

SOLIDS AND SEMICONDUCTOR DEVICES - I

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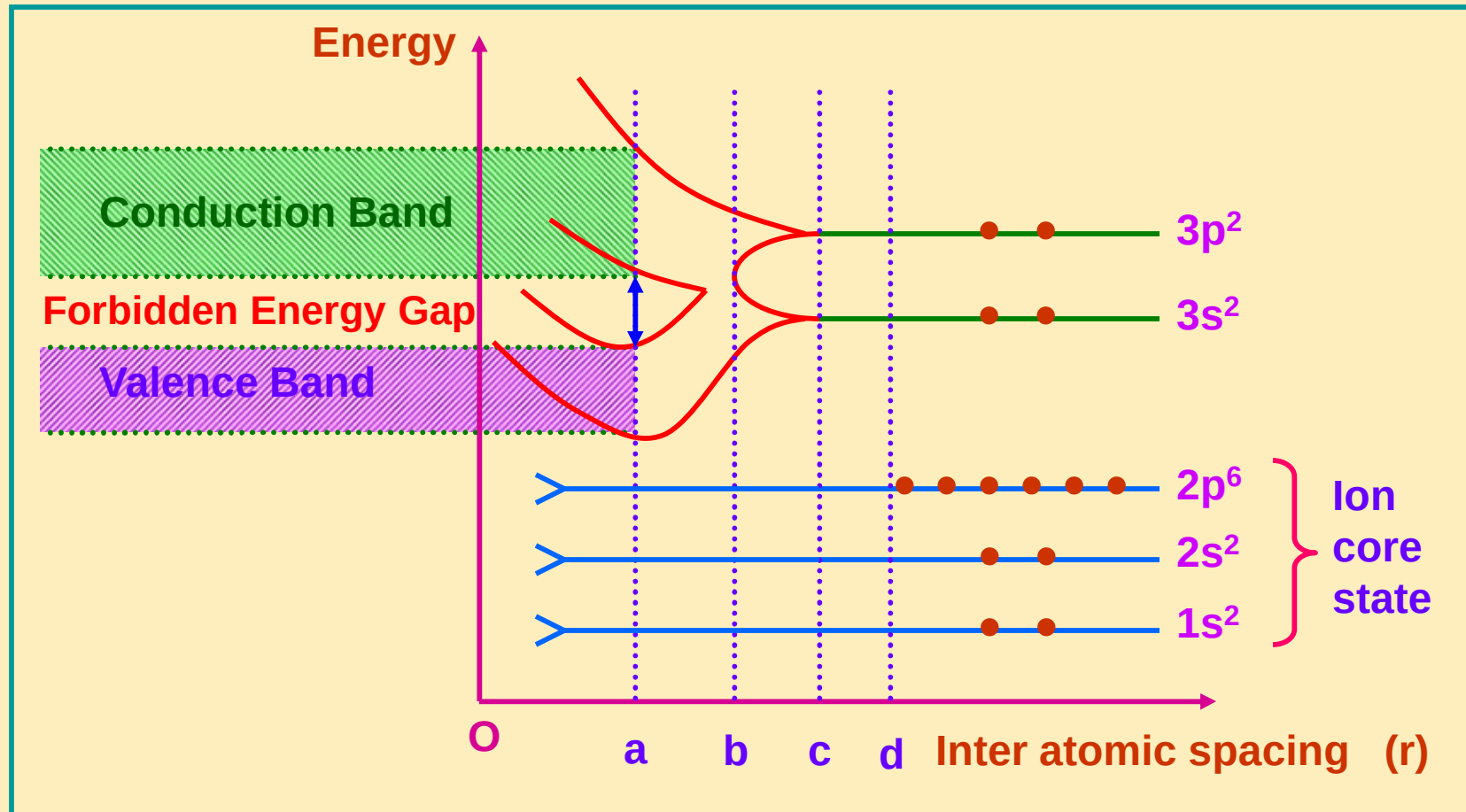
Energy Bands in Solids:

- According to **Quantum Mechanical Laws**, the **energies of electrons** in a free atom can not have arbitrary values but only **some definite (quantized) values**.
- However, if an atom belongs to a **crystal**, then the **energy levels are modified**.
- This modification is **not appreciable** in the case of energy levels of electrons in the **inner shells** (completely filled).
- But in the **outermost shells**, **modification is appreciable** because the electrons are shared by many neighbouring atoms.
- Due to **influence of high electric field** between the core of the atoms and the shared electrons, **energy levels are split-up or spread out forming energy bands**.

