.
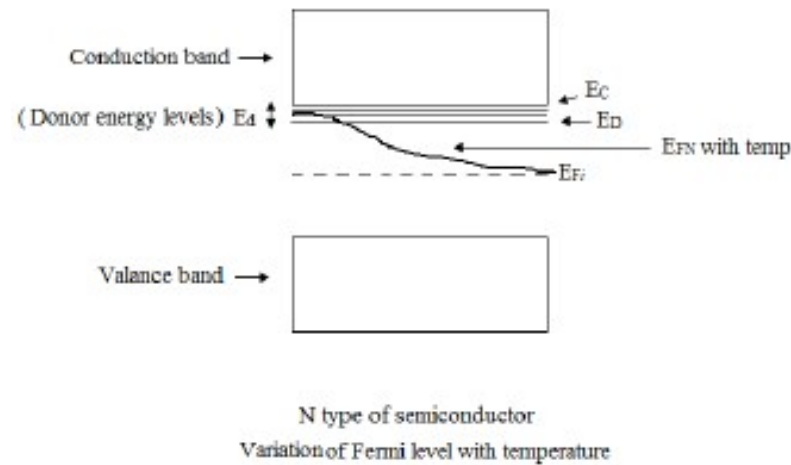As a result, the **Fermi level starts moving down**.

Temperature is **further raised**, the **electrons in the valance band also start going in to the conduction band.**
This results in generation of holes in valance band.
To account for this, the Fermi level further shifts down.
**At moderate temperatures, the Fermi level can never reach the intrinsic Fermi level**,
**in between the lowest donor level and intrinsic Fermi leve**l

Conduction band ⟶

(Donor energy levels) E_d ⇕

← E_C
← E_D

E_FN with temp

E_Fi

Valance band ⟶

N type of semiconductor
Variation of Fermi level with temperature

**At extremely higher temperature**, almost **all electrons in the valance band are excited to the conduction band**.

These electrons are extremely large in number as compared to the electron donated by the donor levels.

Thus **at very high temperatures, the concentration of the electrons in conduction band and holes in the valance band is almost equa**l.

This indicates that at very high temperatures, **N type semiconductor is converted to intrinsic semiconductor**.

In this situation the Fermi level of the N type of semiconductor coincides with the intrinsic Fermi level.
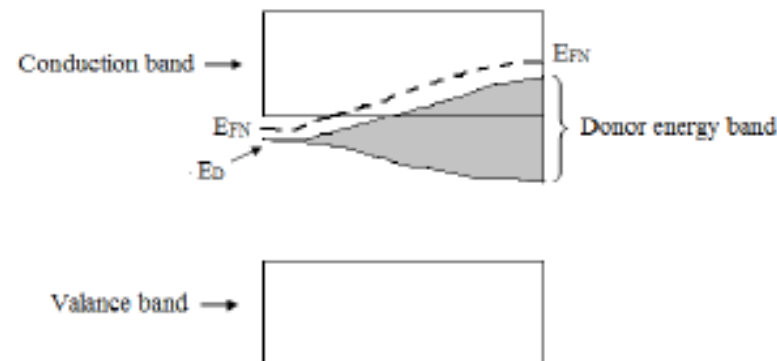
# Effect of dopant concentration on Fermi level of N type semiconductor

**At moderate concentration, the distance between the donor atoms is large enough**.
Interaction between the donor atoms is also weak.
Therefore **the donor levels do not split and they remain discrete**.
If the **concentration is further increased the distance between the donor atoms decreases and they start interacting**.

----> **the donor levels interact and they become a donor band**.
If the **concentration is still increased, donor levels split to a greater extent and the donor band expands and invades in the conduction band**.

As a result the **Fermi level also enters in the conduction band**



N type of semiconductor
Effect of increasing doping concentration

# Fermi Level in P-Type Semiconductors

$E_F$ in P-type is opposite to N-Type semiconductor
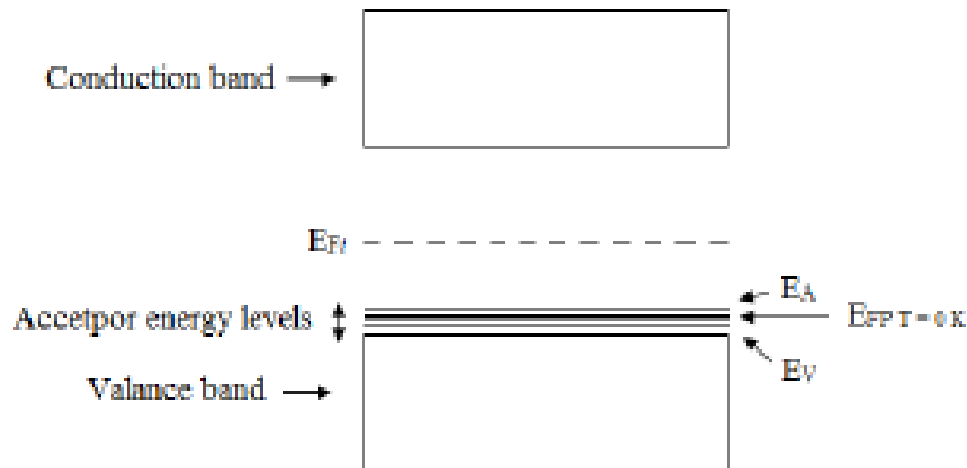
**There are acceptor levels near the valance band**.

The holes in P type semiconductor are only due to transitions of electrons from valance band to the acceptor levels.

As the **valance band is the source of electrons and acceptor levels are recipients of them**, the **Fermi level is situated in the middle of the group of acceptor levels**

$$E_A \geq E_{FPT=0K} \geq E_V$$

$E_A$ is the highest acceptor level

$E_V$ is the highest level in the valance band

Conduction band →

$E_{Fi}$ – – – – – – – – – – –

Acceptor energy levels ↕ ═══════════  ← $E_A$   $E_{FPT=0K}$

Valance band →   $E_V$

P type of semiconductor at T = 0 K

**Temperature is raised**, the electrons in the valance band **gain thermal energy to raise in the acceptor levels.**

As a result, **concentration of electrons in the acceptor levels increases and the Fermi level moves upward.**

As the temperature is further increased, at moderate temperatures, the electrons in the valance band are thermally excited to the conduction band.
Thus, concentration of the electrons in the conduction band increases.
As a result, the Fermi level further shifts up

$$E_{Fi} \geq E_{FP\ T > 0K} \geq E_A$$

**at moderate temperatures, it cannot touch the intrinsic Fermi level**
 if the temperature is extremely high, then the almost all the electrons in the valance band are excited to the conduction band.

concentration of intrinsic charge carriers overcomes the concentration of holes due to acceptor impurity.

 concentration of electrons in the conduction band and holes in the valance band becomes almost equal.



Conduction band ⟶

$E_{Fi}$

$E_{FP}$ with temp

⟂ Acceptor energy levels

Valance band ⟶

P type of semiconductor
Variation of Fermi level with temperature

**Thus at extremely high temperatures, the P type semiconductor is converted in to intrinsic**
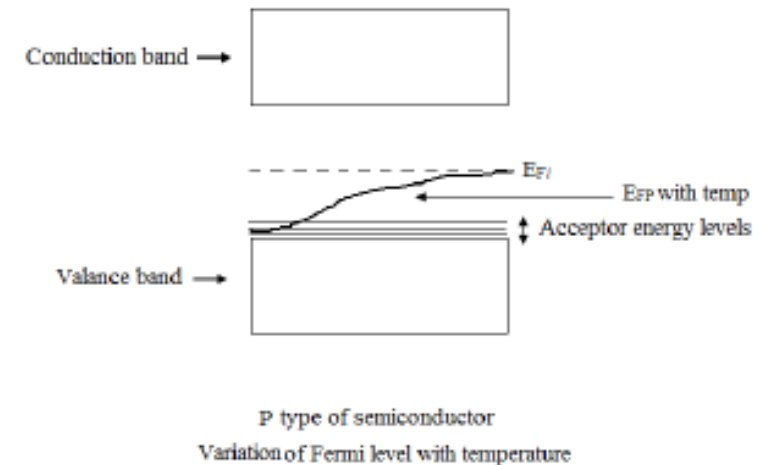
# Effect of dopant concentration on Fermi level of P type semiconductor

**At very low doping level, the distance between the acceptor impurity atoms is comparatively large.**
**Interaction between the acceptor impurity atoms is weak**
**acceptor levels are discrete.**

**Doping level is increased, the atom-to-atom distance of the acceptor impurity decreases. They interact and thus the acceptor levels split.**

**Doping level is further increased, the acceptor levels become acceptor band and then it penetrates in the valance band**

Conduction band →

$E_A$

$E_{FP}$ → Acceptor energy band

Valance band → $E_{FP}$
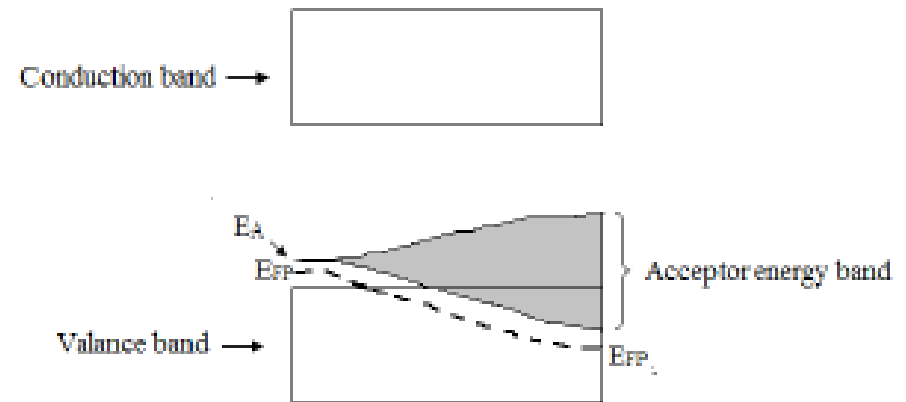
P type of semiconductor
Effect of increasing doping concentration

