Module No.06 : SEMICONDUCTOR PHYSICS

- Direct and Indirect Band Gap Semiconductors,
- Electrical Conductivity of Semiconductors,
- Drift, Velocity, Mobility and Conductivity in Conductors.
- Fermi- Dirac distribution function

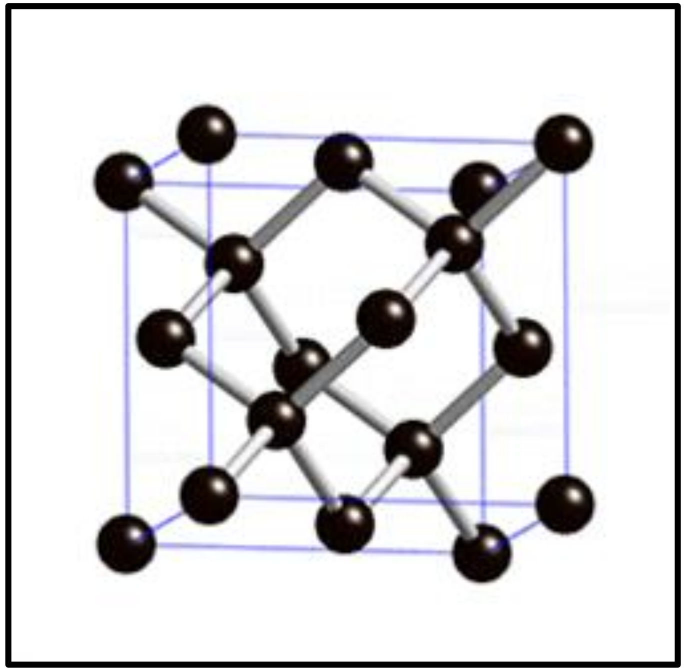
Pre-requisites of Semiconductor

Semiconductors are those materials that possess the properties between a good conductor and an insulator.

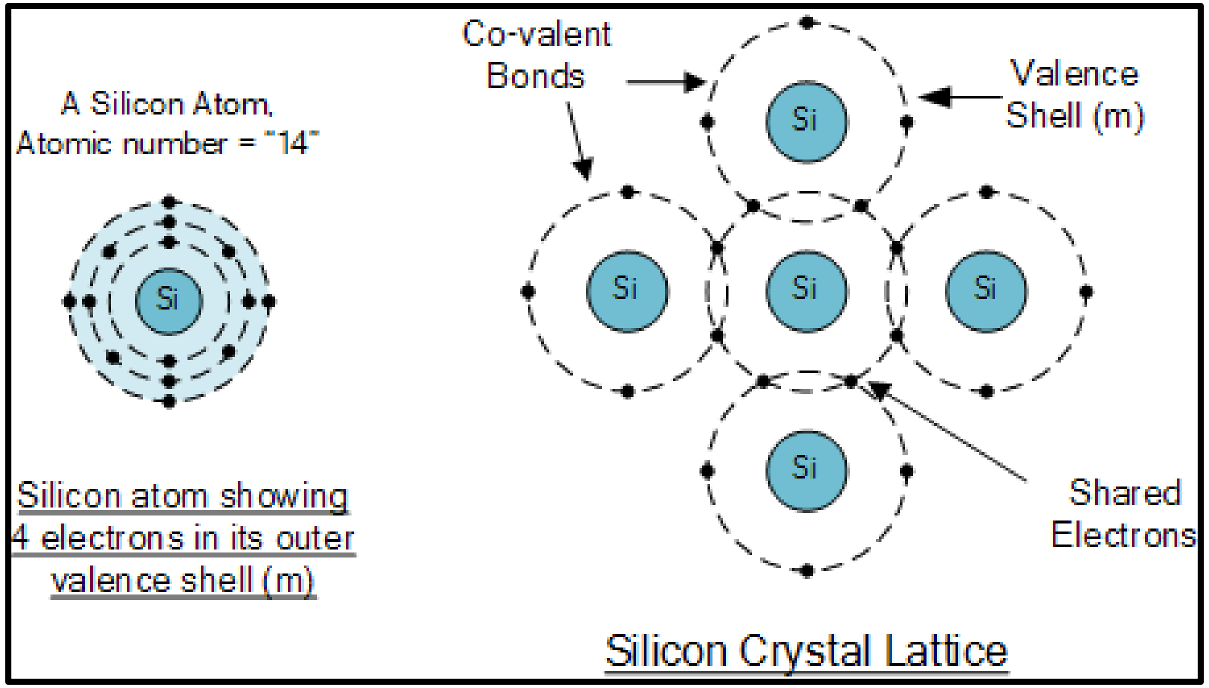
OR

Semiconductors are those materials whose conductivity lies between a good conductor and an insulator.