Consider a single crystal of silicon having N atoms. Each atom can be associated with a lattice site.

Electronic configuration of Si is $1s^2, 2s^2, 2p^6, 3s^2, 3p^2$. (Atomic No. is 14)

Formation of Energy Bands in Solids:



(i) $r = O_d (>> O_a)$:

Each of N atoms has its own energy levels. The energy levels are identical, sharp, discrete and distinct.

The outer two sub-shells (3s and 3p of M shell or $n = 3$ shell) of silicon atom contain two s electrons and two p electrons. So, there are $2N$ electrons completely filling $2N$ possible s levels, all of which are at the same energy.

Of the $6N$ possible p levels, only $2N$ are filled and all the filled p levels have the same energy.

(ii) $O_c < r < O_d$:

There is no visible splitting of energy levels but there develops a tendency for the splitting of energy levels.

(iii) $r = O_c$:

The interaction between the outermost shell electrons of neighbouring silicon atoms becomes appreciable and the splitting of the energy levels commences.

(iv) $O_b < r < O_c$:

The energy corresponding to the s and p levels of each atom gets slightly changed. Corresponding to a single s level of an isolated atom, we get $2N$ levels. Similarly, there are $6N$ levels for a single p level of an isolated atom.

Since N is a very large number ($\approx 10^{29}$ atoms / m^3) and the energy of each level is of a few eV, therefore, the levels due to the spreading are very closely spaced. The spacing is $\approx 10^{-23}$ eV for a 1 cm^3 crystal.

The collection of very closely spaced energy levels is called an **energy band**.

(v) $r = 0b$:

The energy gap disappears completely. $8N$ levels are distributed continuously. We can only say that $4N$ levels are filled and $4N$ levels are empty.

(v) $r = 0a$:

The band of $4N$ filled energy levels is separated from the band of $4N$ unfilled energy levels by an energy gap called **forbidden gap** or **energy gap** or **band gap**.

The lower completely filled band (with valence electrons) is called the **valence band** and the upper unfilled band is called the **conduction band**.

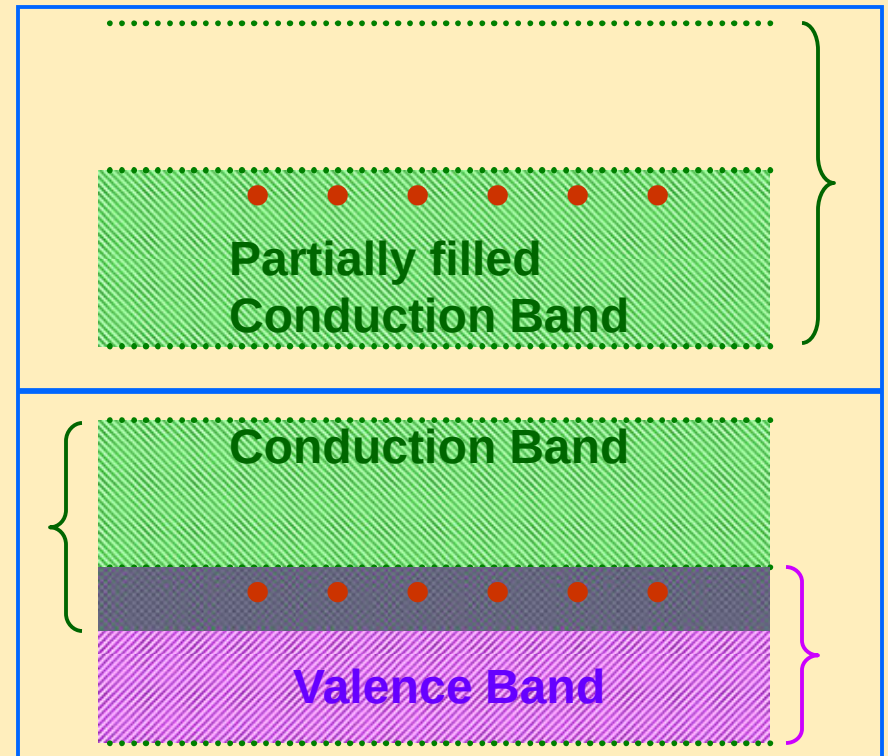
Note:

1. The exact energy band picture depends on the relative orientation of atoms in a crystal.
2. If the bands in a solid are completely filled, the electrons are not permitted to move about, because there are no vacant energy levels available.

Metals:

The first possible energy band diagram shows that the conduction band is only partially filled with electrons.

With a little extra energy the electrons can easily reach the empty energy levels above the filled ones and the conduction is possible.



The second possible energy band diagram shows that the conduction band is overlapping with the valence band.

This is because the lowest levels in the conduction band needs less energy than the highest levels in the valence band.

The electrons in valence band overflow into conduction band and are free to move about in the crystal for conduction.

The highest energy level in the conduction band occupied by electrons in a crystal, at absolute 0 temperature, is called **Fermi Level**.

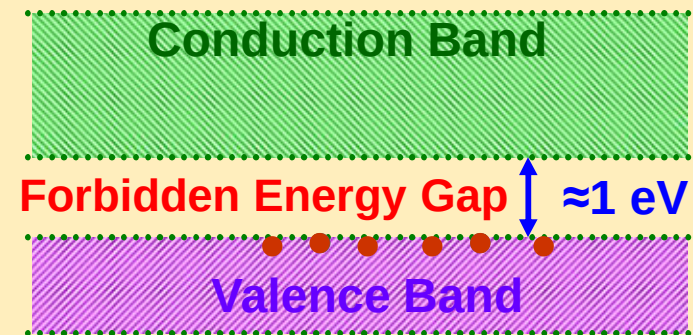
The energy corresponding to this energy level is called **Fermi energy**.

If the electrons get enough energy to go beyond this level, then conduction takes place.

Semiconductors:

At absolute zero temperature, no electron has energy to jump from valence band to conduction band and hence the crystal is an insulator.

At room temperature, some valence electrons gain energy more than the energy gap and move to conduction band to conduct even under the influence of a weak electric field.



$$E_{g-Si} = 1.1 \text{ eV} \quad E_{g-Ge} = 0.74 \text{ eV}$$

The fraction is $p \propto e^{-\frac{E_g}{k_B T}}$

Since E_g is small, therefore, the fraction is sizeable for semiconductors.

As an electron leaves the valence band, it leaves some energy level in band as unfilled.

Such unfilled regions are termed as 'holes' in the valence band. They are mathematically taken as positive charge carriers.

Any movement of this region is referred to a positive hole moving from one position to another.

Insulators:

Electrons, however heated, can not practically jump to conduction band from valence band due to a **large energy gap**. Therefore, conduction is not possible in insulators.

$$E_{g-\text{Diamond}} = 7 \text{ eV}$$

Electrons and Holes:

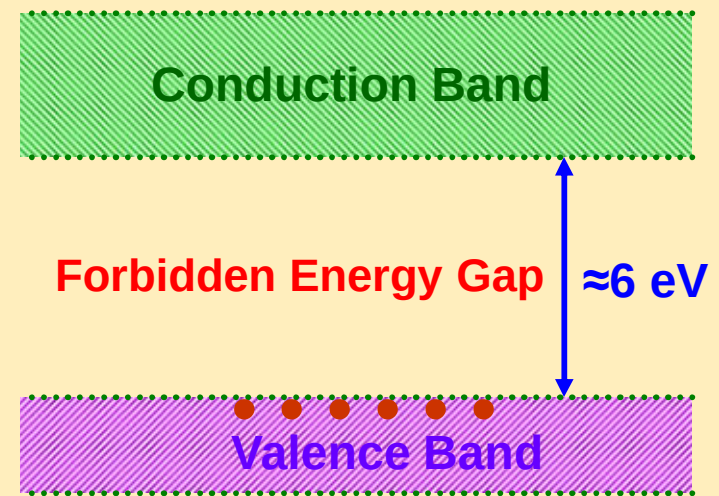
On receiving an additional energy, one of the electrons from a covalent band breaks and is free to move in the crystal lattice.

