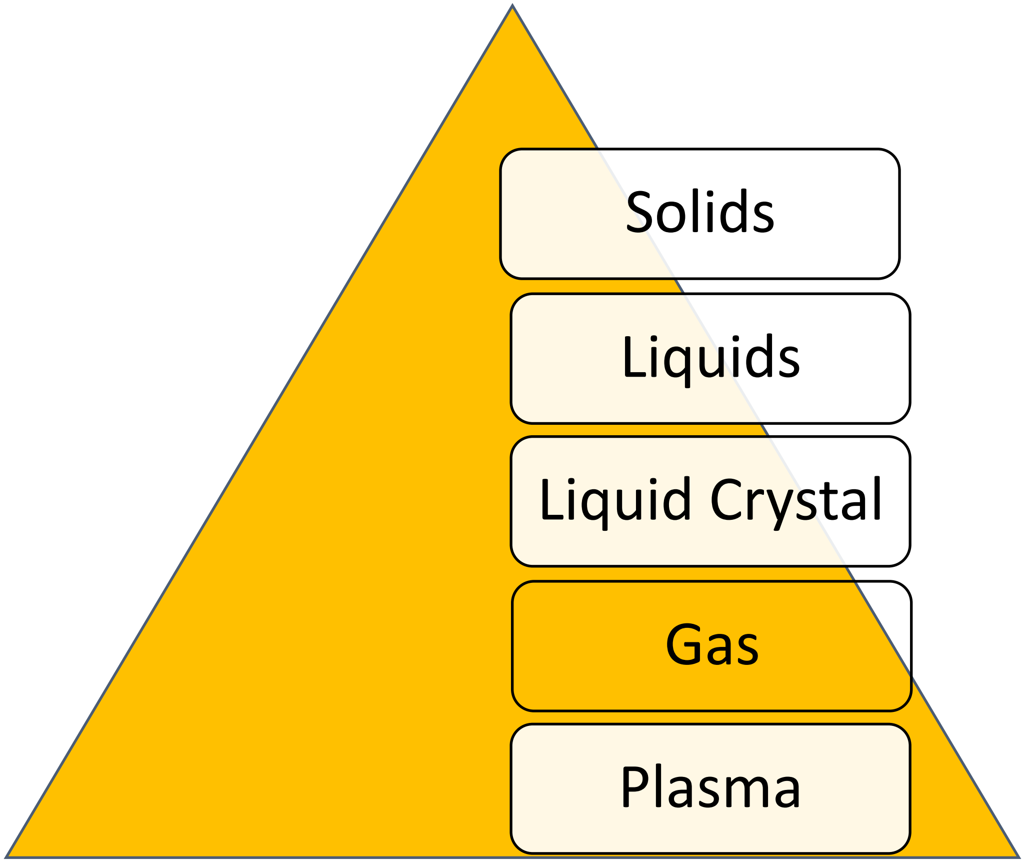
PHYSICS OF SEMICONDUCTORS

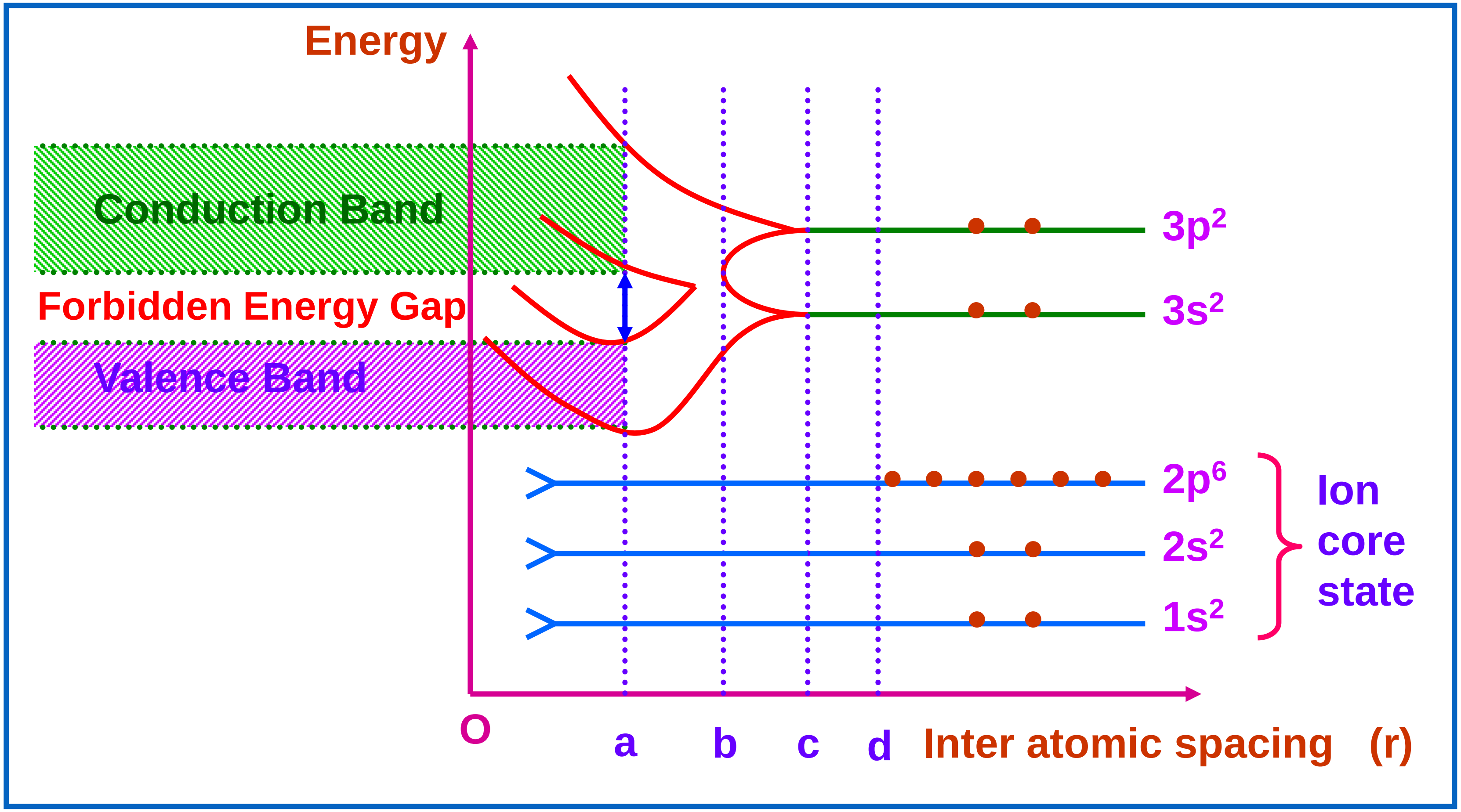
STATES OF MATTER



Energy Bands in Solids

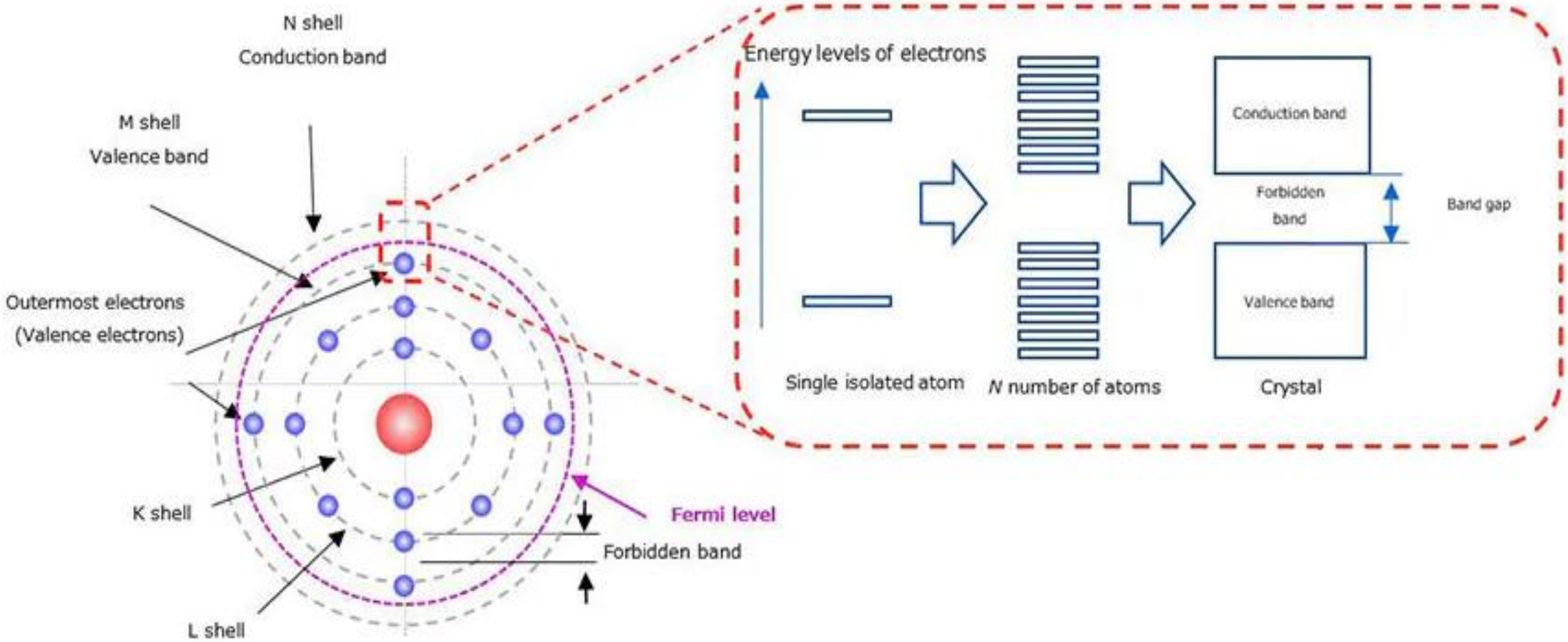