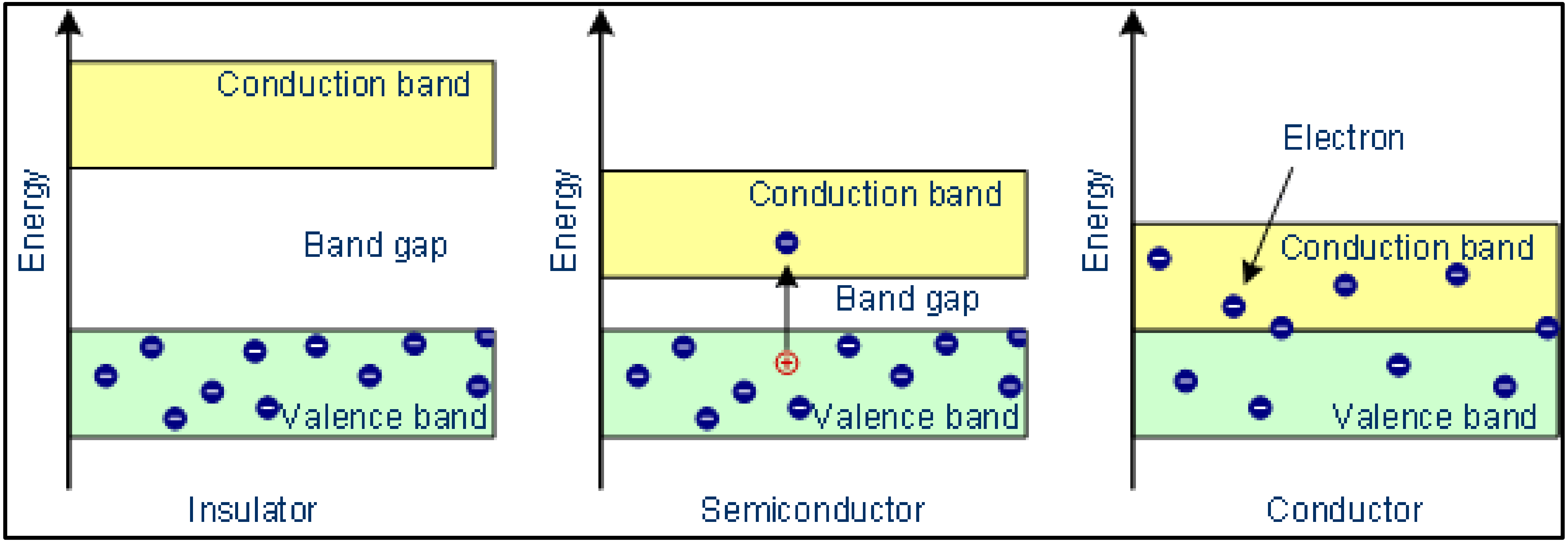
For example: Silicon, Germanium etc.