The current which occurs due to a gradual drift of electrons towards the positive terminal (or holes towards the negative terminal) is called as drift current, The corresponding velocity is called as drift velocity ($v_d$ )

$$v_d = \frac{\Delta l}{\Delta t}$$

Mobility $\mu = \dfrac{v_d}{E}$

Current= $\mathbf{I = nqv_d\ A}$

n-- carrier concentration/charge particle density/number of charge carriers per unit volume
J - current density

$J = \frac{I}{A}$ and $\mu = \frac{v_d}{E}$, we have

$$J = \frac{I}{A} = nqv_d$$

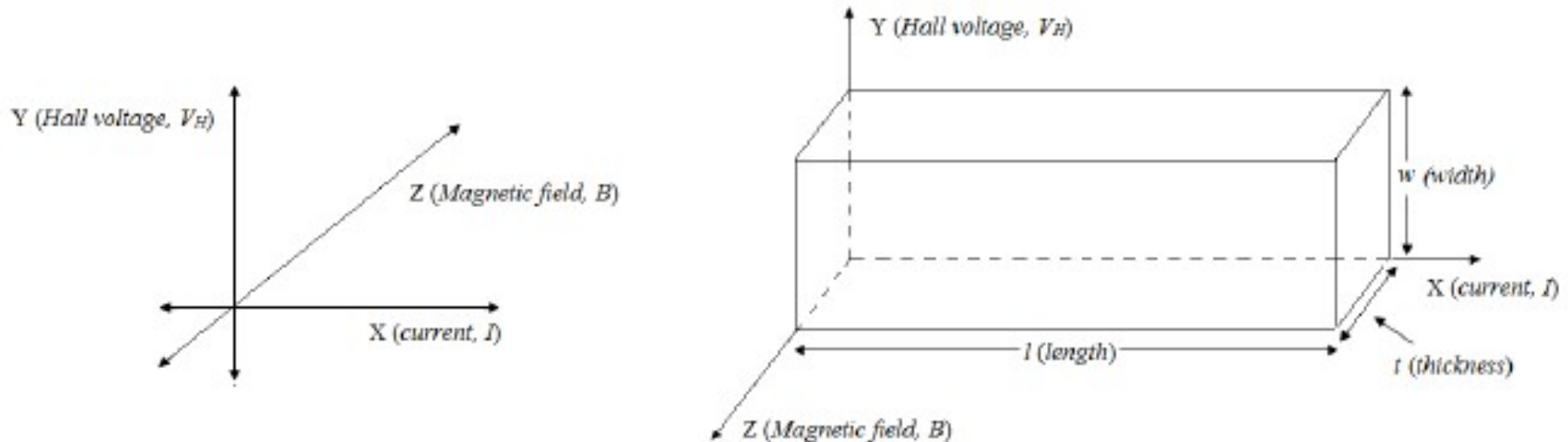$$J = \frac{I}{A} = nq\mu E$$

Conductivity = $\sigma = nq\mu$

semiconductors contain two kinds of charge carriers; electrons and holes

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

# HALL EFFECT

If a metal or semiconductor **carrying current I** is placed in a **transverse magnetic field B**, a **pottential diffrence is produced** in the **direction normal to both the current and magnetic field** direction. This is called as Hall Effect



It showed that **electrons responsible for electrical conduction in metals and there exist two types of charge carrier in semiconductors**

**Importance:**

1. determines sign of a charge carrier
2. determines charge carrier concerntration
3. determine the mobility of charge carriers, if conductivity of the material is known
4. detrmines the semiconductor is P-Type or N-Type
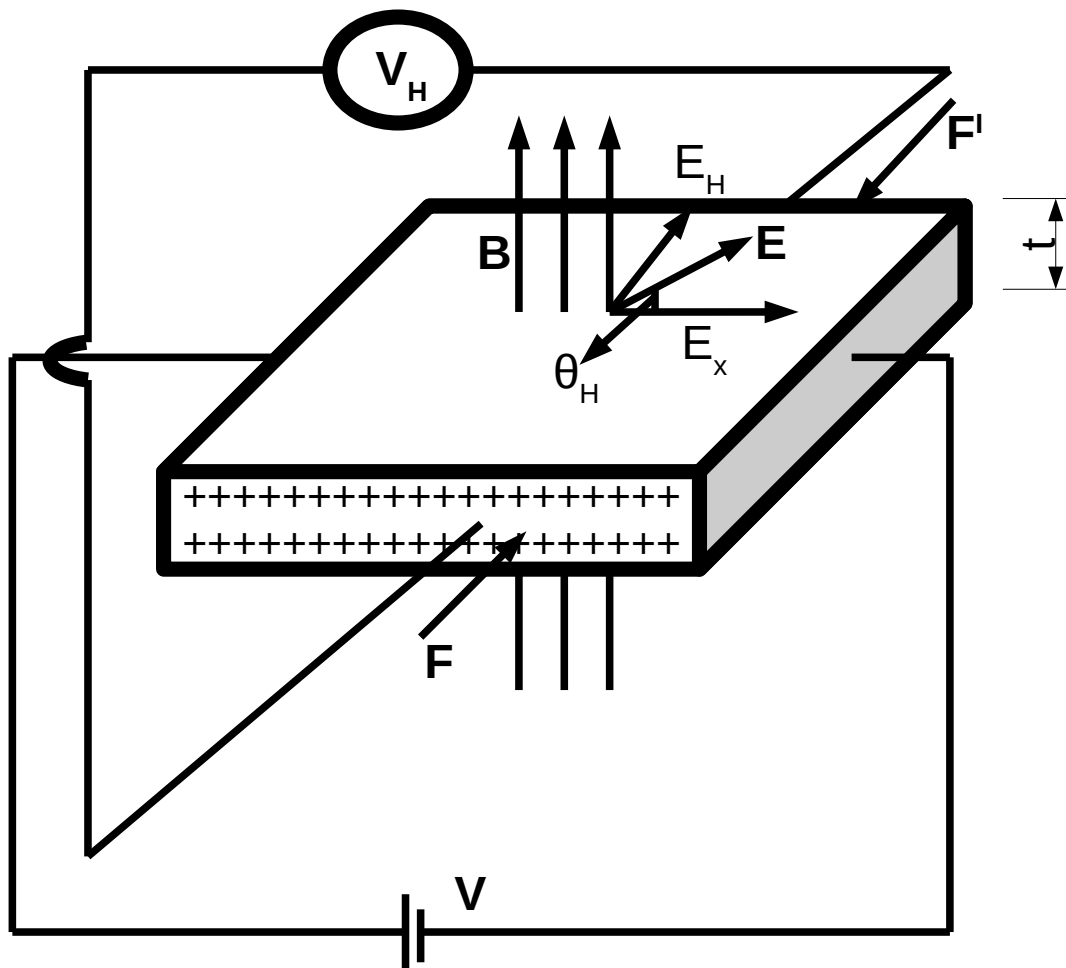
Let us consider a rectangular P-type semiconductor

When a pottential diffrence (V) is applied across its ends, current of strength I flows through it along X-direction

If holes are the charge carriers in P-Type semiconductor, then

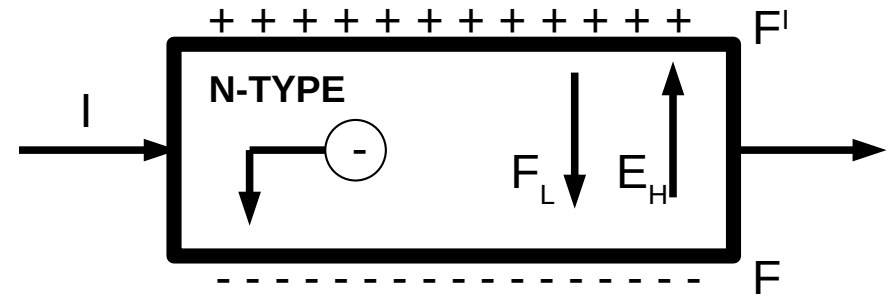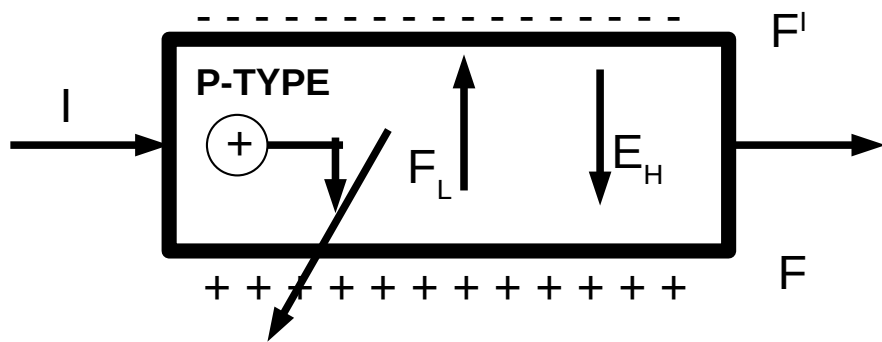$$I = pAev_d \qquad ----[1]$$

**p**--- concerntration of holes
**A** --- Area of cross section of the end face
**e**--- charge on the hole
**$V_d$** --- average drift velocity of holes

**Current Density= $J_x = I/A = pev_d$ ----[2]**

Any plane perpendiclar to the current flow direction is an **equipottential surface**. Therefore the pottential diffrence between the front and rare faces F and $F^I$ is zero

If a **magnetic field B is applied normal to the surface** and also to **the current flow**, a **transverse pottential diffrence is produced between F and F'**. It is called as **Hall Voltage V$_H$**.

after the application of B, the holes experiances a side way deflection due to **Lorentz force F$_L$**. The magnitude of the magnetic force is given by

$$F_L = eBv_d \qquad \text{---[3]}$$

**Because of this force, holes are deflected towards the face F and pile up there and corresponding equivalent negative charge is left on F'.**

As a result an **electric field is generated across F and F'**.

