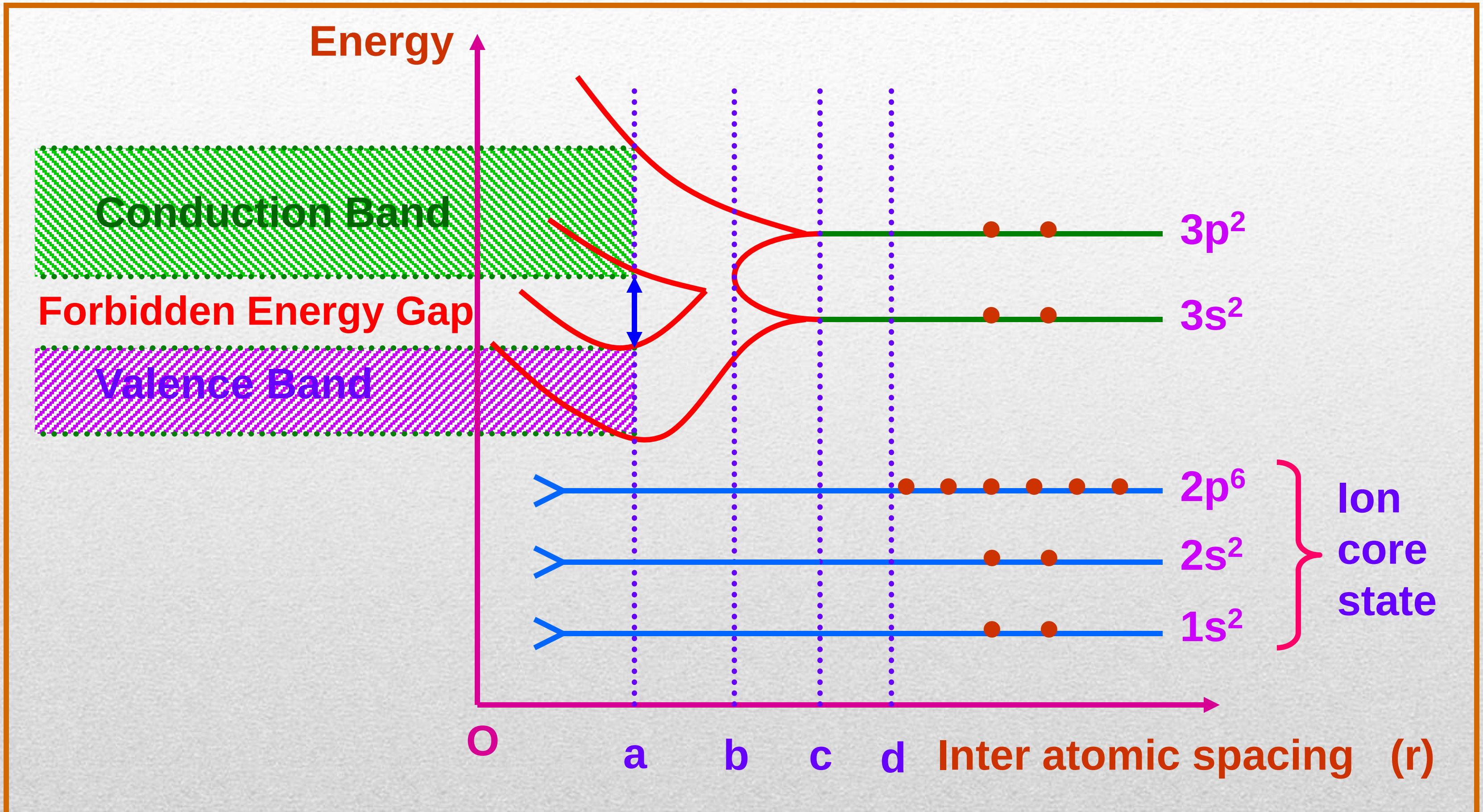
Energy Bands in Solids

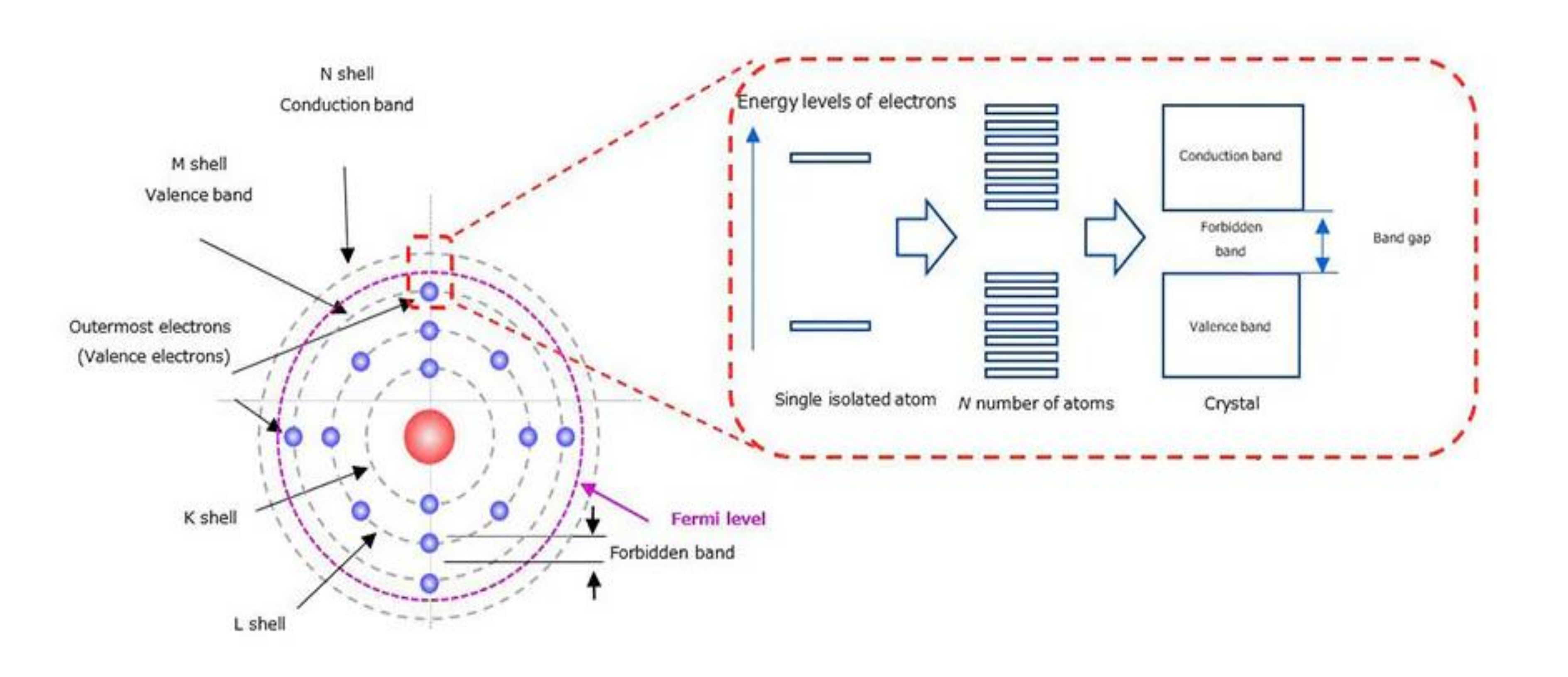
- According to Quantum Mechanical Laws, the energies of electrons in a free atom can not have arbitrary values but only some definite (quantized) values.