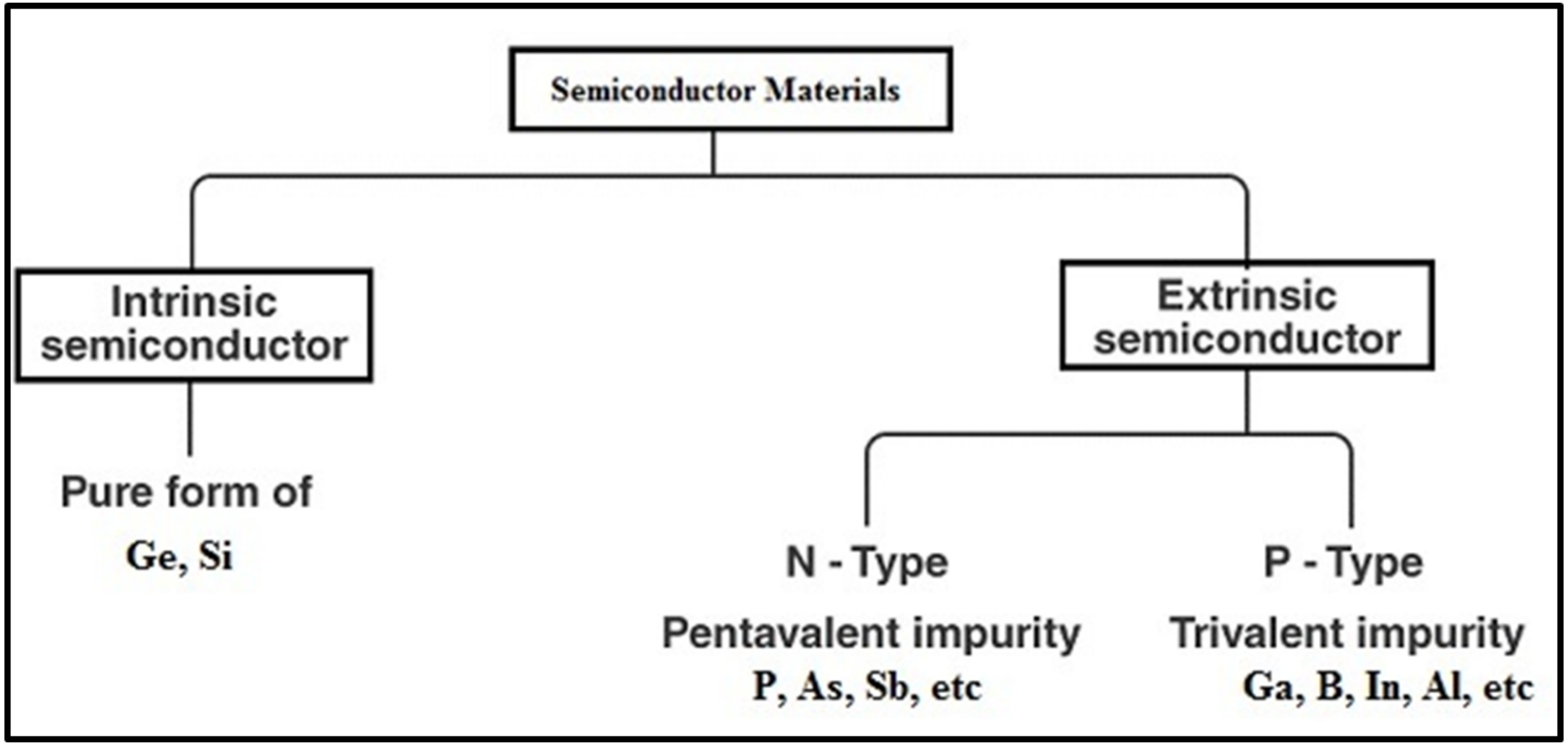
Silicon OR Germanium Crystal Structure



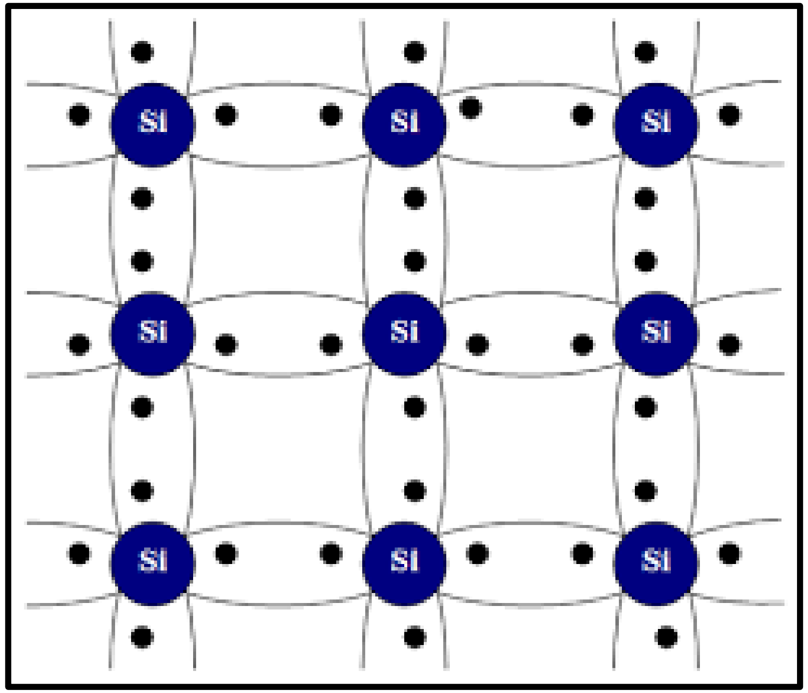
Distinction on the basis of Energy Band Diagram