The direction of the electric field will be from the front to rare face

It is such that it opposes the furthur piling up of holes on front face F.

A **condition of equilibrium** will be reached when the force F$_E$ due to transverse field E$_H$ balances the Lorentz force, F$_L$. The transverse field E$_H$ is known as **Hall Field**.

Equilibrium state is usually attained in about **10⁻⁴ s** and after that the holes flow once again along x-direction parallel to the faces F and F$^I$.

At equilibrium,

$$F_E=F_L$$

$$F_E= eE_H = e[V_H/W] \qquad\qquad \text{--- [4]}$$

W --- width of the semiconductor plate

$$F_L=eBv_d$$

From [2]

$$v_d= J_x/pe$$

$$F_L=BJ_x/p \qquad\qquad \text{---[5]}$$

Equating [4] and [5]

$$e[V_H/W]=BJ_x/p$$

$$e[V_H/W]=BJ_x/p$$

$$V_H = \textcolor{red}{WBJ_x/pe} = WBI/peA$$

**If t thickness of the semiconductor then A=Wt**

$$V_H = WBI/peWt = BI/pet \qquad \text{---[6]}$$

**Hall field per unit magnetic induction is called as Hall coefficient, $R_H$ then**

$$R_H = E_H/BJ_x$$
$$= (V_H/W)/(BJ_x)$$
$$= V_H/WBJ_x$$
$$= WBJ_x/WpeBJ_x$$

$$R_H = 1/pe \qquad \text{---[7]}$$

**Now [6] becomes**

$$V_H = R_HBI/t \qquad \text{---[8]}$$

$$R_H = V_h t/BI \qquad \text{---[9]}$$

**Hall voltage is areal voltage which can be measured with a voltmeter**

**The direction of the B and I, the $V_H$ is positive in p type semiconductor but negative in N-type semiconductor and type of majority charge carriers will be known**

From [7] and [8]

$$p = 1/R_H e = BI/V_H te \qquad ---[10]$$

In case of N-type semiconductor

$$R_H = -1/ne \qquad ---[11]$$

$$n = -1/R_H e = -BI/V_h te \qquad ---[12]$$

**Hall coefficients in metals are independent of temperatures**
In case of **semiconductor $R_H$, drops sharply with a rise in temperature, indicating that the concerntration of free electrons increases with temperature**
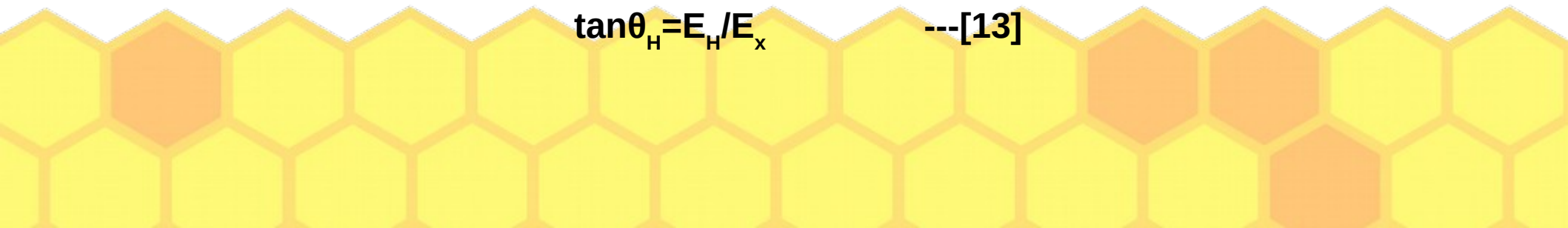
The net electric field E in the semiconductor is a vector sum of $E_x$ and $E_H$

It acts at an angle $\theta_H$ to the X- axis,

**$\theta_H$ is the Hall angle**

Now from figure

$$\tan\theta_H = E_H/E_x \qquad ---[13]$$

From [5]

$$E_H = V_H/W = Bj_x/pe \qquad \text{---[14]}$$

Also

$$E_x = \rho J_x \qquad \text{---[15]}$$

From [13], [14], [15]

$$\tan\theta_H = B/pe\rho \qquad \text{---[16]}$$

$$\tan\theta_H = \sigma R_H B$$

The product $\sigma R_H$ is mobility ($\mu_H$) of holes

$$\tan\theta_H = \mu_H B \qquad \text{---[17]}$$

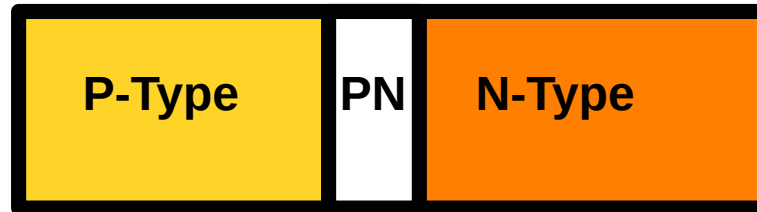The appropriate value of RH is

$$R_H = (3\pi/8)(1/pe) \qquad \text{---[18]}$$

$$\mu_H = (8/3\pi)\sigma R_H \qquad \text{---[19]}$$

# PN Junction diode

When a crystal of pure semiconductor is doped, so that one half of it is P- type and the other half is N-Type, then the border between P-Type and N-Type is called P-N Junction
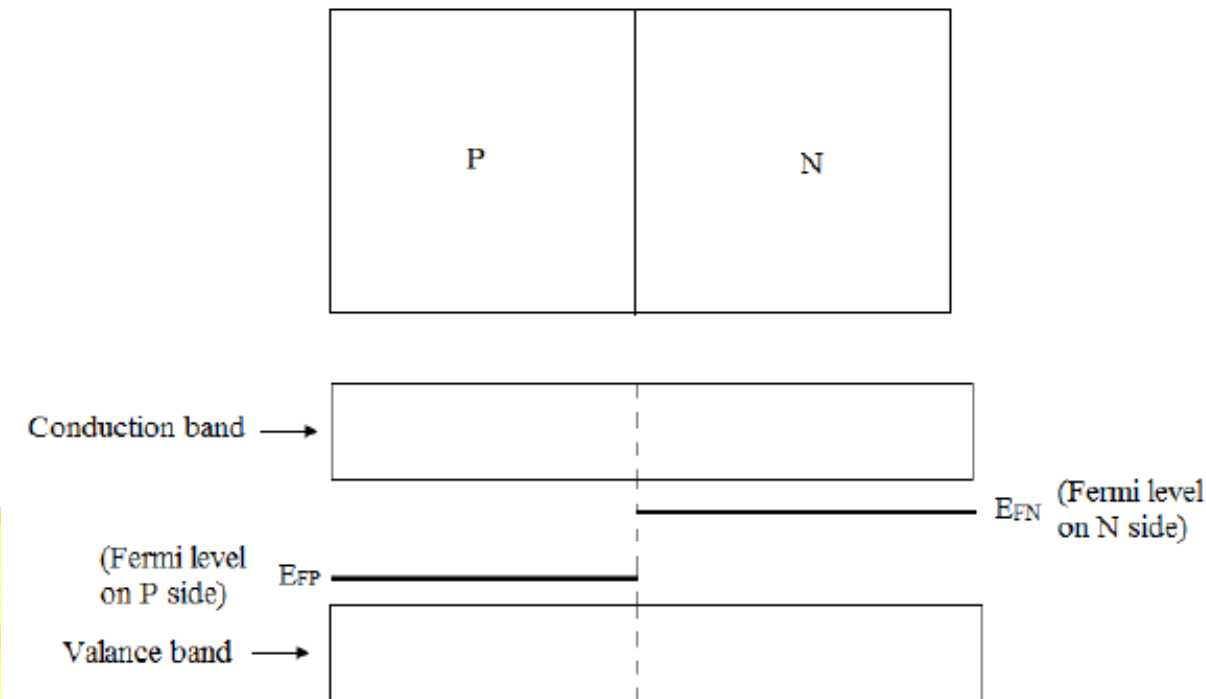


It has non linear resistance
A junction diode is **two terminal device having P-N Junction**

## Fermi Level in Unbiased P-N junction diode

**just at the moment of formation (t=0)**
**Non-equilibrium condition**



The Fermi level in P-Type material is located close to the top of the valance band, where as in N-Type material Fermi level lies close to the bottom of the conduction band

In P-Type holes and in N-Type free electrons are the majority charge carriers

The closeness of Fermi level to the valance band on P side indicates that the lower energy states of the electrons are empty

the closeness of Fermi level to the conduction band on N side indicates that the electrons on N side are in majority and their overall energy is high

# Unbiased diode a few moments after its formation

To **reach the equilibrium condition**

The electrons diffuses toward P-type from N-Type
The holes diffuses toward N-type from P-Type
This is due to difference in charge carrier concerntration in P and N side of semiconductor.
This process is called **diffusion**