- However, if an atom belongs to a crystal, then the energy levels are modified.
- This modification is not appreciable in the case of the inner shells (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.

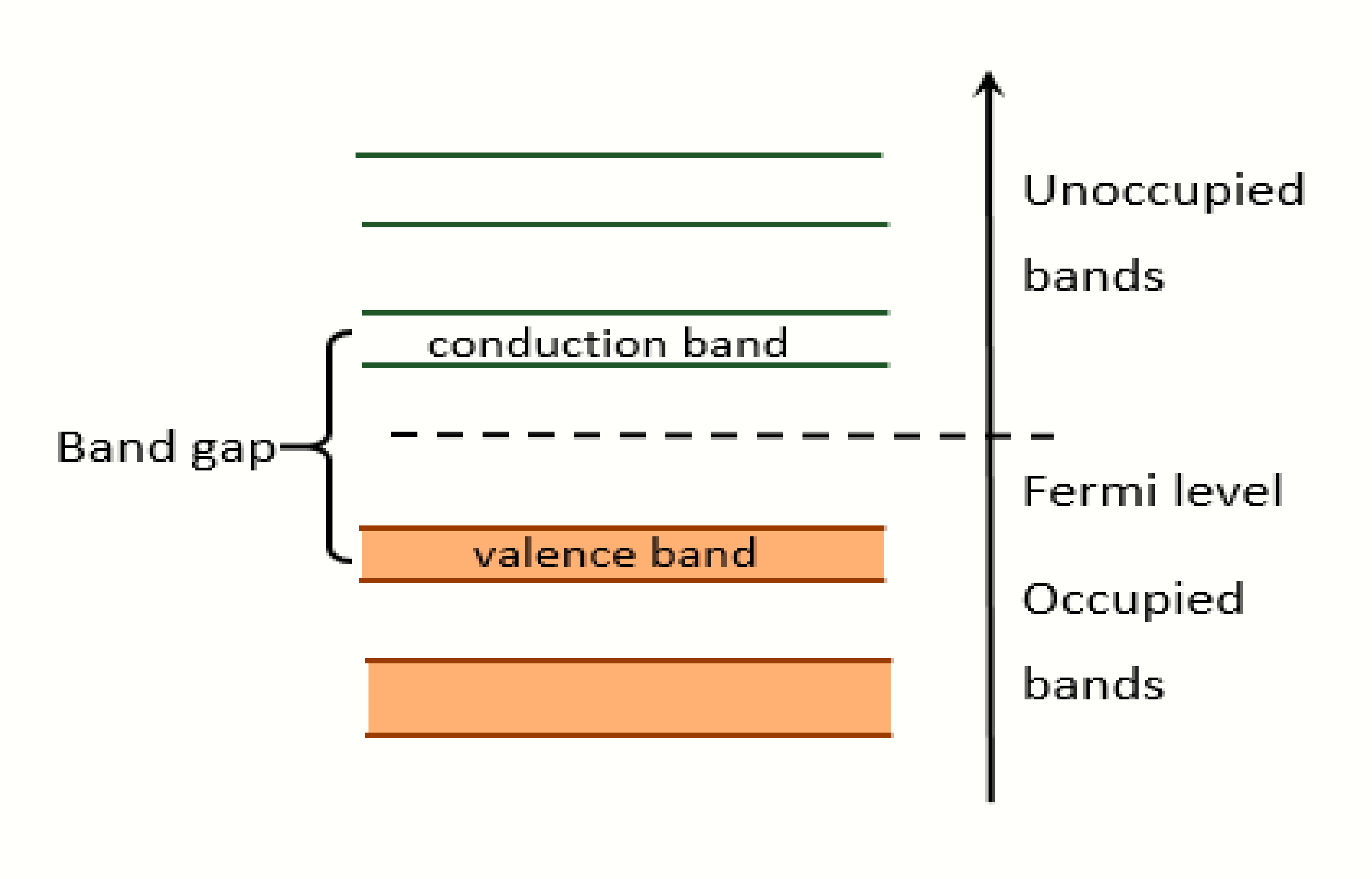
Formation of Energy Bands in Solids:

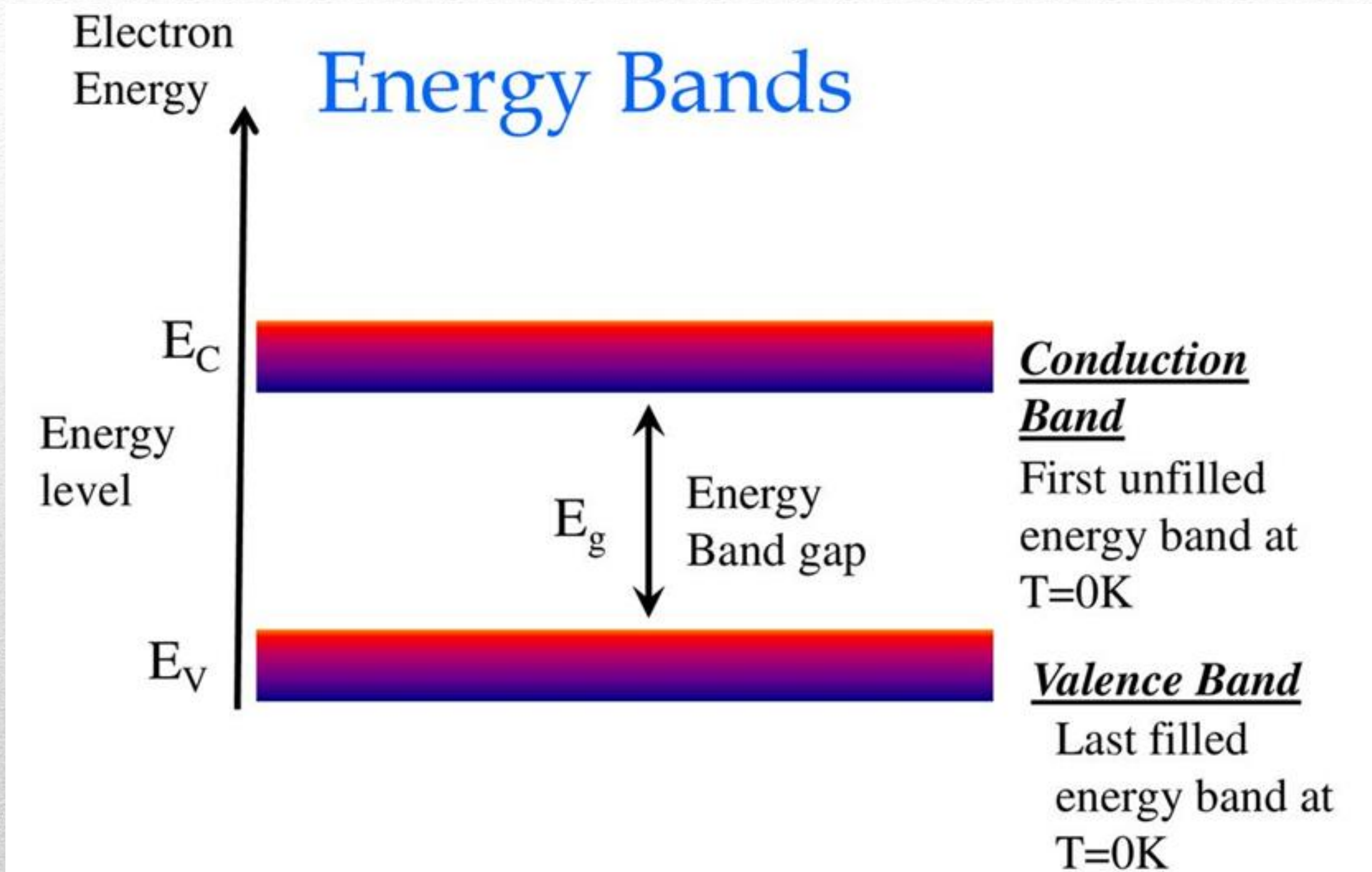


The highest energy level in the conduction band occupied by electrons in a crystal, at absolute 0 temperature, is called **Fermi Level.**

The energy corresponding to this energy level is called Fermi energy (Ef).