While coming out of the covalent bond, it leaves behind a vacancy named 'hole'.

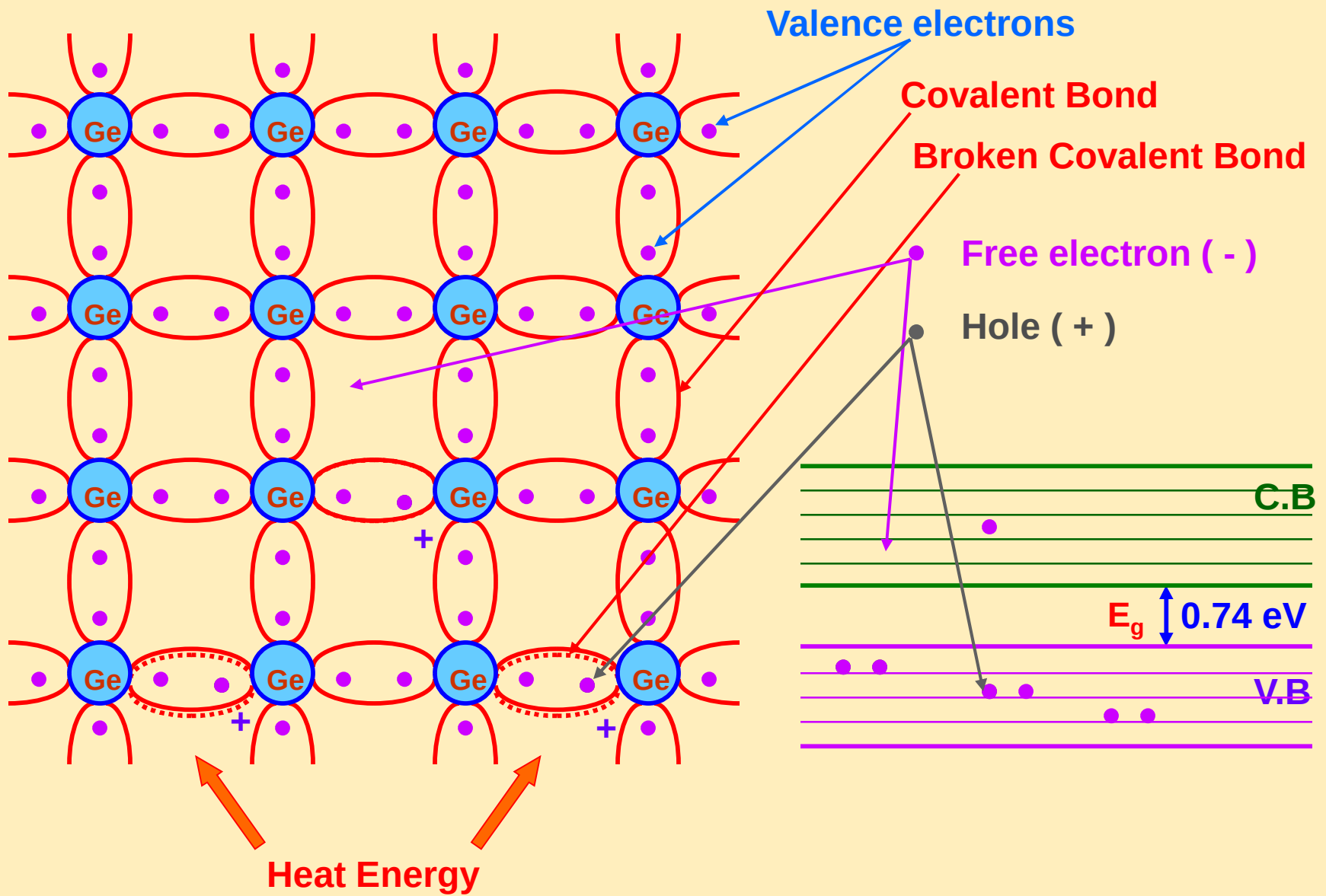
An electron from the neighbouring atom can break away and can come to the place of the missing electron (or hole) completing the covalent bond and creating a hole at another place.