The diffused charge carriers combine at the junction to neutralize each other

Due to this neutralisation, a **charge free space** called **depletion layer** is formed near the junction



Due to diffusion of holes from P to N region, negative ions are produced in P-region
Similarly Positive ions in N region
Both these ions are immobile and form barrier across the depletion layer (**Charge separation**)
Because of this charge separation,
An electric pottential or barrier pottential is formed then the **diffusion of majority charge carrier across the junction is prevented**
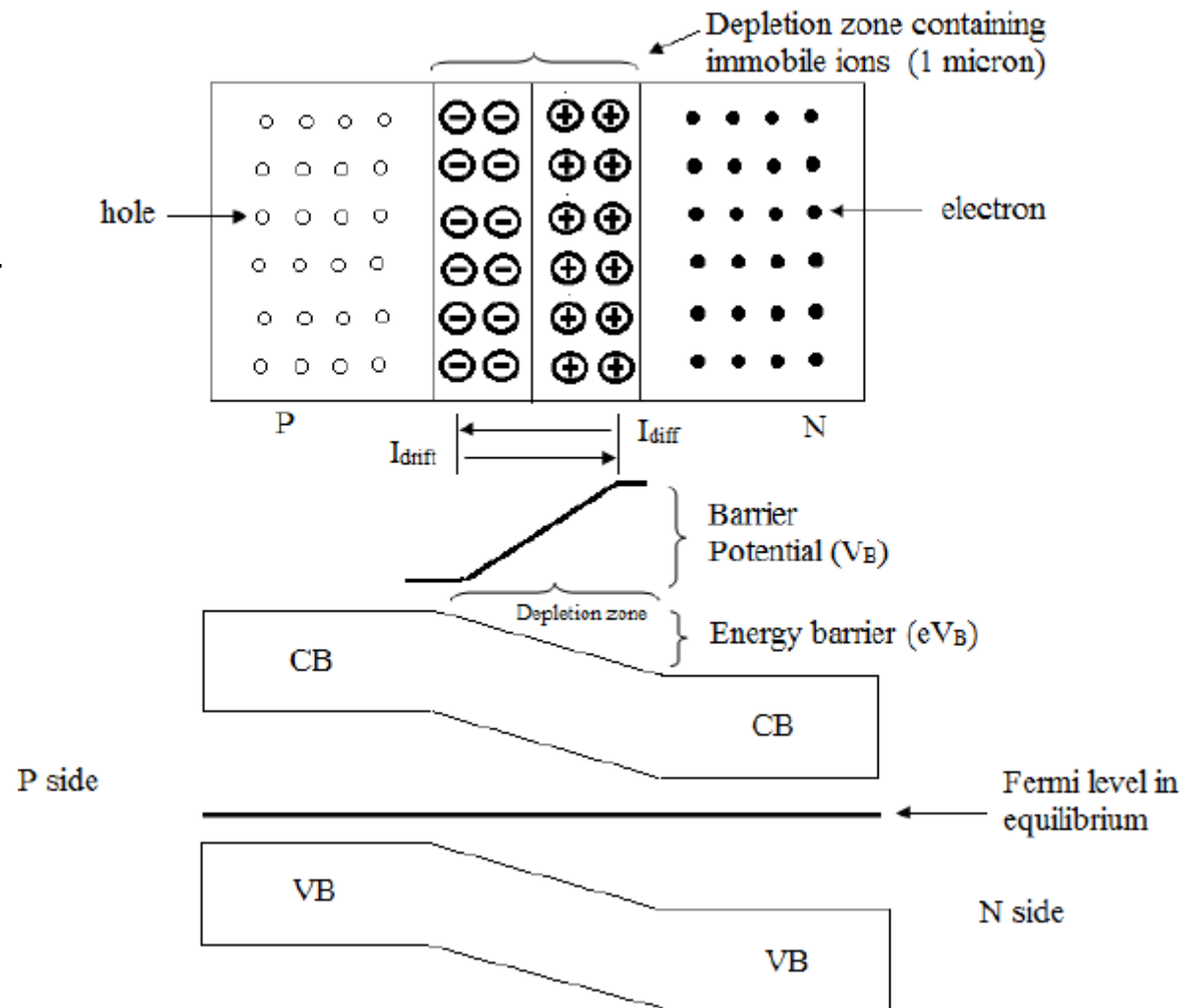
# PN junction diode under forward bias

P-Side is connected to positive terminal and N side is connected to negative side of the battery

Due to forward bias equilibrium conditions are disturbed

Therefor energy bands and fermi levels were altered

Due to **forward bias energy of an electron in N-side increases by an amount eV$_F$** (V$_F$- voltage)

Fermi level is **raised** by eV and the energy bands adjust their positions so as to suit the elevation of the fermi level

Due to increase in energy in N-side, the **pottential barrier is reduced** to **e(V$_B$-V$_F$)** and the **barrier width is reduced**

Hence the electrons crossing the junction from N-side will now face a **low potential barrier** and they can easily cross the junction

For conduction to take place, forward bias potential should be greater than the barrier potential
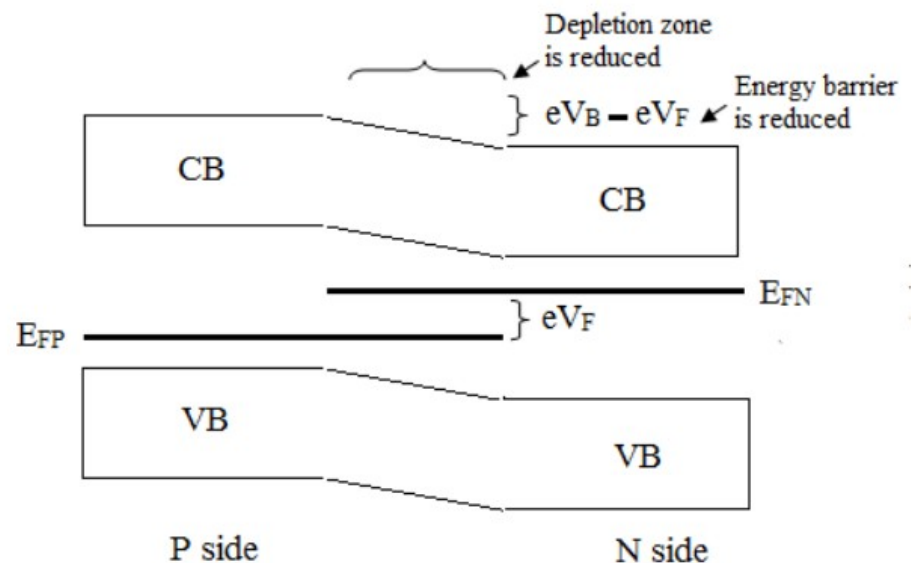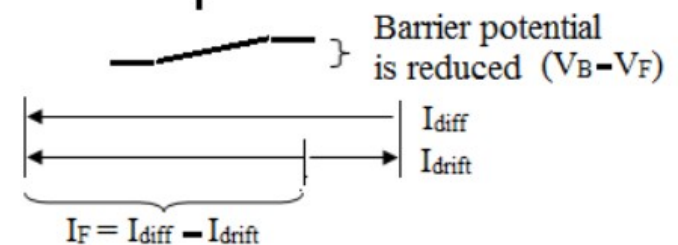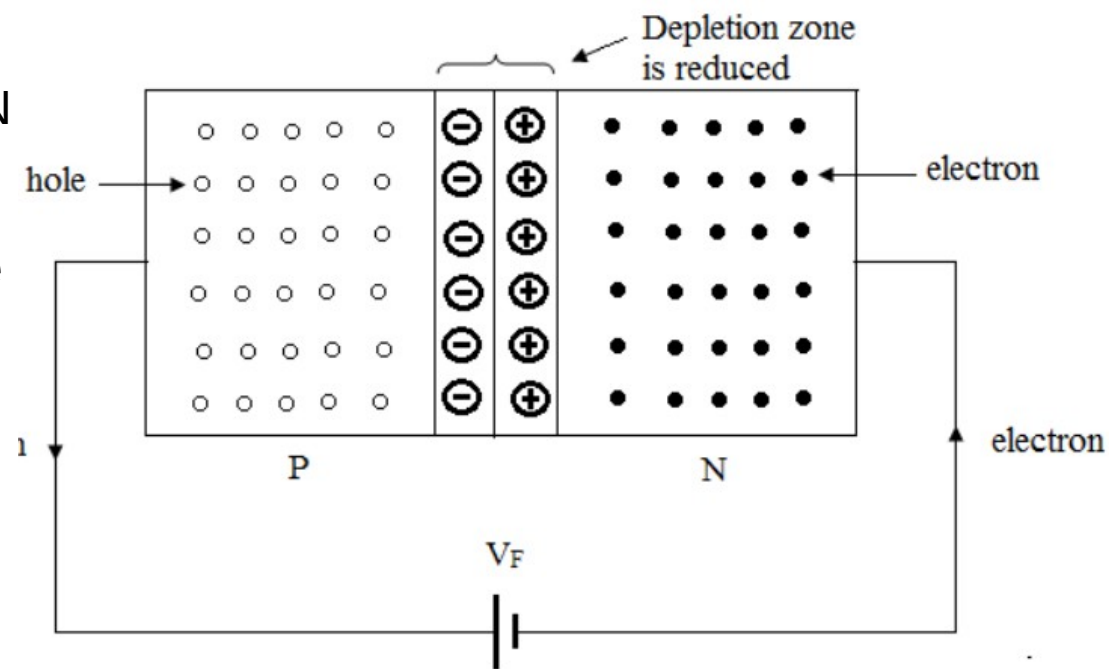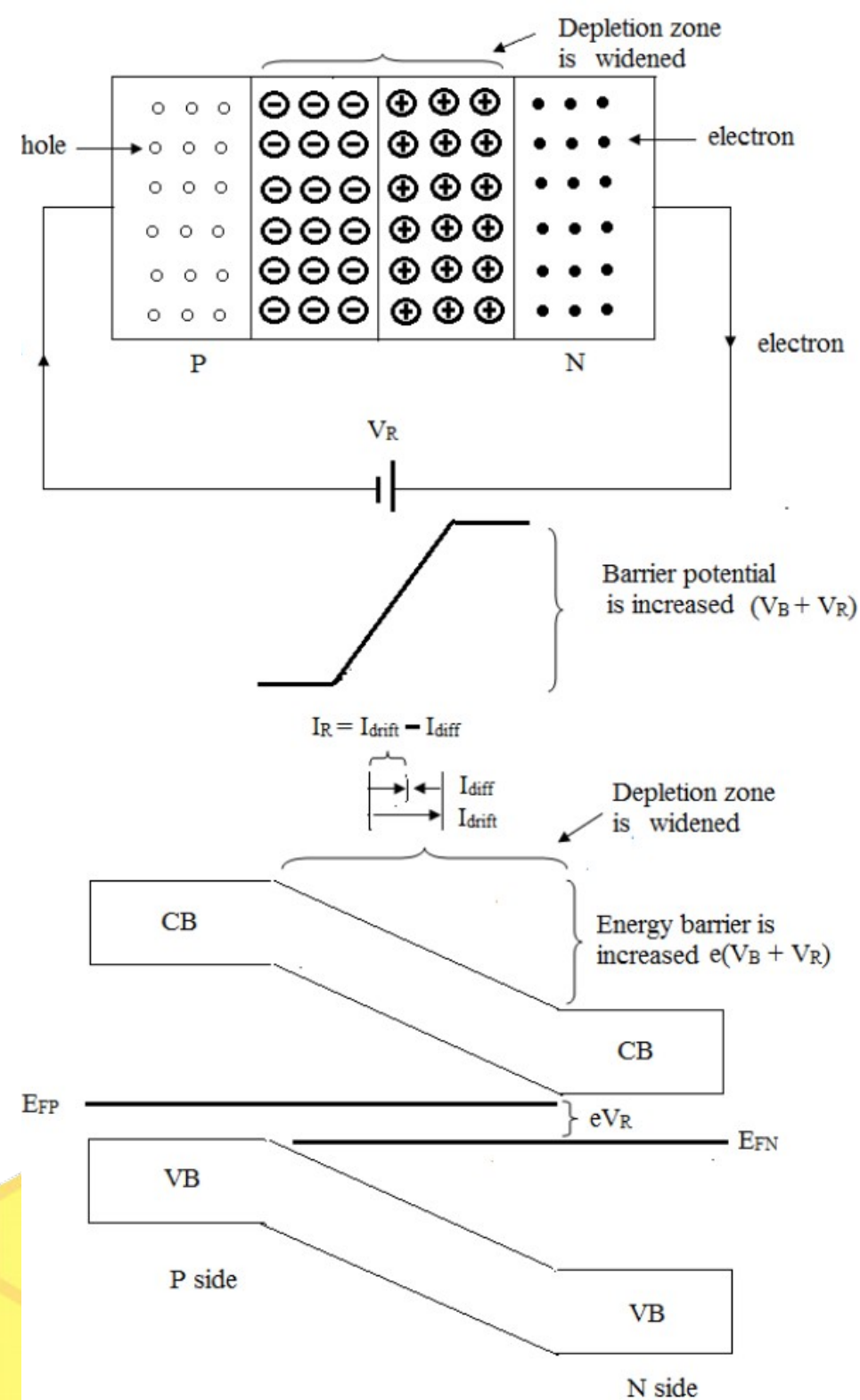
# PN junction diode in reverse bias