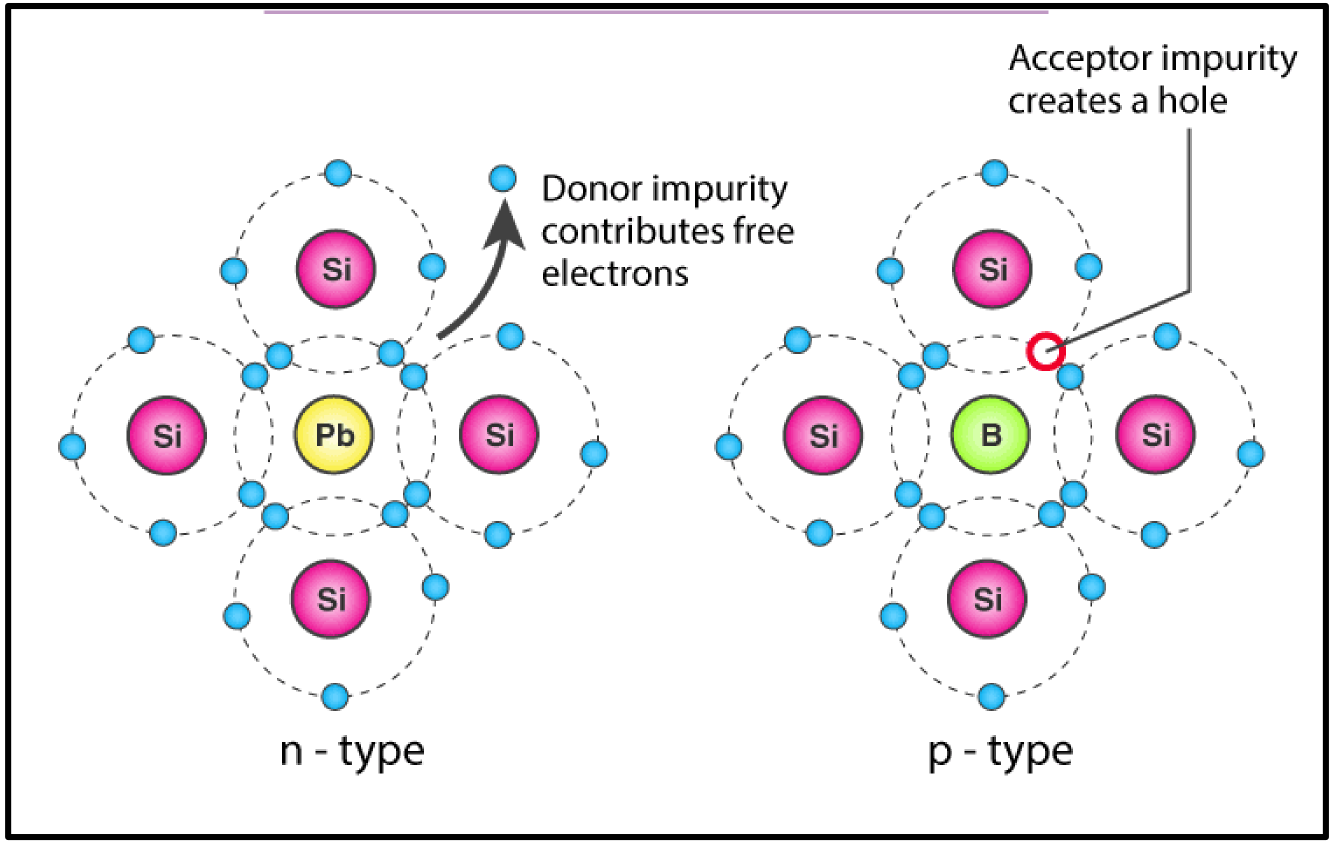
TYPES OF SEMICONDUCTORS



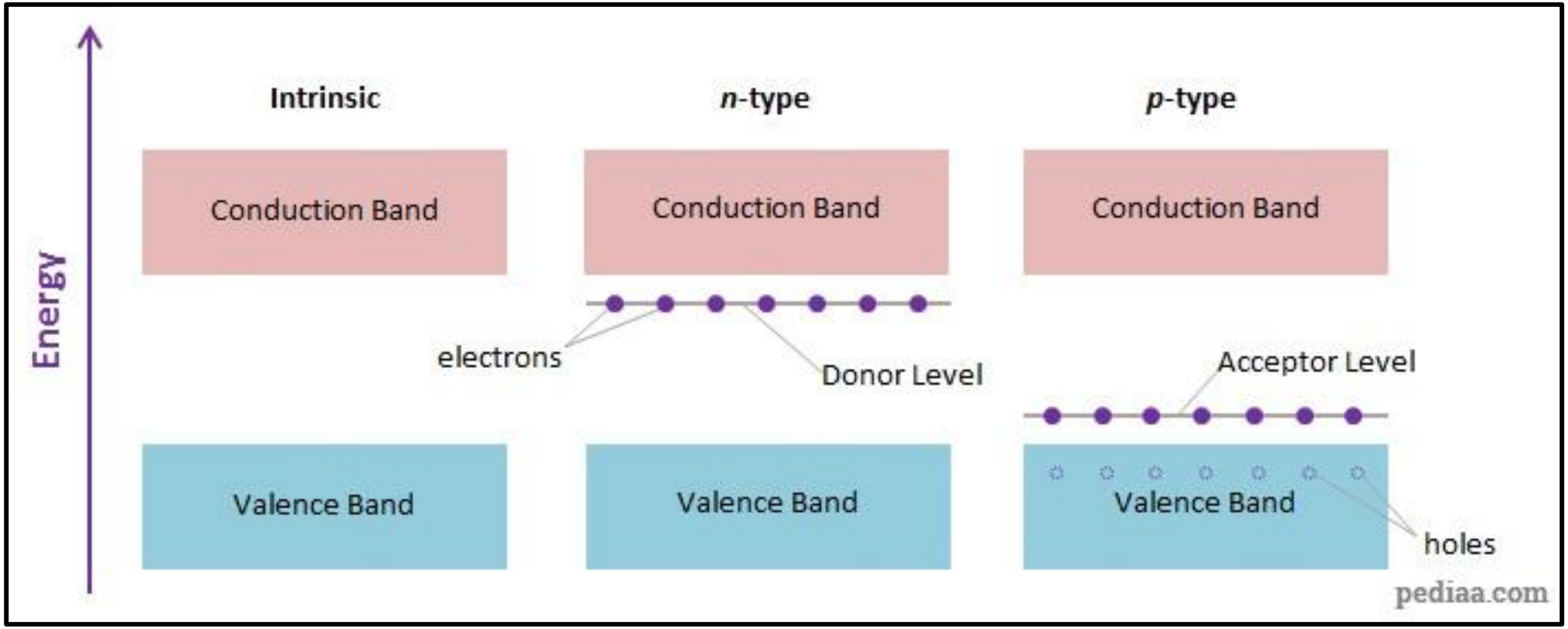
INTRINSIC SEMICONDUCTOR



EXTRINSIC SEMICONDUCTOR

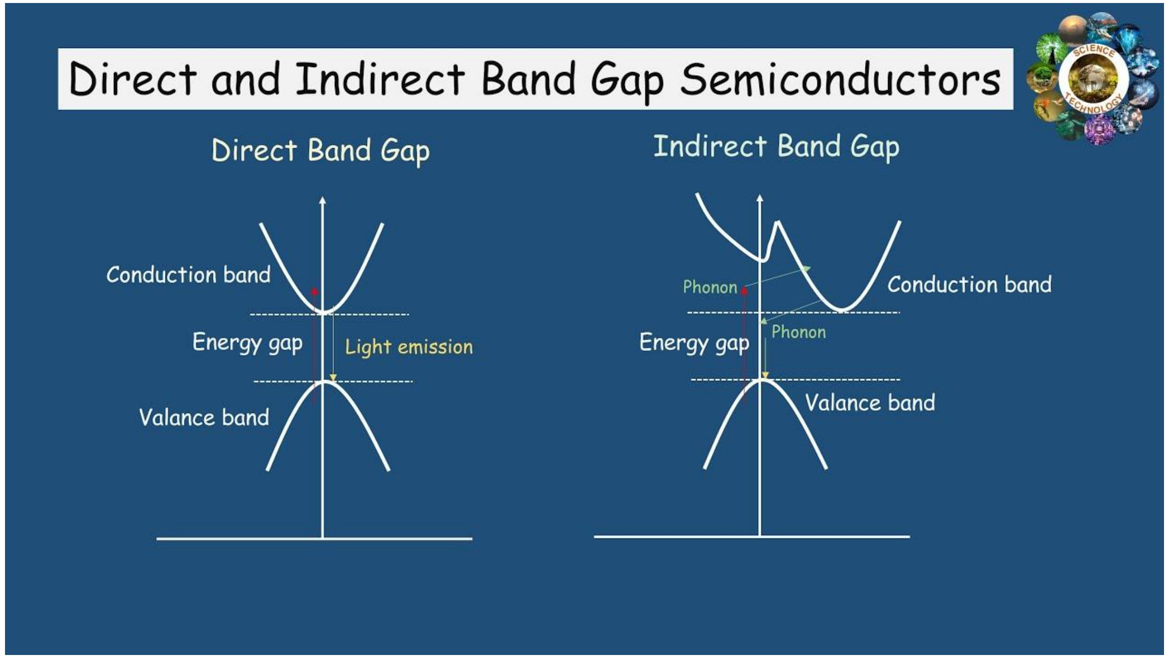


Energy Band Diagram



Difference between Direct and Indirect band gap Semiconductors

Sr. No	Direct Band gap semiconductor	Indirect band gap semiconductor
1	A direct band-gap (DBG) semiconductor is one in which the maximum energy level of the valence band aligns with the minimum energy level of the conduction band with respect to momentum.	A indirect band-gap (DBG) semiconductor is one in which the maximum energy level of the valence band are misaligned with the minimum energy level of the conduction band with respect to momentum.
2	In a DBG semiconductor, a direct recombination takes place with the release of the energy equal to the energy difference between the recombining particles.	Due to a relative difference in the momentum, first, the momentum is conserved by release of energy and only after both the momenta align themselves, a recombination occurs accompanied with the release of energy.