Unoccupied
bands
conduction band
Band gap
Fermi level
valence band
Occupied
bands


Energy Bands
Electron Energy
E_C
Energy level
E_g
Energy Band gap
E_V
Conduction Band
First unfilled energy band at T=0K
Valence Band
Last filled energy band at T=0K

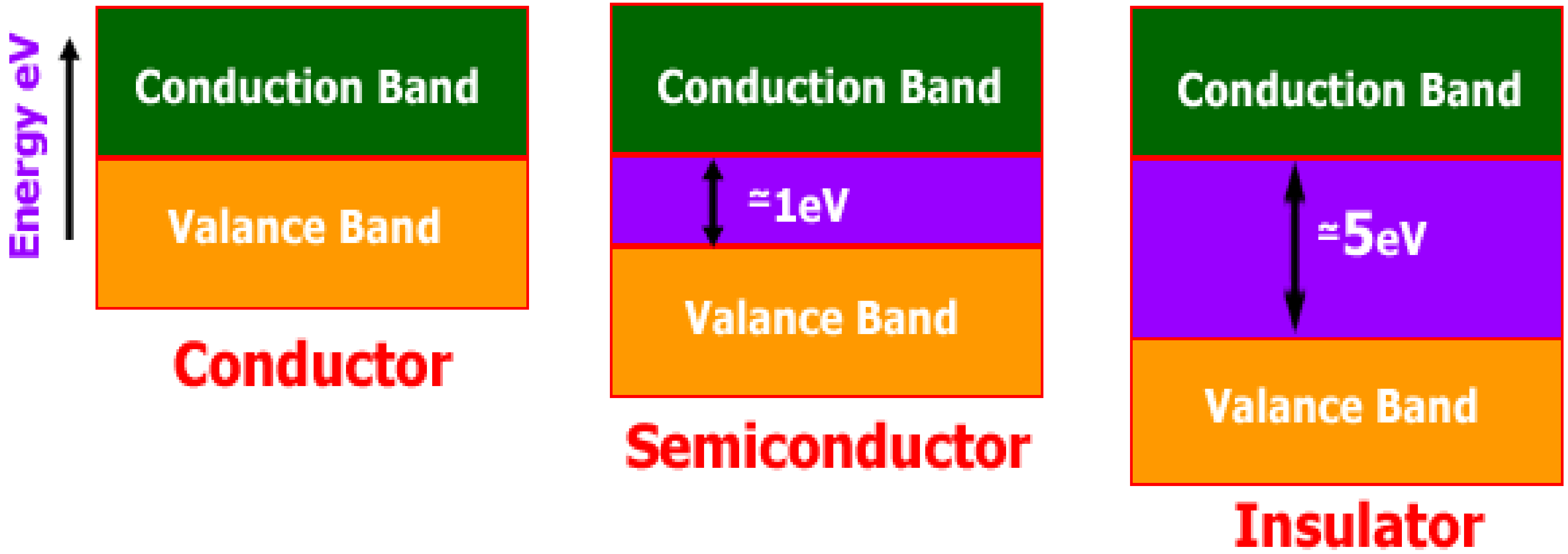


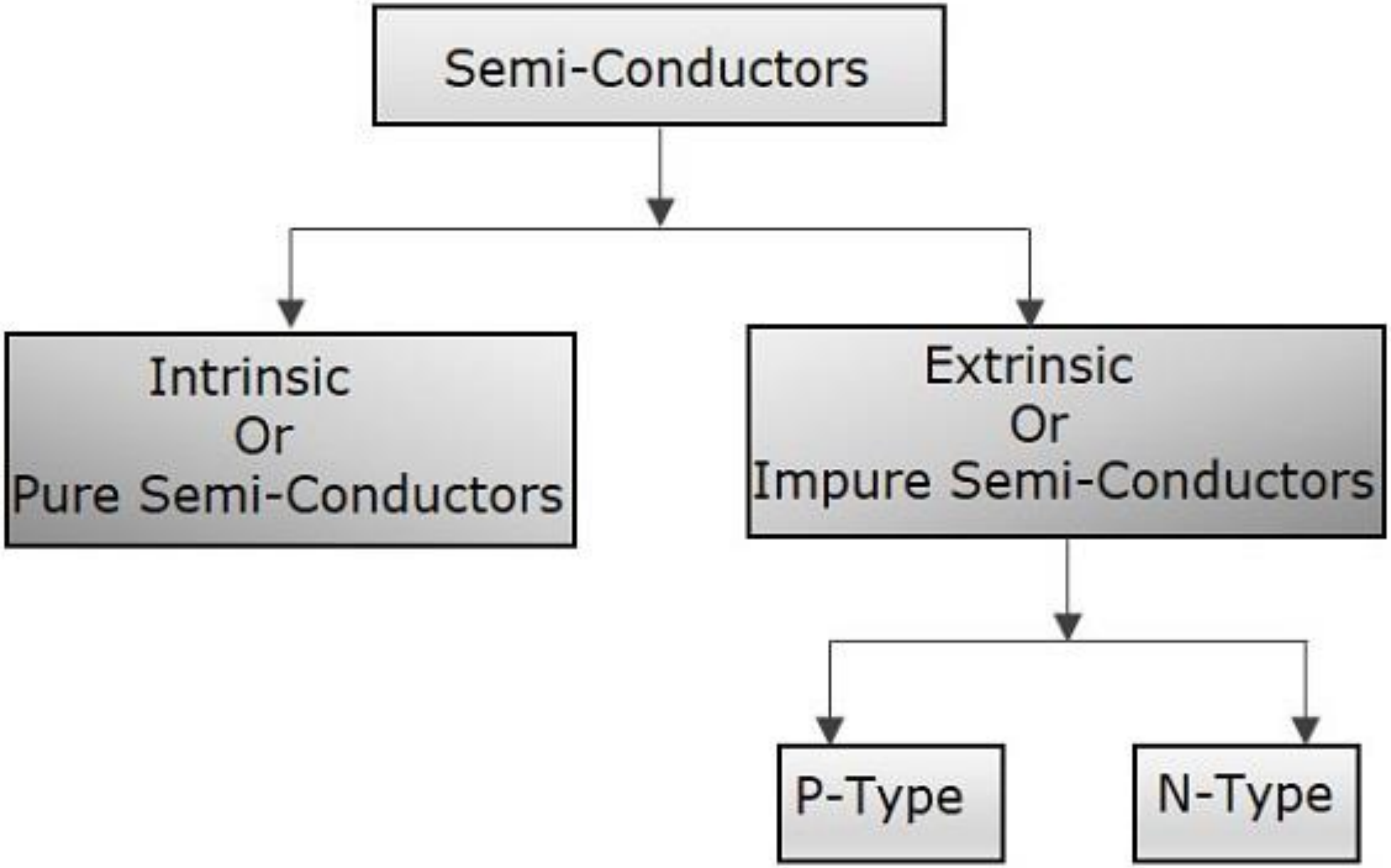
Fig: Classification of Solids on the basis of electricity Conduction