The holes move randomly in a crystal lattice.

The completion of a bond may not be necessarily due to an electron from a bond of a neighbouring atom. The bond may be completed by a conduction band electron. i.e., free electron and this is referred to as '**electron – hole recombination**'.



Intrinsic or Pure Semiconductor:



Intrinsic Semiconductor is a pure semiconductor.

The energy gap in Si is 1.1 eV and in Ge is 0.74 eV.

Si: $1s^2, 2s^2, 2p^6, 3s^2, 3p^2$. (Atomic No. is 14)

Ge: $1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 3d^{10}, 4s^2, 4p^2$. (Atomic No. is 32)

In intrinsic semiconductor, the number of thermally generated electrons always equals the number of holes.

So, if n_i and p_i are the concentration of electrons and holes respectively, then $n_i = p_i$.

The quantity n_i or p_i is referred to as the 'intrinsic carrier concentration'.

Doping a Semiconductor:

Doping is the process of deliberate addition of a very small amount of impurity into an intrinsic semiconductor.

The impurity atoms are called 'dopants'.

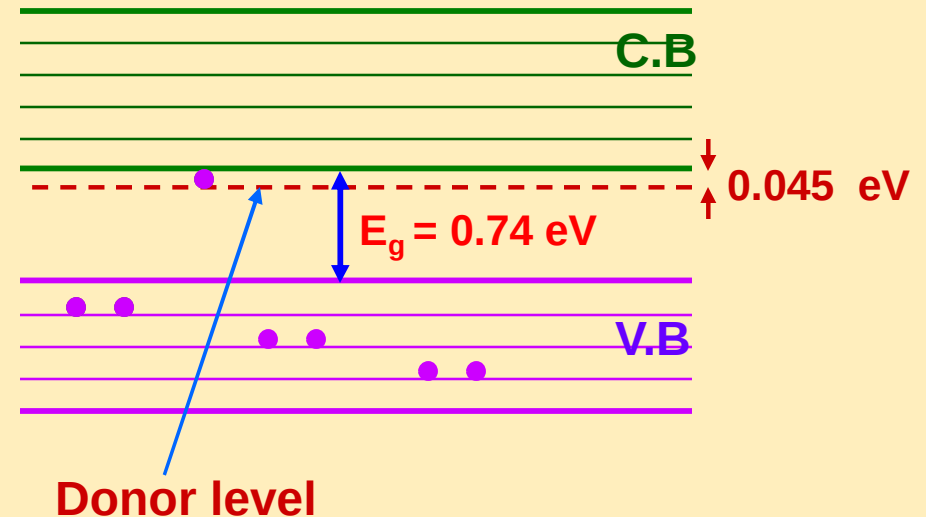
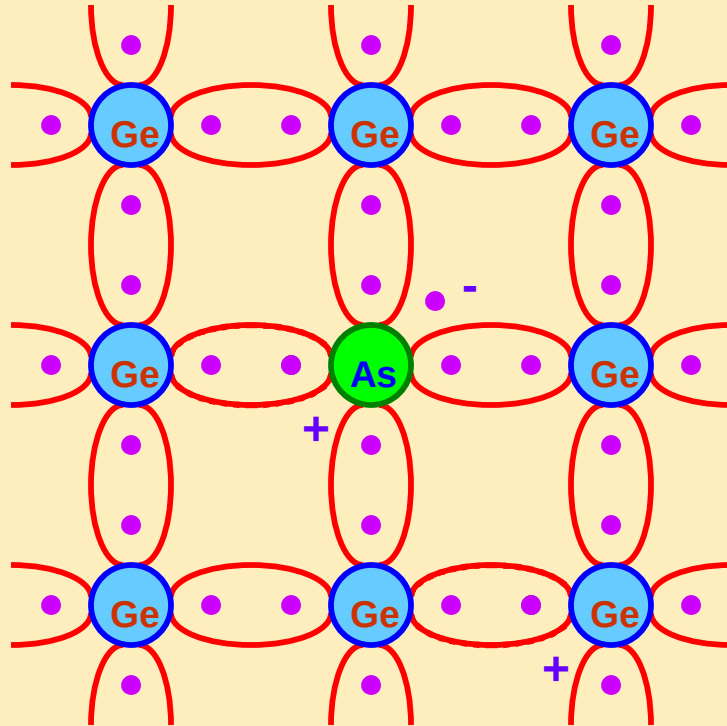
The semiconductor containing impurity is known as 'impure or extrinsic semiconductor'.