- According to Quantum Mechanical Laws, the energies of electrons in a free atom can not have arbitrary values but only some definite (quantized) values.
- However, if an atom belongs to a crystal, then the energy levels are modified.
- This modification is not appreciable in the case of the inner shells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

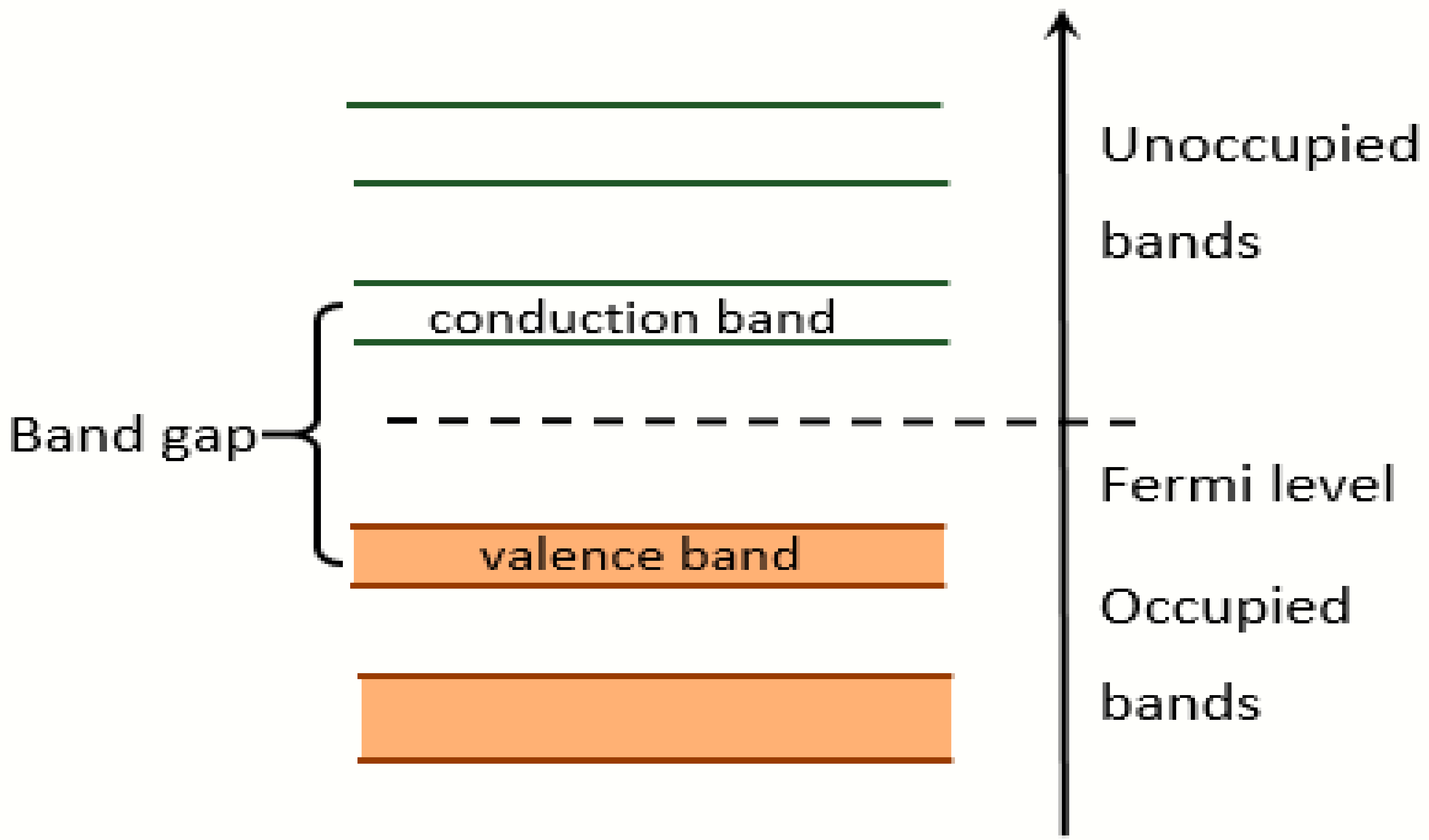
Formation of Energy Bands in Solids:



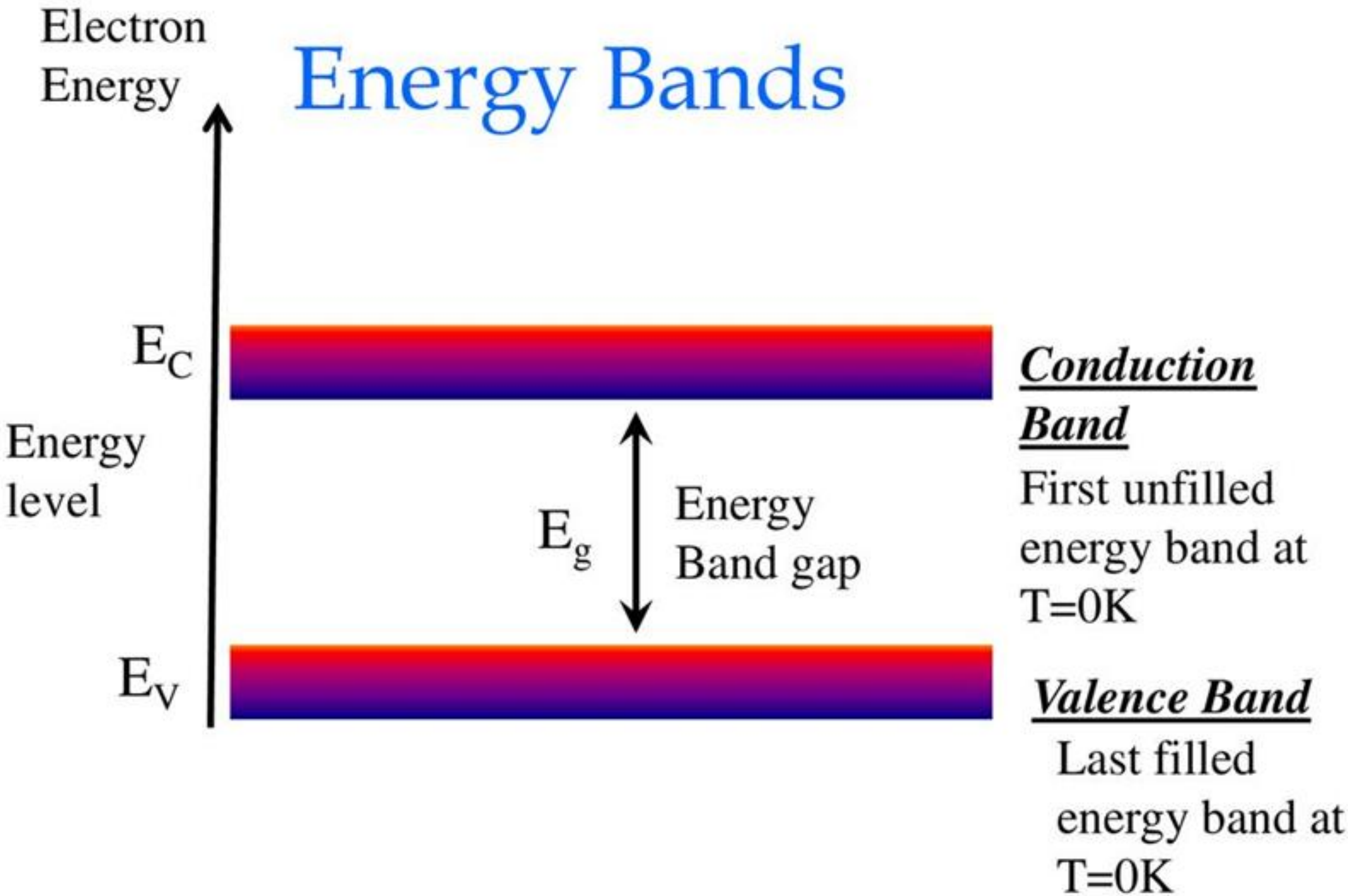
The highest energy level in the