N-side is connected to the positive terminal and P side negative terminal of the battery

This **lowers the Fermi level on N-side by an atom eV raising the barrier height to e($V_B$+$V_R$) and there by increasing barrier width**

The electrons which are the majority charge carriers in the N-side will now face **a greater pottential barrier** in crossing the junction

The number of electrons crossing from N-Side toP-side decreases and hence the current is very much reduced

Depletion zone is widened

hole

electron

electron

P

N

$V_R$

Barrier potential is increased ($V_B$+ $V_R$)

$I_R = I_{drift} - I_{diff}$

$I_{diff}$
$I_{drift}$

Depletion zone is widened

CB

Energy barrier is increased e($V_B$ + $V_R$)

CB

$E_{FP}$

$eV_R$

$E_{FN}$

VB

P side

VB

N side

# NPN Transistor

Majority charge carriers are **electrons**

A lightly doped and thin P-type semiconductor is sandwiched between two N-type semiconductor

**Emitter:** Source of charge carriers, heavily doped
**Base:** thin and lightly doped, captures only negligible numl
        charge carriers, ie. Controls the flow of charge carrie
**Collector:** collects the charge carriers, large size

**Transistor: used to amplify the signal**

Normally,

E-B junction is always forward biased – low resistance
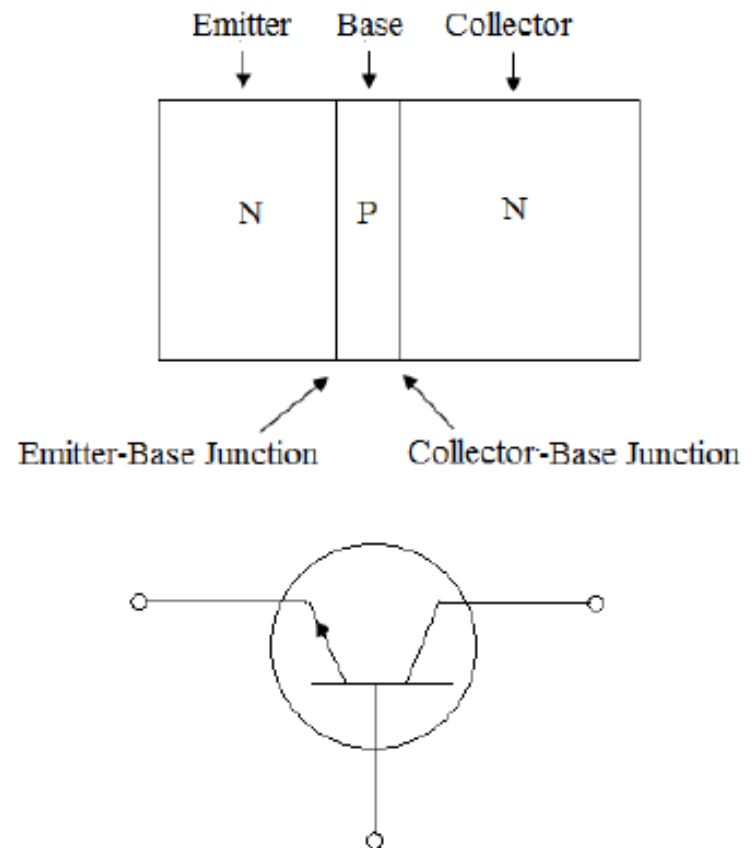C-B junction is always Reverse biased – has high resistan
Thus transistor- transfers resistance from low resistance -i
E-B junction to high resistance output CB junction

Due to **low resistance the voltage across input is low**
        **High resistance the voltage across the output b**

Transistor is used as an amplifier
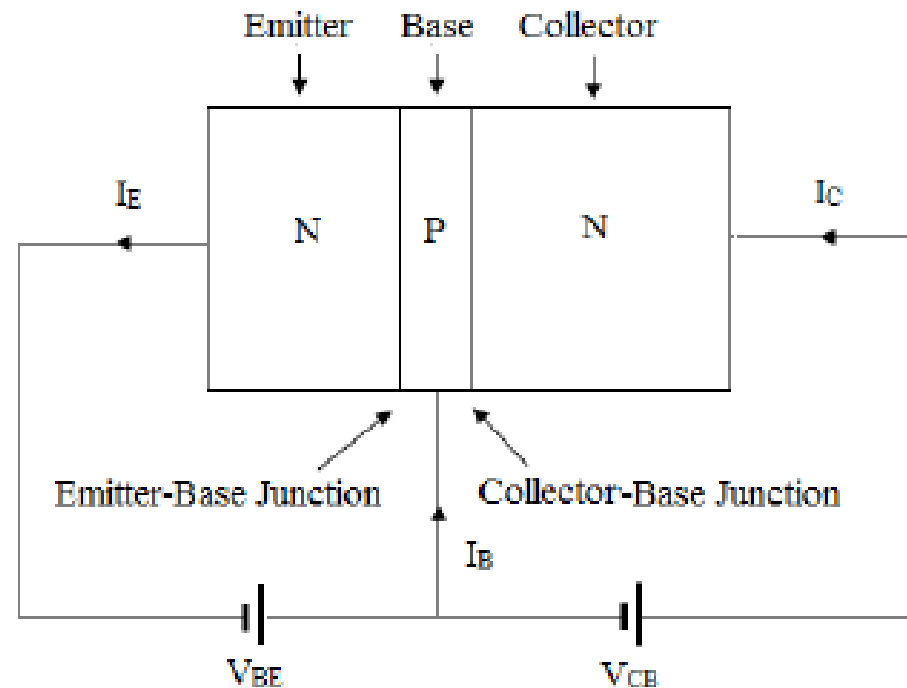
The base is lightly doped, therfor it also amplify current