3	The efficiency factor of a DBG semiconductor is much more than that of an IBG semiconductor.	The probability of a radiative recombination, is much less in comparison to that in case of DBG semiconductors
4	The most thoroughly investigated and studied DBG semiconductor material is Gallium Arsenide (GaAs).	The two well-known intrinsic semiconductors, Silicon and Germanium are both IBG semiconductors.
5	DBG semiconductors are always preferred over IBG for making optical sources.	The IBG semiconductors cannot be used to manufacture optical sources.



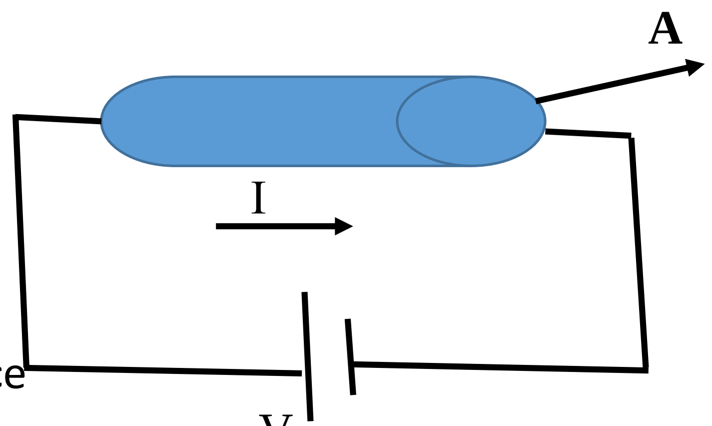
Concept of Conductivity, Mobility and Drift Velocity

Conductivity: It is the property of a given material by virtue of which it conducts electricity due to the availability of free charges (electrons).

It is denoted by ‘ σ ’

Unit: mho/m

It is the reciprocal of resistivity ‘ ρ ’.



Consider any conductor (cylindrical shaped) has area of cross section (A), is applied with a potential difference (V), then there is current flowing across it as (I).