conduction band occupied by electrons in a crystal, at absolute 0 temperature, is called Fermi Level.

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



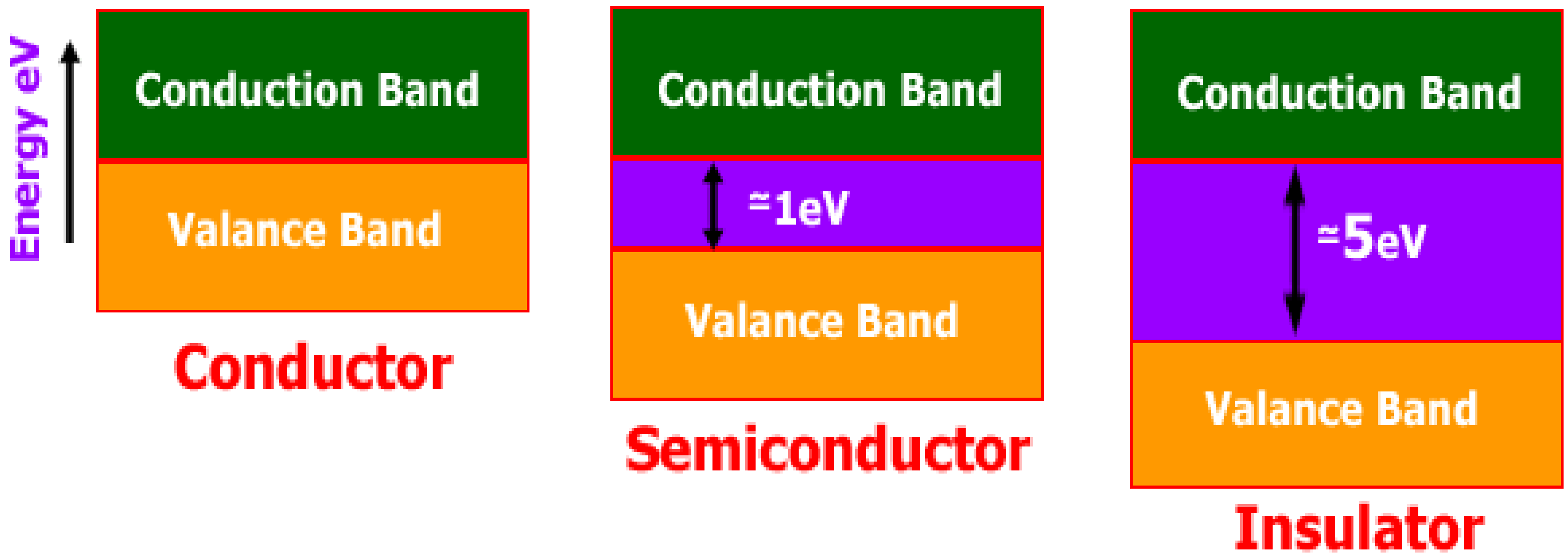


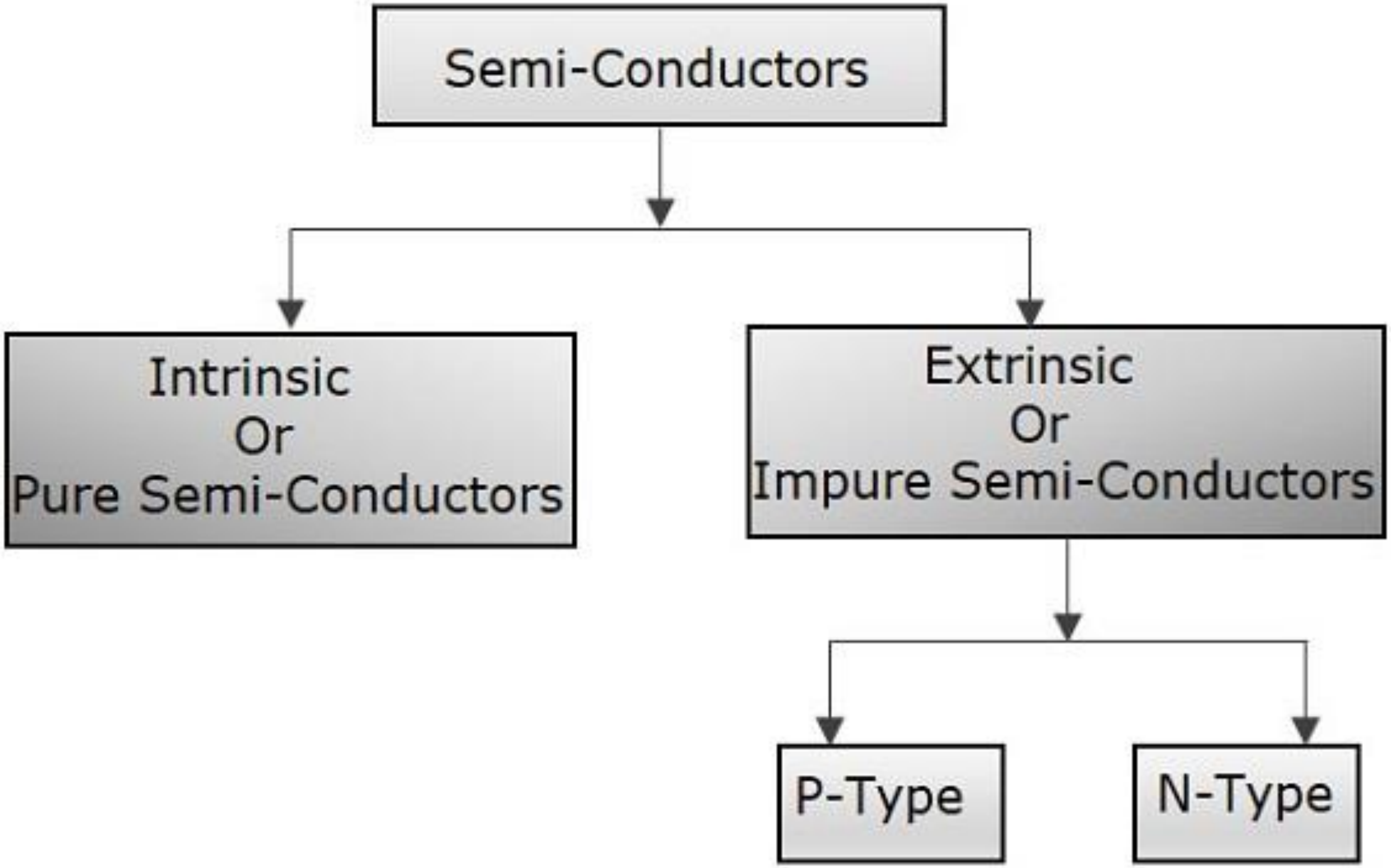
Fig: Classification of Solids on the basis of electricity Conduction

Semiconductors

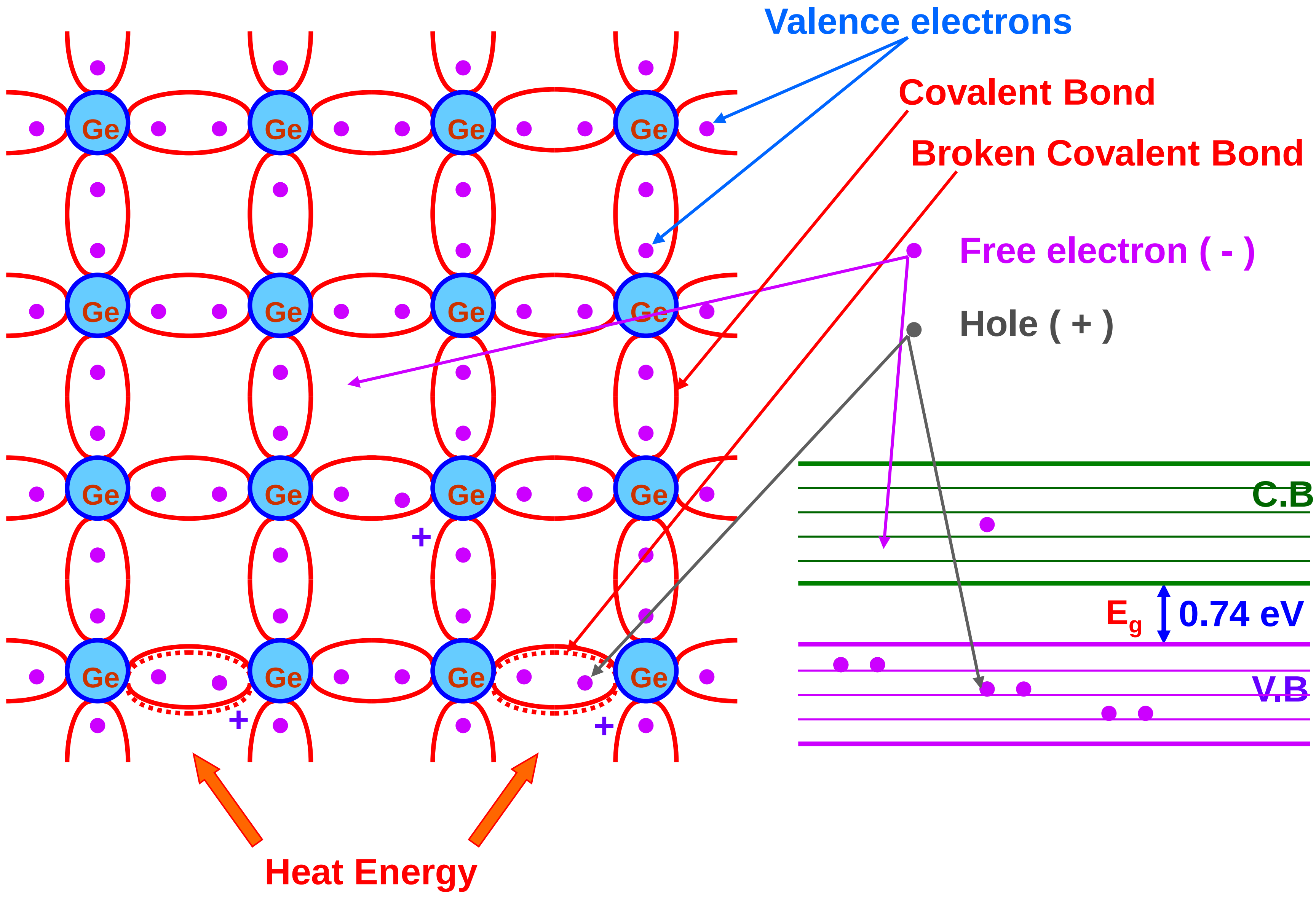