Methods of doping:

- i) Heating the crystal in the presence of dopant atoms.**
- ii) Adding impurity atoms in the molten state of semiconductor.**
- iii) Bombarding semiconductor by ions of impurity atoms.**

Extrinsic or Impure Semiconductor:

N - Type Semiconductors:



When a semiconductor of Group IV (tetra valent) such as Si or Ge is doped with a penta valent impurity (Group V elements such as P, As or Sb), N – type semiconductor is formed.

When germanium (Ge) is doped with arsenic (As), the four valence electrons of As form covalent bonds with four Ge atoms and the fifth electron of As atom is loosely bound.

The energy required to detach the fifth loosely bound electron is only of the order of 0.045 eV for germanium.

A small amount of energy provided due to thermal agitation is sufficient to detach this electron and it is ready to conduct current.

The force of attraction between this mobile electron and the positively charged (+ 5) impurity ion is weakened by the dielectric constant of the medium.

So, such electrons from impurity atoms will have energies slightly less than the energies of the electrons in the conduction band.

Therefore, the energy state corresponding to the fifth electron is in the forbidden gap and slightly below the lower level of the conduction band.

This energy level is called 'donor level'.

The impurity atom is called 'donor'.

N – type semiconductor is called 'donor – type semiconductor'.

Carrier Concentration in N - Type Semiconductors:

When intrinsic semiconductor is doped with donor impurities, not only does the number of electrons increase, but also the number of holes decreases below that which would be available in the intrinsic semiconductor.

The number of holes decreases because the larger number of electrons present causes the rate of recombination of electrons with holes to increase.

Consequently, in an N-type semiconductor, free electrons are the majority charge carriers and holes are the minority charge carriers.

If n and p represent the electron and hole concentrations respectively in N-type semiconductor, then