Semiconductors

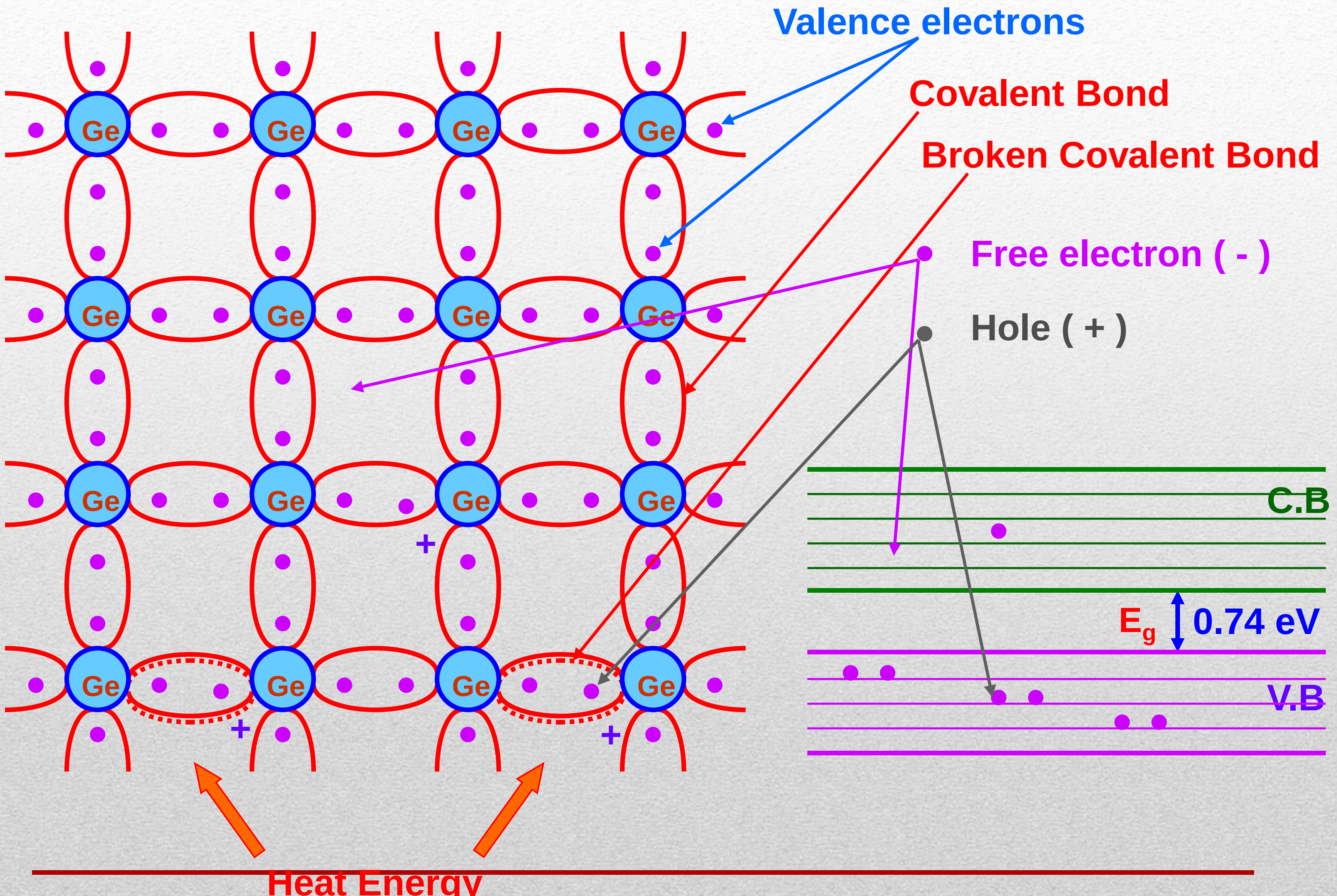
- Semiconductors are materials having energy band gap in between conductors and insulators (approximately 1eV)

- They have a conductivity between conductors (generally metals) and nonconductors or insulators (such as most ceramics).

- Semiconductors can be pure elements, such as silicon or germanium, or compounds such as gallium arsenide or cadmium selenide.