Using ohm’s law,

$V = I\,R$

$R = \rho\, L/A$ ------ (1)

As we know that current density $J = I/A$ and Electric field $E = V/L$

Therefore, substituting in the above equation, we get

$J = \sigma E$ (where, $\sigma = 1/\rho$)

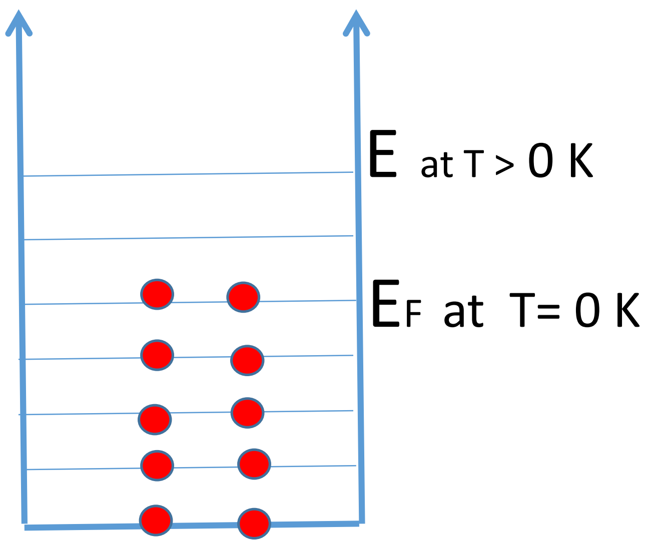
<u>Mobility</u>: It is the ease with which any charge carrier flow through the internal structure of a given material.
It depends upon the strength of the electric field (E).
$v_d \propto$ E   ($v_d = drift\ velocity$)
$v_d =$ μ E
Where,
μ is the constant of proportionality known as mobility of the material.
$Unit\ is \frac{m^2}{Vs}$

<u>Drift Velocity</u> ($\boldsymbol{v_d}$): It is defined as the average velocity with which charge carriers moves through the conductor under the action of an electric field.

Relation between conductivity, mobility:
For a given conductor,
If n is the concentration of charge carriers.
Then the current density J = n e v_d ------ (1)
Also we know that J = σ E ------ (2)
From equation (1) and (2) ,
We get, n e v_d = σ E
But, $v_d =$ μ E therefore, ne μ E= σ E
Hence, σ = ne μ
For Semiconductor materials: (1) Extrinsic σ = $(n_e e\mu_e + n_h e\mu_h)$ N-Type σ = $n_e e\mu_e$ and for P-type σ = $n_h e\mu_h$
(2) Intrinsic σ = ne$(\mu_e+\mu_h)$ ($where, n_e = n_h = n$) (n_e is concentration of electrons and n_h concentration of holes)

Fermi Level , Fermi Energy and Fermi Dirac Statistics

Fermi Level :
The highest energy level that an electron can occupy at the absolute zero temperature is known as the Fermi Level.



Fermi Energy: E_F
The maximum energy possessed by an electron at absolute zero temperature.

Fermi-Dirac Statistics (Quantum law):
(1) This statistics applicable to the identical, indistinguishable particles of half spin.
(2) These particles obey Pauli's exclusion principle and are called fermions (e.g.) Electrons, protons, neutrons …, Wave function is antisymmetric.
(3) In such system of particles, not more than one particle can be in one quantum state (orbital).

Fermi-Dirac Function

The probability of a state of energy E to be occupied by an electron is given by

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

The probability of a state of energy E to be occupied by a hole is given by $1 - F(\mathrm{E})$

If the level is certainly empty, then F (E) = 0

If the level is filled, then F (E) = 1

For Conductor

(a) At absolute zero,

(1) When E< E_F (i.e.,) for energy levels lying below E_F, (E –E_F) is a negative quantity and hence,

$$F(\mathrm{E}) = \frac{1}{\mathrm{e}^{-\infty}+1} = 1$$

All levels below E_F are completely filled.

(2) When E > E_F (i.e.) for energy levels lying aboveE_F, (E –E_F) is a positive quantity.

$$F(\mathrm{E}) = \frac{1}{\mathrm{e}^{\infty}+1} = 0$$

All levels above E_F are completely empty. This level, which divides the filled and vacant states, is known as the Fermi energy level.

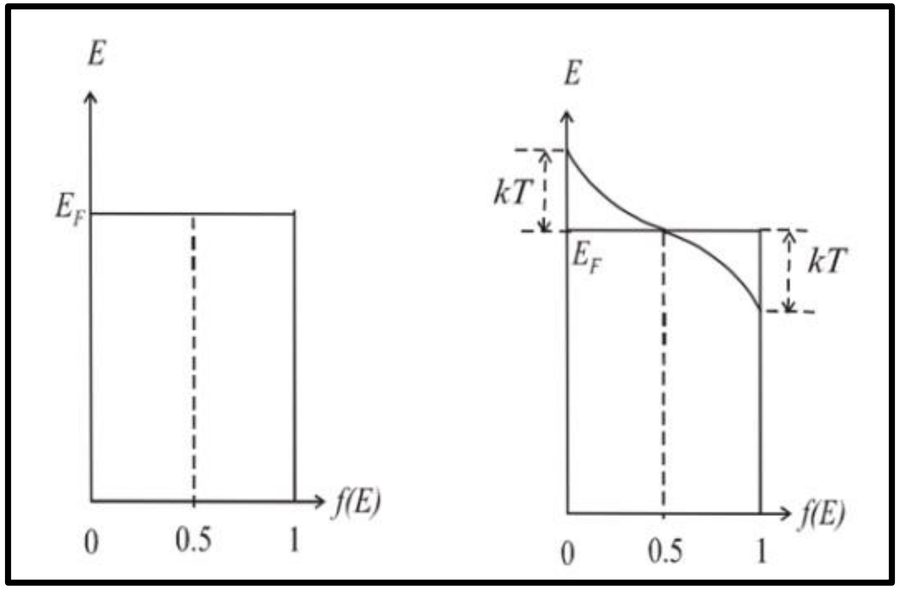
(b) At $T > 0$ K and When $E = E_F$

$$F(E) = \frac{1}{e^0 + 1} = \frac{1}{2}$$

Energy state is 50% occupied.