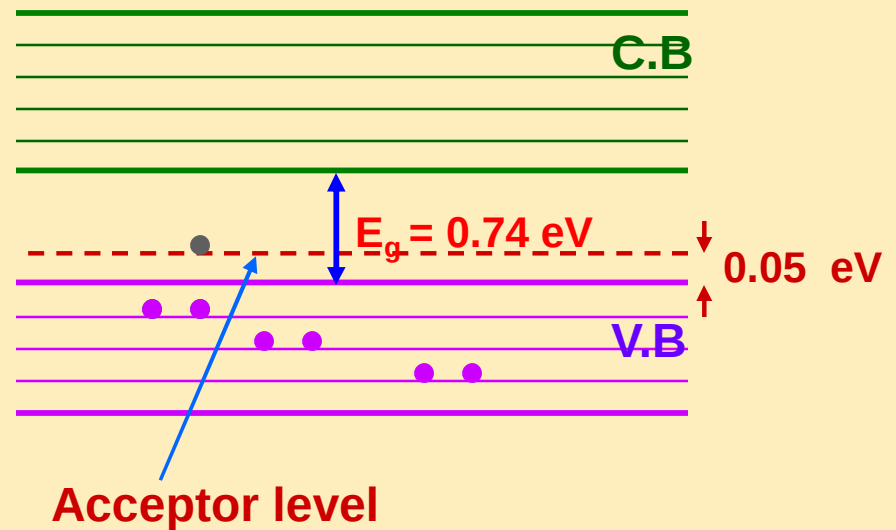
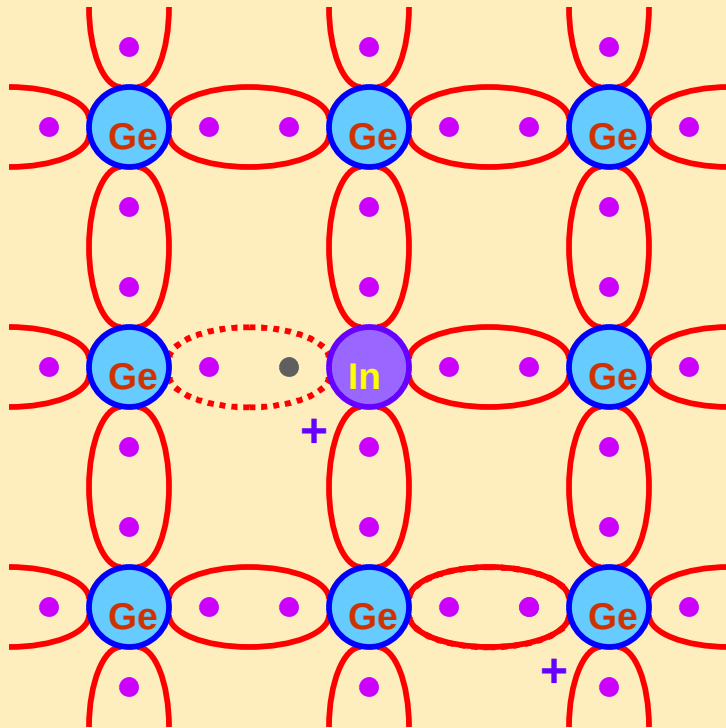
$$np = n_i p_i = n_i^2$$

where n_i and p_i are the intrinsic carrier concentrations.

The rate of recombination of electrons and holes is proportional to n and p . Or, the rate of recombination is proportional to the product np . Since the rate of recombination is fixed at a given temperature, therefore, the product np must be a constant.

When the concentration of electrons is increased above the intrinsic value by the addition of donor impurities, the concentration of holes falls below its intrinsic value, making the product np a constant, equal to n_i^2 .

P - Type Semiconductors:



When a semiconductor of Group IV (tetra valent) such as Si or Ge is doped with a tri valent impurity (Group III elements such as In, B or Ga), P – type semiconductor is formed.

When **germanium** (Ge) is doped with **indium** (In), the three valence electrons of In form three covalent bonds with three Ge atoms. The **vacancy** that exists with the fourth covalent bond with fourth Ge atom constitutes a **hole**.

The hole which is deliberately created may be filled with an electron from neighbouring atom, creating a hole in that position from where the electron jumped.

Therefore, the tri valent impurity atom is called 'acceptor'.

Since the **hole** is associated with a **positive charge** moving from one position to another, therefore, this type of semiconductor is called **P – type semiconductor**.

The acceptor impurity produces an energy level just above the valence band.

This energy level is called 'acceptor level'.

The energy difference between the acceptor energy level and the top of the valence band is much smaller than the band gap.

Electrons from the valence band can, therefore, easily move into the acceptor level by being thermally agitated.

P – type semiconductor is called 'acceptor – type semiconductor'.

In a **P – type semiconductor**, **holes** are the **majority charge carriers** and the **electrons** are the **minority charge carriers**.