Semi-Conductors
Intrinsic
Or
Pure Semi-Conductors
Extrinsic
Or
Impure Semi-Conductors
P-Type
N-Type

Intrinsic or Pure Semiconductor:

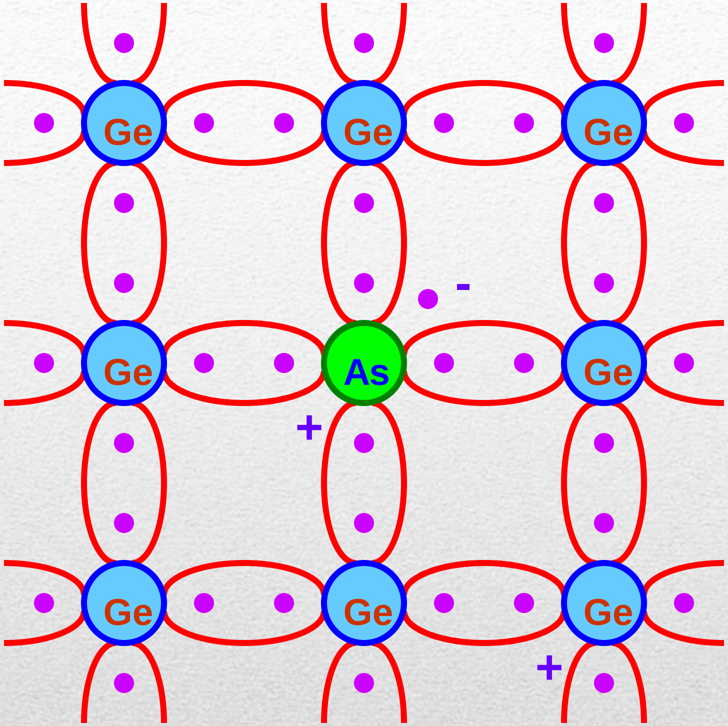


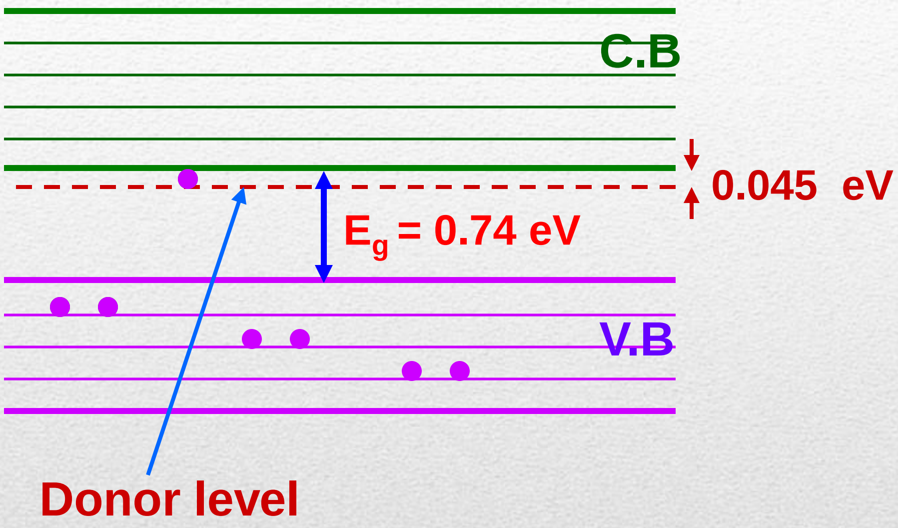
DOPING IN SEMICONDUCTORS

- **Semiconducting materials are very sensitive to impurities in the crystal lattice**.
- **The controlled addition of these impurities is known as doping.**
- **Allows the tuning of the electronic properties: technological applications**.
- **Introduction of dopants → 'extrinsic semiconductors'**.
- **Introduction of dopants → (i) new intra-band, energy levels**

  (ii) Generation of positive or negative charge carriers.

N - Type Semiconductors:





When a semiconductor of Group IV (tetra valent) such as Si or Ge is doped with a pentavalent 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.