When the temperature is raised there is a greater probability of electrons being found to be occupied.

When $T > 0$ K, some levels above E_F are partially filled while some levels below E_F are partially empty.



<u>Question</u>: Show that the position of fermi level in intrinsic semiconductor lies in the middle of the band gap (5M)

Ans:

Carrier concentration of electron in conduction band (n_e):

$$n_e = 2\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{\frac{3}{2}} e^{-\left[\frac{E_C - E_F}{K_B T}\right]}$$

Where m_e^* = effective mass of electron

K_B = Boltzmann's constant = 1.38×10^{-23} J/K

T = Temperature in kelvin

h = Planck's constant = 6.63×10^{-34} JSec

E_c = energy of conduction band edge

E_F = Fermi energy

Carrier concentration of hole in valence band (n_h):

$$n_h = 2\left(\frac{2\pi m_h^* K_B T}{h^2}\right)^{\frac{3}{2}} e^{-\left[\frac{E_F - E_V}{K_B T}\right]}$$

Where m_h^* = effective mass of hole

K_B = Boltzmann's constant = 1.38×10^{-23} J/K

T = Temperature in kelvin

h = Planck's constant = 6.63×10^{-34} JSec

E_v = energy of valence band edge

E_F = Fermi energy

Continue….

Fermi level in intrinsic semiconductor:

In intrinsic semiconductor $n_e = n_h = n_i$

n_i = intrinsic charge carrier density

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

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

Or

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

Taking logarithm of both sides

$$\left[\frac{2E_F - (E_c + E_v)}{K_B T}\right] = \log_e\left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}}$$

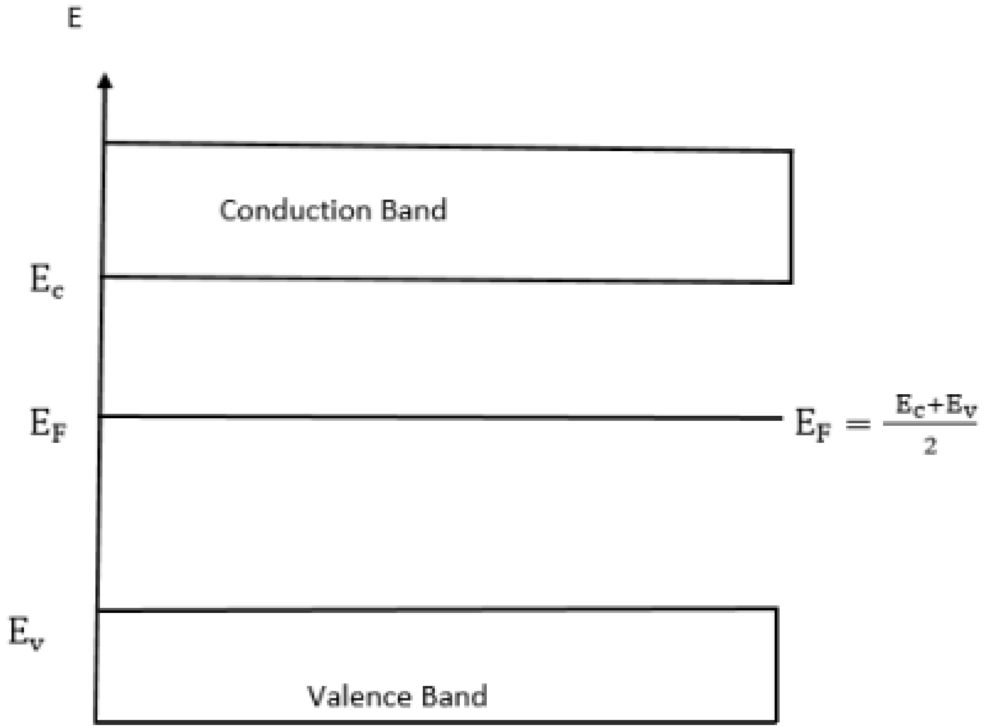
$$E_F = \frac{E_c + E_v}{2} + \frac{3}{4} K_B T \log_e\left(\frac{m_h^*}{m_e^*}\right)$$

Continue….

Since $m_e^* = m_h^*$

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

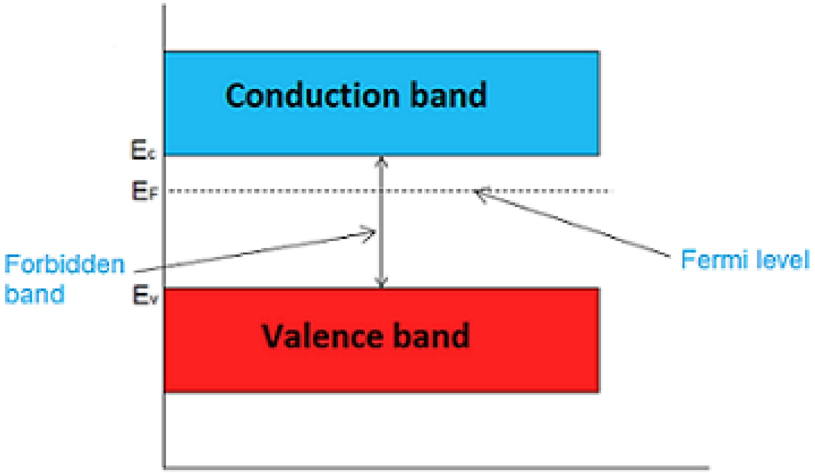
Thus, the Fermi level is located half way between the valence and conduction band and its position is independent of temperature. Since m_h^* is greater than m_e^*, E_F is just above the middle, and rises slightly with increase in temperature.