It can be shown that,

$$n p = n_i p_i = n_i^2$$

Distinction between Intrinsic and Extrinsic Semiconductor:

S. No.	Intrinsic SC	Extrinsic SC
1	Pure Group IV elements.	Group III or Group V elements are introduced in Group IV elements.
2	Conductivity is only slight.	Conductivity is greatly increased.
3	Conductivity increases with rise in temperature.	Conductivity depends on the amount of impurity added.
4	The number of holes is always equal to the number of free electrons.	In N-type, the no. of electrons is greater than that of the holes and in P-type, the no. holes is greater than that of the electrons.

Distinction between Semiconductor and Metal:

S. No.	Semiconductor	Metal
1	Semiconductor behaves like an insulator at 0 K. Its conductivity increases with rise in temperature.	Conductivity decreases with rise in temperature.
2	Conductivity increases with rise in potential difference applied.	Conductivity is an intrinsic property of a metal and is independent of applied potential difference.
3	Does not obey Ohm's law or only partially obeys.	Obeys Ohm's law.
4	Doping the semiconductors with impurities vastly increases the conductivity.	Making alloy with another metal decreases the conductivity.

Electrical Conductivity of Semiconductors:

$$I = I_e + I_h$$

$$I_e = n_e e A v_e \quad I_h = n_h e A v_h$$

$$\text{So, } I = n_e e A v_e + n_h e A v_h$$

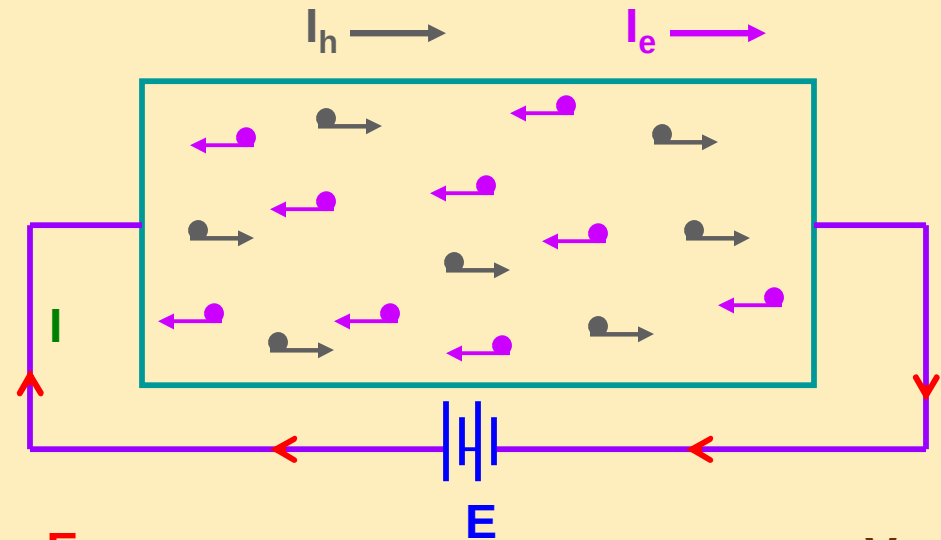
If the applied electric field is small, then semiconductor obeys Ohm's law.

$$\begin{aligned} \therefore \frac{V}{R} &= n_e e A v_e + n_h e A v_h \\ &= e A (n_e v_e + n_h v_h) \end{aligned}$$

$$\begin{aligned} \text{Or } \frac{V A}{\rho l} &= e A (n_e v_e + n_h v_h) \\ \text{since } R &= \frac{\rho l}{A} \end{aligned}$$

Note:

1. The electron mobility is higher than the hole mobility.
2. The resistivity / conductivity depends not only on the electron and hole densities but also on their mobilities.
3. The mobility depends relatively weakly on temperature.



$$\frac{E}{\rho} = e (n_e v_e + n_h v_h) \quad \text{since } E = \frac{V}{l}$$

Mobility (μ) is defined as the drift velocity per unit electric field.

$$\therefore \frac{1}{\rho} = e (n_e \mu_e + n_h \mu_h)$$

Or

$$\sigma = e (n_e \mu_e + n_h \mu_h)$$

End of S & SC - I