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

Therefore 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

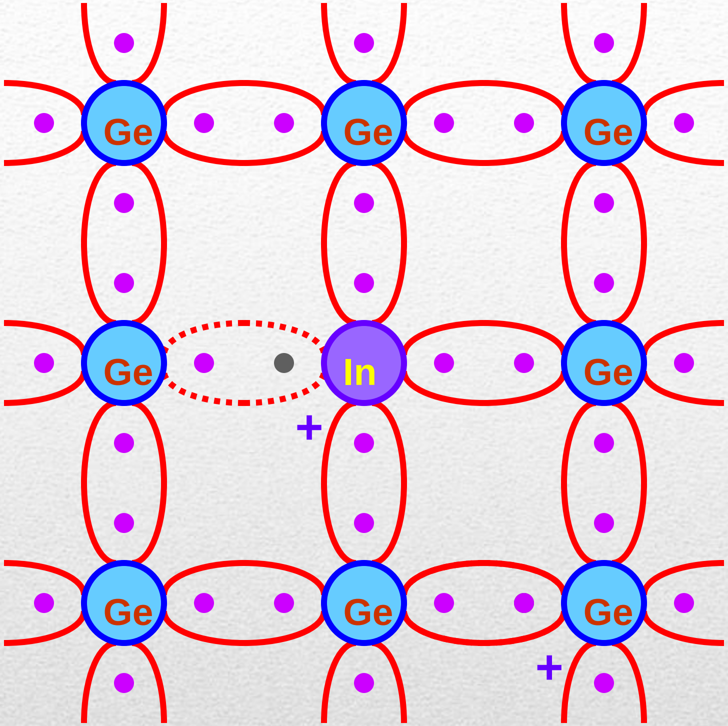
$$\boxed{n\,p = n_i\,p_i = n_i^2}$$

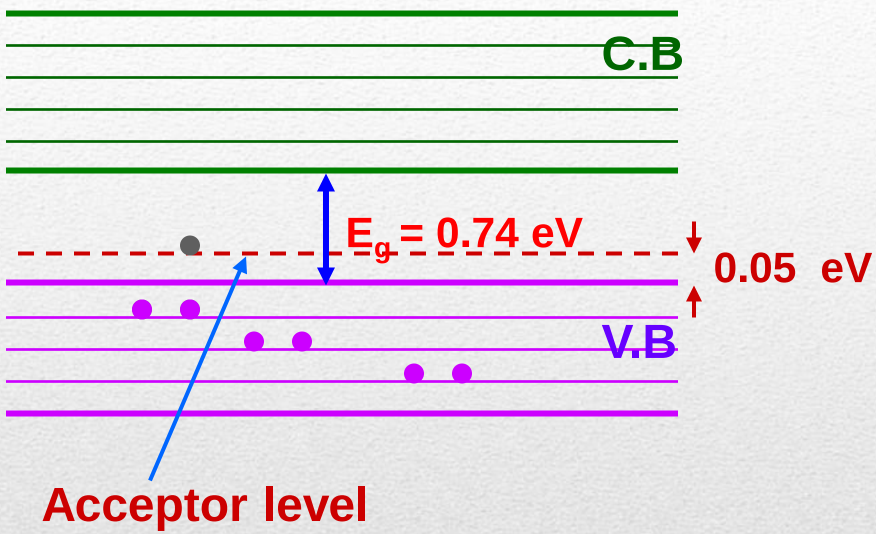
where n_i and p_i are the intrinsic carrier concentrations.

The rate of recombination of electrons and holes is proportional to n and p.

Since the rate of recombination is fixed at a given temperature, therefore, the product np must be a constant.

P - Type Semiconductors





When a semiconductor of Group IV (tetra valent) such as Si or Ge is doped with a trivalent 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 may be filled with an electron from neighbouring atom, creating a hole in that position from where the electron jumped.

Therefore, the trivalent 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,

$$\boxed{n\,p = n_i\,p_i = n_i^2}$$

Electron and Hole Density

The number of electrons in conduction band at temperature T is given by

$$\boxed{n = N_C e^{-(E_C - E_F)/kT}}$$

Where

$$N_C = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$$

The number of holes in valence band at temperature T is given by

$$\boxed{p = N_V e^{-(E_F - E_V)/kT}}$$

Where

$$N_V = 2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{3/2}$$

POSITION OF FERMI LEVEL IN INTRINSIC SC

Let, n be the number of electrons in the semiconductor band.
p be the number of holes in the valence band.
At temperature T > 0 K

$$n = N_c e^{-(E_c - E_F)/kT} \qquad p = N_v e^{-(E_F - E_V)/kT}$$

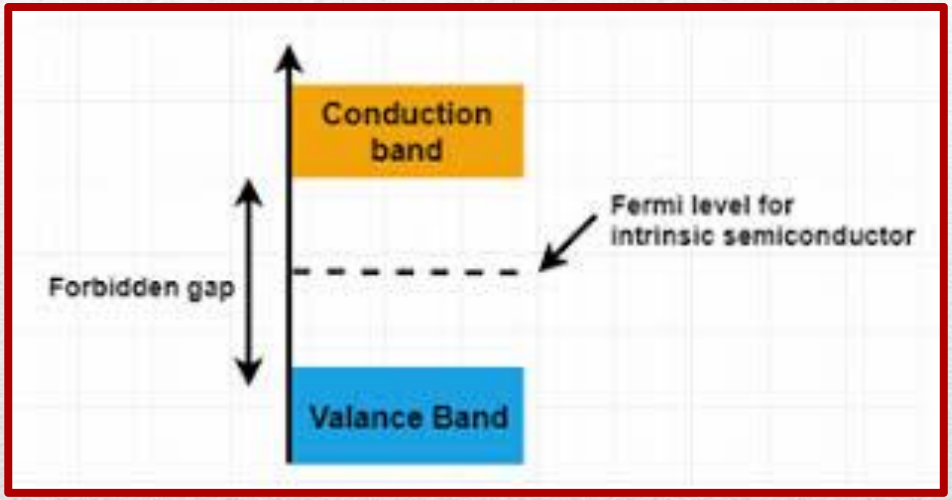
N_c is the effective density of states in the conduction band and N_v is the effective density of states in the valence band. For an intrinsic semiconductor, $n_e = n_v$

$$N_c e^{-(E_c - E_F)/kT} = N_v e^{-(E_F - E_v)/kT} \Rightarrow \frac{N_C}{N_v} = \frac{e^{-(E_F - E_V)/kT}}{e^{-(E_c - E_F)/kT}}$$

$$\Rightarrow e^{\frac{-(2E_F - E_V - E_C)}{kT}} = 1 \qquad \text{as } N_c = N_v$$

Taking log on both sides, we get $\frac{E_c + E_v - 2E_F}{kT} = 0 \Rightarrow \boxed{E_F = \frac{E_C + E_V}{2}}$

∴ Fermi level in an intrinsic SC →at the centre of the band gap.