<u>Question</u>: Explain the position of fermi level in extrinsic semiconductor (5M)

Fermi level in n-type semiconductor

In n-type semiconductor pentavalent impurity is added. Each pentavalent impurity donates a free electron. The addition of pentavalent impurity creates large number of free electrons in the conduction band.



The Fermi level for n-type semiconductor is given as:

$$\boxed{E_F = E_C - K_B T \log \frac{N_C}{N_D}}$$

Where,

E_F is the fermi level.

E_C is the conduction band.

K_B is the Boltzmann constant.

T is the absolute temperature.

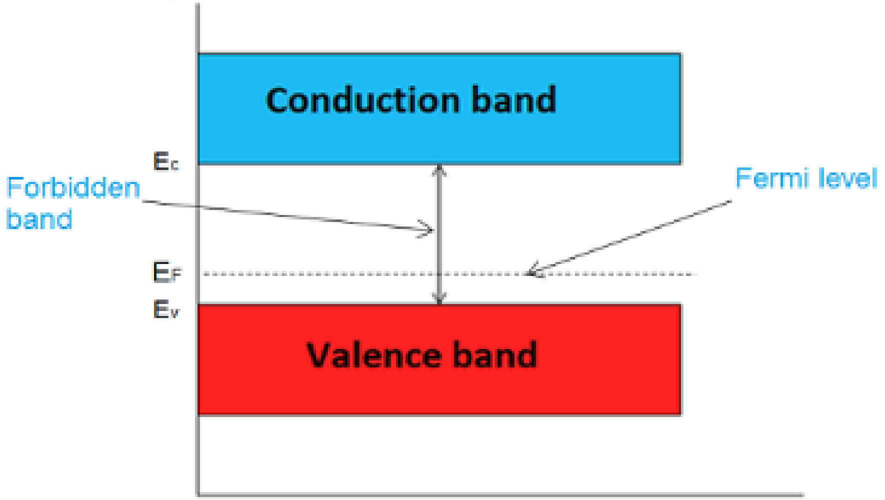
N_C is the effective density of states in the conduction band.

N_D is the concentration of donar atoms.

- **At room temperature, the number of electrons in the conduction band is greater than the number of holes in the valence band. Hence, the probability of occupation of energy levels by the electrons in the conduction band is greater than the probability of occupation of energy levels by the holes in the valence band.**
- **This probability of occupation of energy levels is represented in terms of Fermi level. Therefore, the Fermi level in the n-type semiconductor lies close to the conduction band.**

Fermi level in p-type semiconductor

In p-type semiconductor trivalent impurity is added. Each trivalent impurity creates a hole in the valence band and ready to accept an electron. The addition of trivalent impurity creates large number of holes in the valence band.



The Fermi level for p-type semiconductor is given as:

$$\boxed{E_F = E_V + K_B T \log \frac{N_V}{N_A}}$$

Where,
N_V is the effective density of states in the valence band.
N_A is the concentration of acceptor atoms.

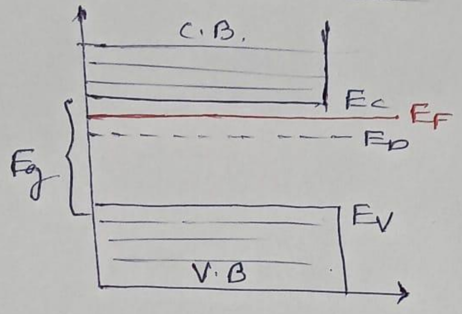
- At room temperature, the number of holes in the valence band is greater than the number of electrons in the conduction band. Hence, the probability of occupation of energy levels by the holes in the valence band is greater than the probability of occupation of energy levels by the electrons in the conduction band.
- This probability of occupation of energy levels is represented in terms of Fermi level. Therefore, the Fermi level in the p-type semiconductor lies close to the valence band.

Question: Draw the fermi position in extrinsic semiconductors (3M)

Ans:

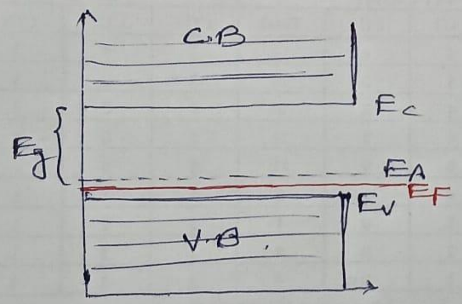
Position of Fermi level in Extrinsic Semiconductor:-

For N-type-semiconductor-



In N-type semiconductor fermi level lies near the Conduction band.
Mostly between doner level (E_D) and E_c. (Conduction Band)

For P-type - Semiconductor-



In-P-type semiconductor fermi-level lies near the Valence band.
Mostly between Accepter level (E_A) and Valence level (E_V).