The battery ($V_{BE}$) across E-B junction repels the charge carrier in emitter towards base
This constitutes emitter current ($I_E$)

Now the **base has opposite polarity**,a few charge carriers undergo recombination. These results in to base current ($I_B$)
rest of the charge carriers enter the collector ($I_C$) and afterwards they are attracted towards the battery ($V_{CB}$)

Thus

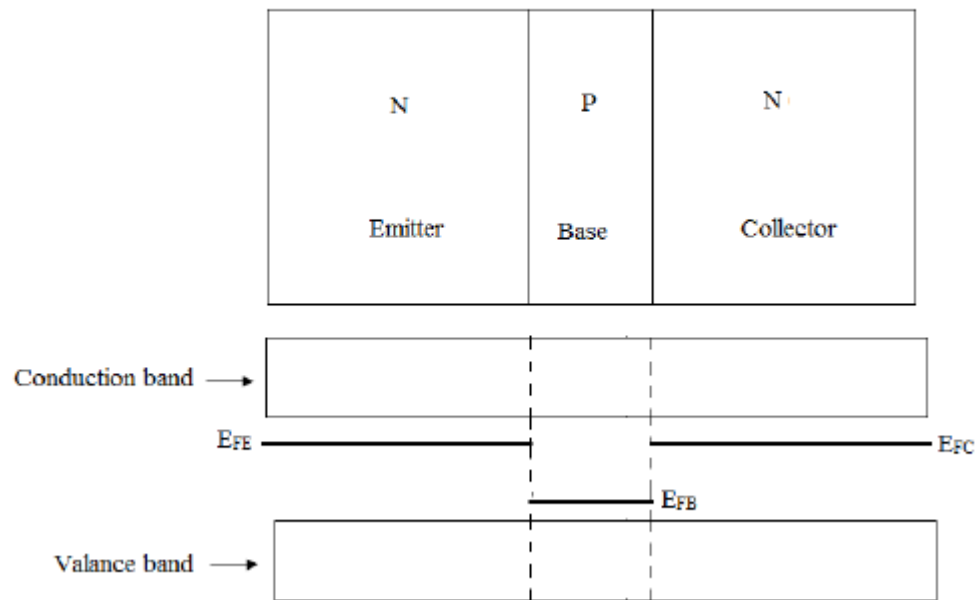$$I_E = I_B + I_C$$

Emitter    Base    Collector

$I_E$          N    |    P    |    N          $I_C$

Emitter-Base Junction          Collector-Base Junction

$I_B$

$V_{BE}$          $V_{CB}$

*( Arrows indicate conventional currents )*

# Energy Band Diagram of Unbiased NPN transistor

## At the instant of its formation (t=0 or non equilibrium)



Pure semiconductor is appropriately doped with suitable pentavalent and trivalent impurities
Here emitter and Collector are N-Type
Due to higher concerntration of free electrons in conduction band the fermi levels of these electrodes are near the conduction band

High concerntration of energetic electrons present in these electrodes (in CB)

Base is made up of P-Type semiconductor, due to high concerntration of holes, the fermi level of base electrode is near the valence band
---> absence of energetic free electrons in the conduction band
Presence of Fermi levels at diffrent positions indicates the **non equilibrium condition**

**In the equilibrium condition Fermi leve**ls  in all the regions is equalised
EF of E and C move down and of B should move UP

# Few second after its formation

The electrons in the emitter and collector diffuse in the base (near the junction)

The atoms near the junction from which the elctron leave become positive ions

**The diffusion of electrons from emitter and collector to base and the diffusion of holes from base to emitter and collector results in to formation of -VE immobile ions in the base near the junction**

This form barrier at the junction and opposes the further diffusion of electrons from E andC to base and holes from B to E and C

**In energy Band diagram**

This indicates as equilibrium situation in which the Fermi levels in all the regions are equalised resulting in to a single Fermi level of the entire transistor
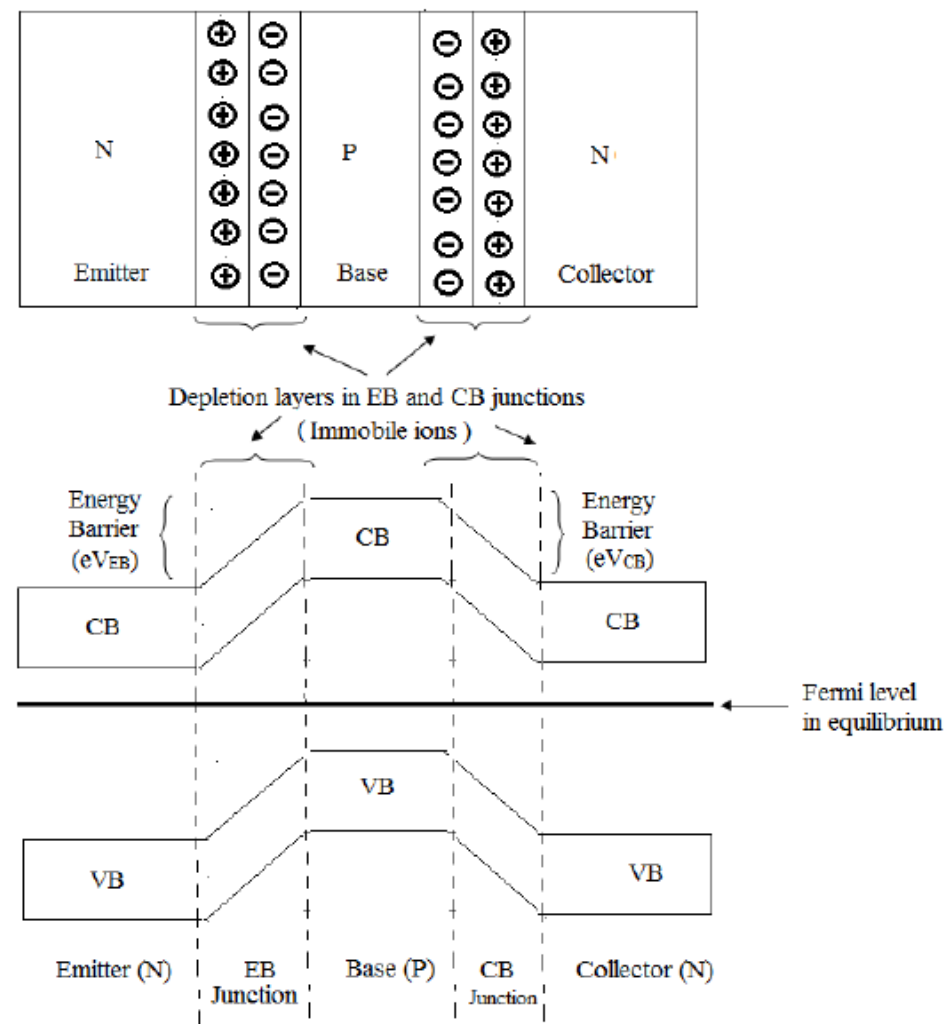
**The bending of bands results in to the formation of the energy barriers with heights $eV_{EB}$ in emitter- base junction**

Electron in the emitter and collector are at lower levels than those in base

They require an energy of about $eV_{BE}$ and $eV_{CB}$ to reach base

Fermi level is equalised

An unbiased transistor does not conduct

# Biasing NPN transistor

**To work as an Amplifier, Transistor should be biased**

NP junction is **forward biased** the energy barrier decreases ($eV_{BE}$-$eV_{BE\ ext}$)

PN junction is **reverse biased** the energy barrier increases($eV_{CB}$-$eV_{CBext}$)

Negative terminal is connected to N-Type, electrons get energised and there concerntration also increases