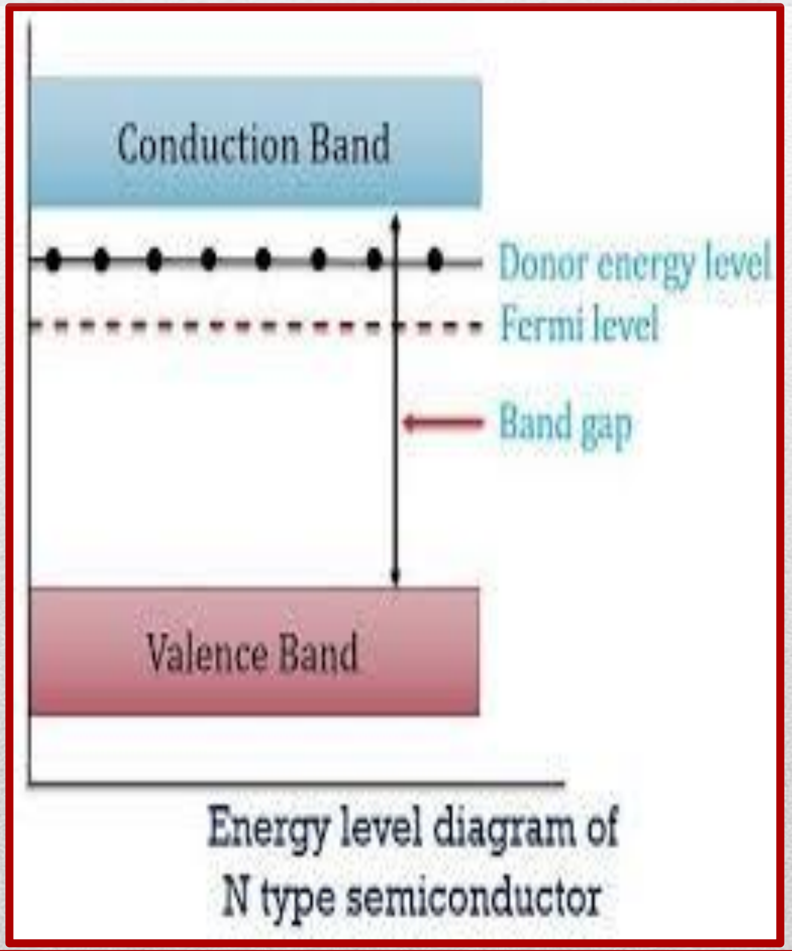
$$E_F = \frac{E_C + E_V}{2}$$

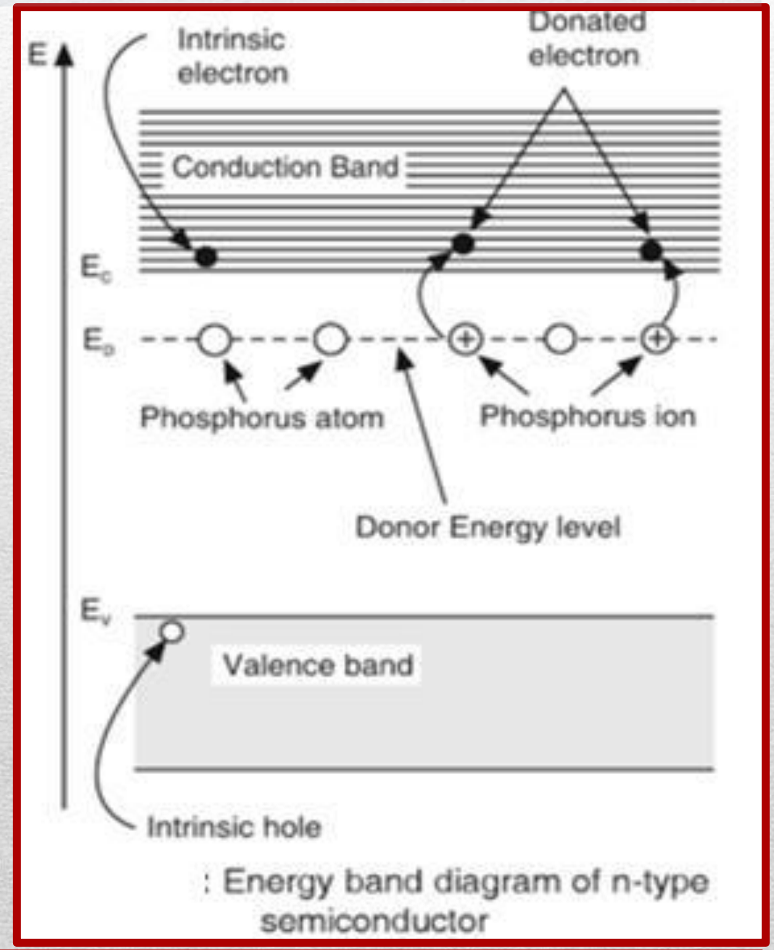
Show that carrier concentration depends exponentially on the band gap and is given as

$$n_i = \sqrt{N_c N_v}\exp\left(-\frac{E_g}{2KT}\right)$$

FERMI LEVEL IN EXTRINSIC SC

N-type SC- pentavalent impurity : electrons as majority charge carriers: donor impurities





https://sites.google.com/site/puenggphysics/home/unit-5/fermi-level-of-extrinsic-semiconductor