---> $E_{FE}$ **increases by** $eV_{BEext}$

---> pull up energy bands of emitter **reduces energy barrier across E-B junction**
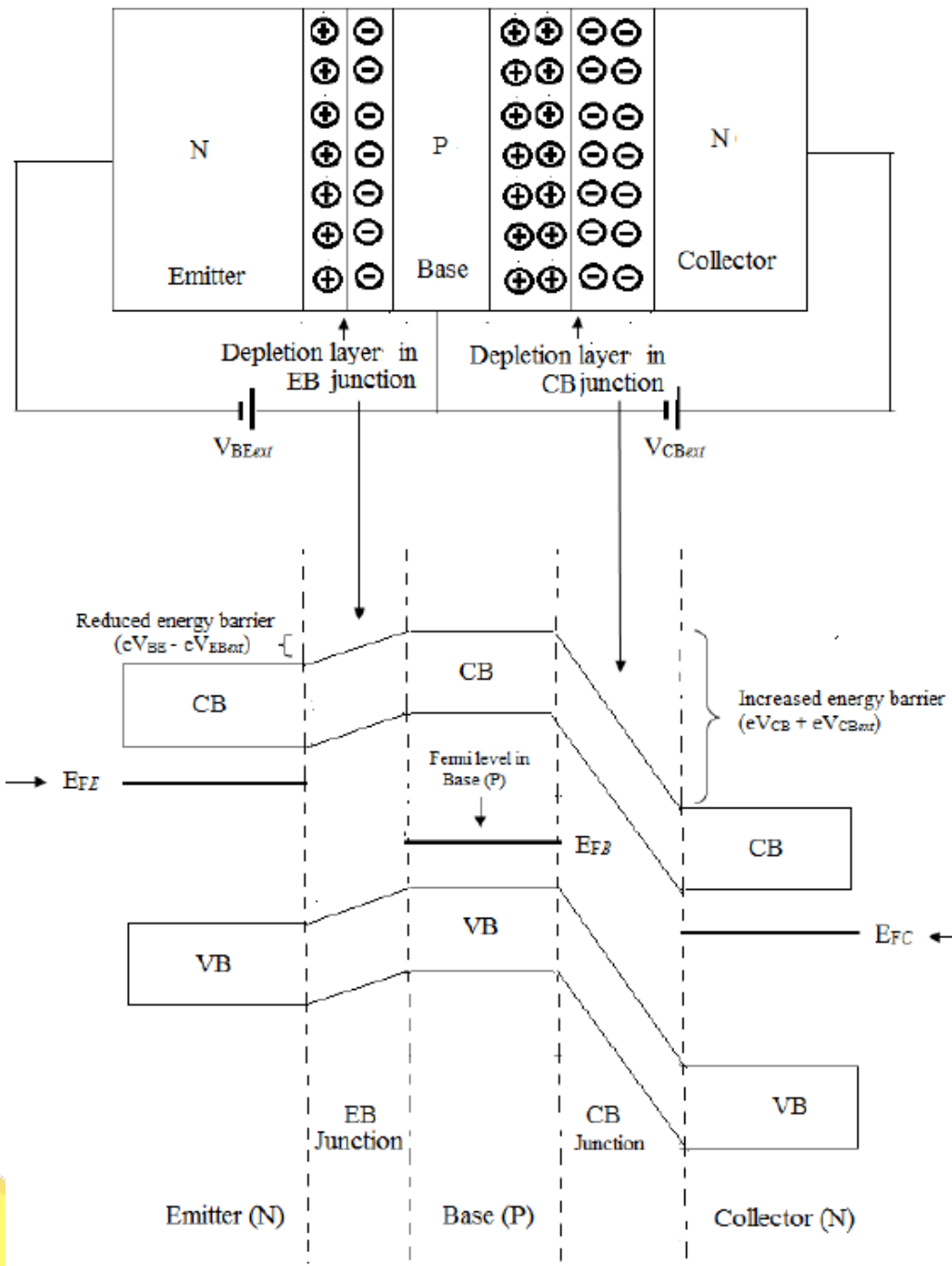Energy band and fermi level slightly **moves down** due to connection of +VE terminal to B

**If C-B junction is reverse biased**

---> this **depletes the concerntration** and **energy of electron in C**

--->$E_{FC}$ moves down by $eV_{CBext}$

---> Energy band pulls down

---> Increases energy barrier acros the C-B junction

**To get Equilibrium, electron must flow from E to B then B to C**
**i.e. $E_{FE}$ at higher position, $E_{FB}$ at Intermediate position and $E_{FC}$ at lower position**
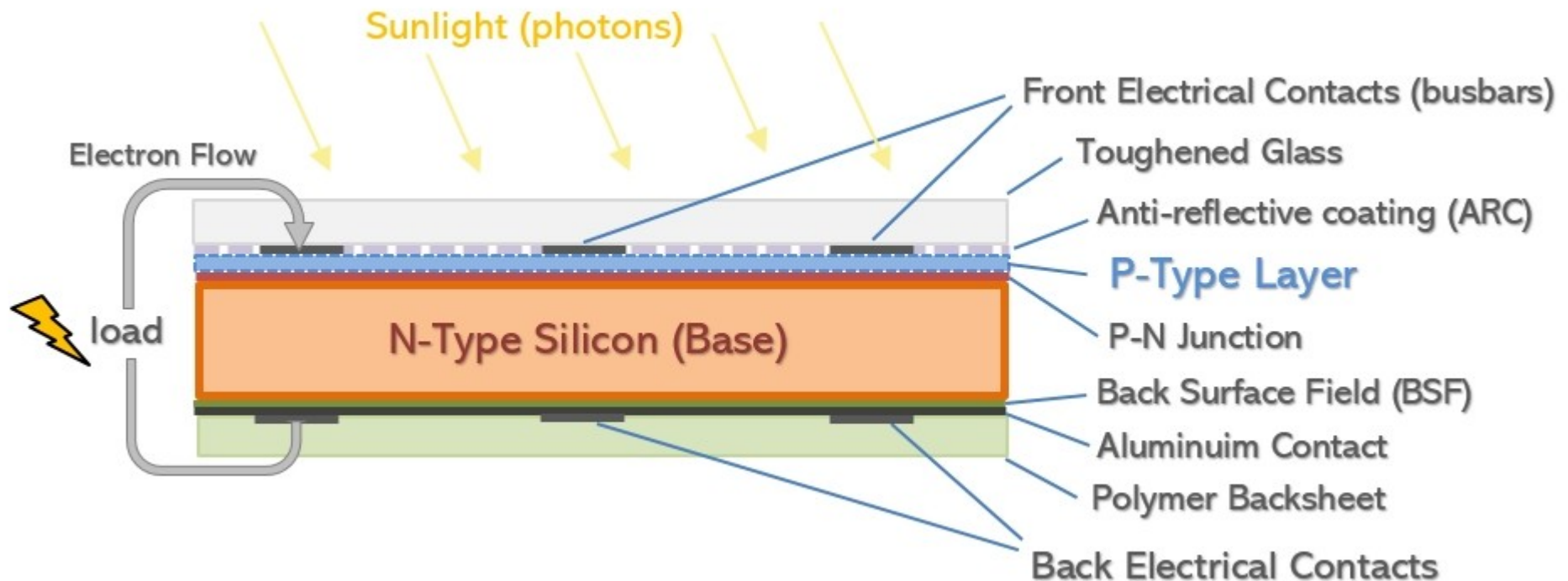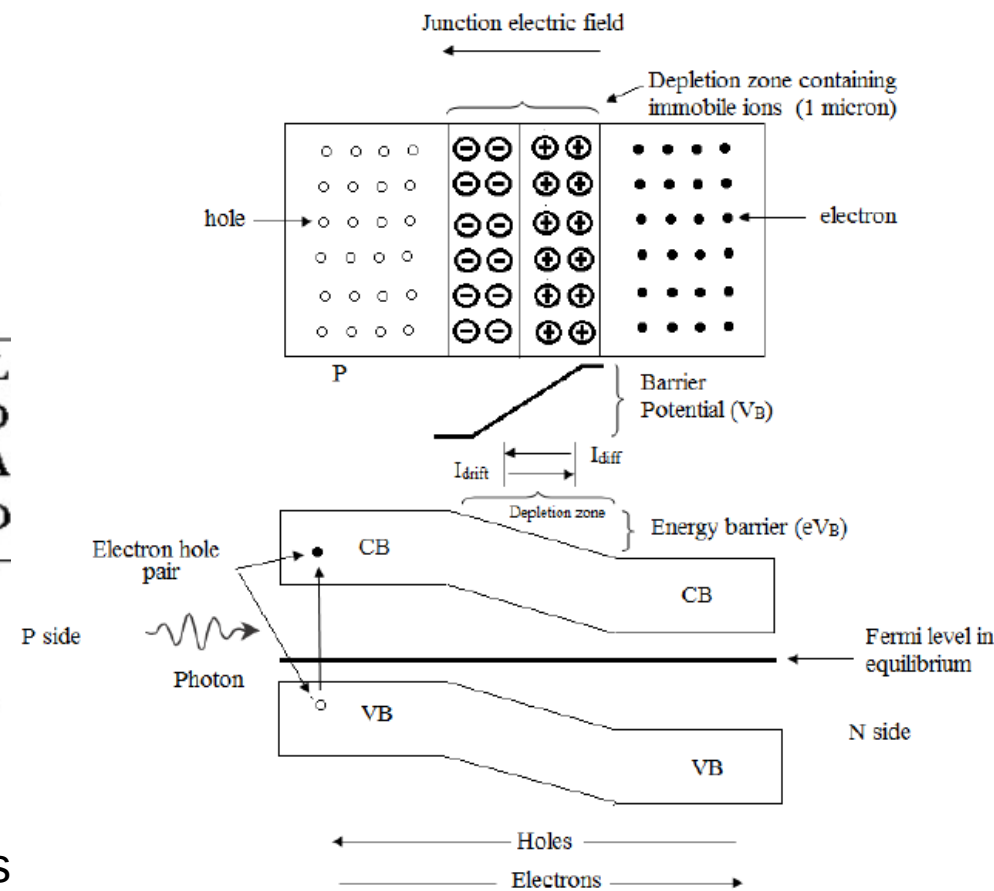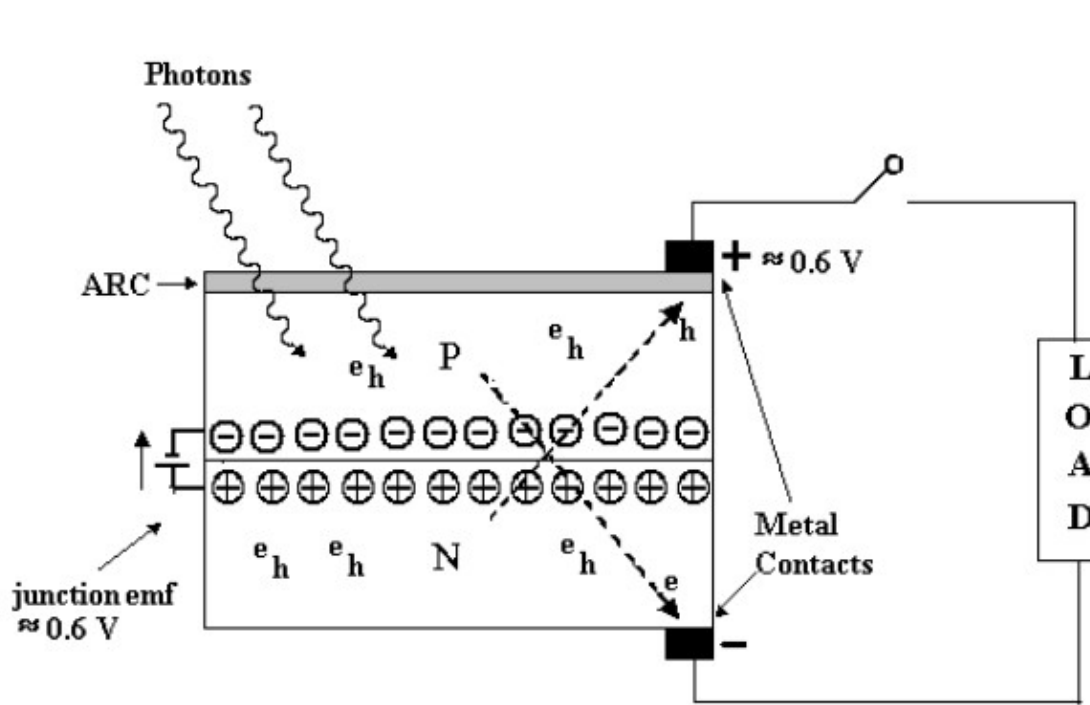
# SOLAR CELL

Diodes which converts light in to electricity are called as solar cells.

The phenomenon of converting the light in to voltage is called as Photovoltaic Effect

Thus solar cells also called as Photovoltaic Cells.

Solar cells are  called as Solar Batteries as they give electrical power

Photons

ARC →

P

junction emf ≈ 0.6 V

N

Metal Contacts

+ ≈ 0.6 V

L O A D

P side

Photon

Junction electric field

Depletion zone containing immobile ions (1 micron)

hole → electron

P

Barrier Potential (V$_B$)

I$_{drift}$ | I$_{diff}$

Depletion zone

Electron hole pair

CB

Energy barrier (eV$_B$)

CB

Fermi level in equilibrium

VB

N side

VB

Holes

Electrons

solar cell generates the electrical power in four steps

1. Generation of electrons and holes due to light

2. Separation of these electrons and holes due to junction- electric-field

3. Their accumulation across the metal contacts and thus the generation of emf

4. Flow of current due to this emf, when solar cell is connected across a load

**When a PN junction is exposed to light,**

**Photons excite the electrons in the valance band in to conduction band.**

**These electrons and holes move in opposite direction due to the action of the junction electric field.**

**Thus all electrons in P region are swept in N region**
**all holes are swept from N region to P region**

**The electrons entered in N region continue to flow towards the surface and they accumulate in the metal contact provided on the surface.**

**Similarly holes entered in to P region continue to flow towards the surface and accumulate in the metal contact on the surface.**

**Thus the N side metal contact acquires negative potential and P side metal contact acquires positive potential and consequently a potential difference is created across the diode.**

**If the diode is connected to a load then this PD drives a current in the circuit.**

**Thus we get electrical power**

# I-V Characteristics of Solar cell

When the load is not connected (or connected, but very high), the **current in the circuit is zero.** Consequently the **voltage across the cell is maximum**. This is open circuit condition and the corresponding voltage is called as **open circuit voltage ($V_{oc}$)**
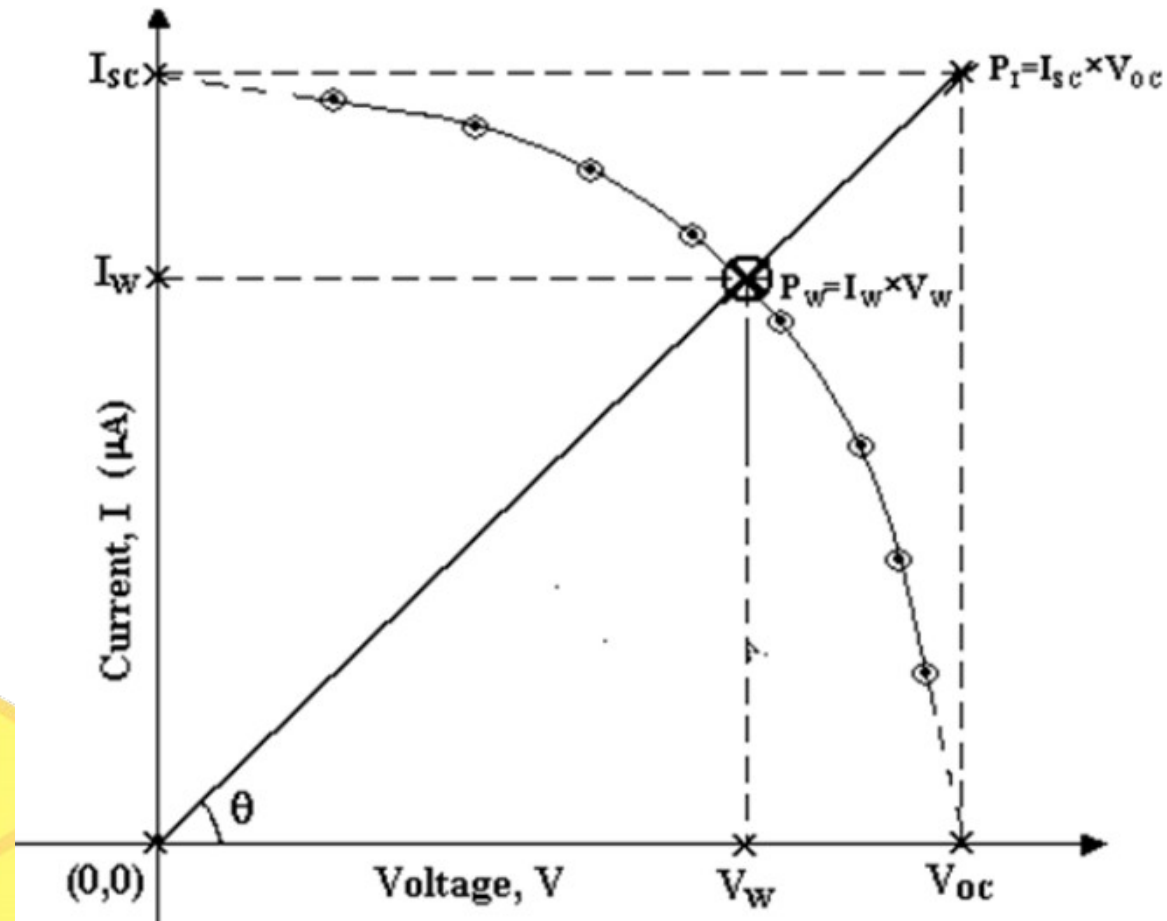
The **load resistance is reduced to zero**, **maximum current flows through the circuit**, then the **voltage drops to zero**. This is short circuit condition and the corresponding current is called as **short circuit current ($I_{sc}$)**

$V_{oc}$ corresponds to **infinite load**
$I_{sc}$ corresponds to **zero load**

**Ideal power = $P_I = I_{sc} \times V_{oc}$**

**Workable power = $P_w = I_w \times V_w$**

some fraction of ideal power rectangle is 'filled' by workable
power rectangle. Greater the 'filling', more close is the workable point to the ideal power point. This
can be described by introducing a physical quantity called as fill factor

$$fill\ factor = f = \frac{P_W}{P_I} \times 100\ \%$$

The optimum load is workable load

$$Workable\ load = R_W = \frac{V_W}{I_W} \qquad\qquad efficiency = \varepsilon = \frac{P_{output}}{P_{input}} = \frac{P_{workable}}{P_{optical}}$$

**Merits:**

1. **Sunlight is abundantly available and it is inexhaustible.**
2. **Solar cell does not create any pollution. There is no global warming**
3. **Solar electricity is risk free electricity. It is safe. There is no fear of accidents.**
4. **Especially in case of hydraulic power, dams are necessary. This leads to displacement of people and their rescue. Such problems do not occur in solar electricity.**
5. **Skilled manpower is not necessary in solar power plant**
6. **The solar panels can be fitted on houses, street lights or agricultural pumps. This reduces the transmission losses to a great extent**
7. **The process of conversion of sunlight in to electricity occurs instantly**
8. **Low maintenance**

## Demerits:

1. The sunlight follows day night cycle. The availability of sunlight is also affected due to change in seasons, change in climate and cloudy weather. Thus solar electricity cannot be generated continously
2. The electricity generated by solar cells can be stored. But the storage methods are costly.
3. The efficiency of solar cells is very low (around 10%).
4. Solar electricity is not cheap electricity.
5. Solar electricity is a weak electricity. It is not used when heavy power is required.
6. Solar cells generate DC electricity. In many cases, especially for effective transmission, AC electricity is required. Therefore conversion of electricity from DC to AC is required. This requires additional facilities.

## Aplications

➢ Supply of electricity in remote areas including villages and deserts, high altitude places where conventional electricity cannot be transmitted

➢ Satellites are the unique application of solar electricity

➢ Low power devices such as calculators, toys, LEDs, chargers, Street lights, marine lights, lights in airports, Solar bicycles, solar cars, solar boats, solar aircrafts etc.

➢ Street signals, railway signals etc.

➢ Agricultural pumps

| Silicon diode | Germanium diode | Zener diode | Thermistor |
| LED | Photodiode | LDR | Solar cell |
| Bipolar junction transistor (BJT) | Field Effect Transistor (FET) | Silicon Controlled Rectifier (SCR) | (Metal-Oxide Semiconductor Field-Effect Transistor) MOSFET |

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