- Semiconductors are materials having energy band gap in between conductors and insulators (approximately 1eV)

- 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

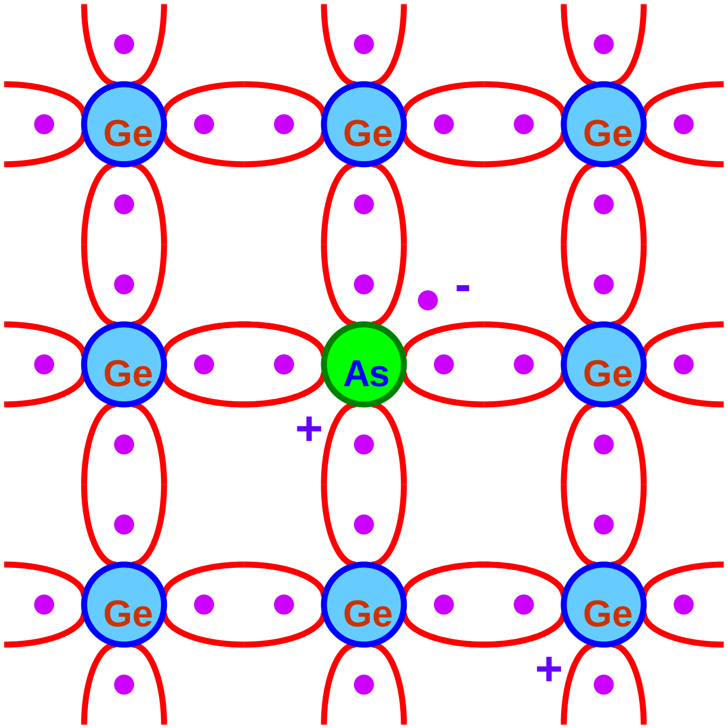


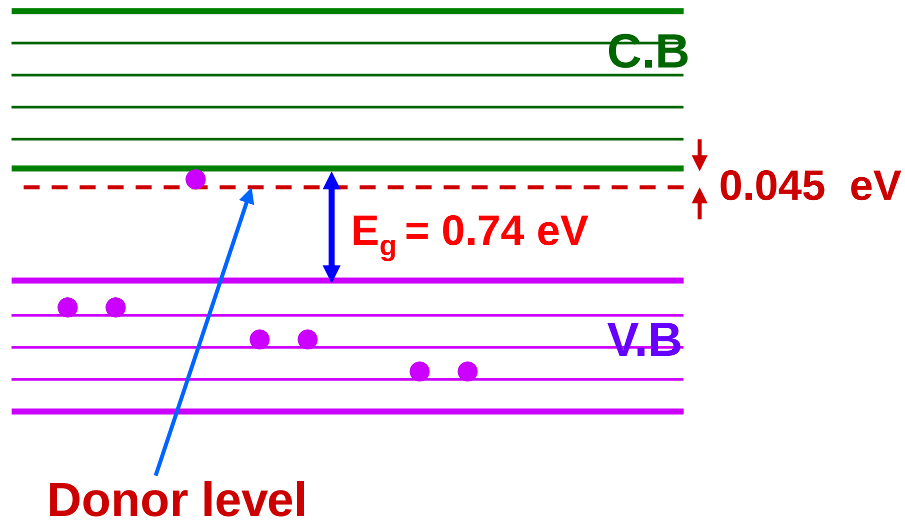
DOPING IN SEMICONDUCTORS

- 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

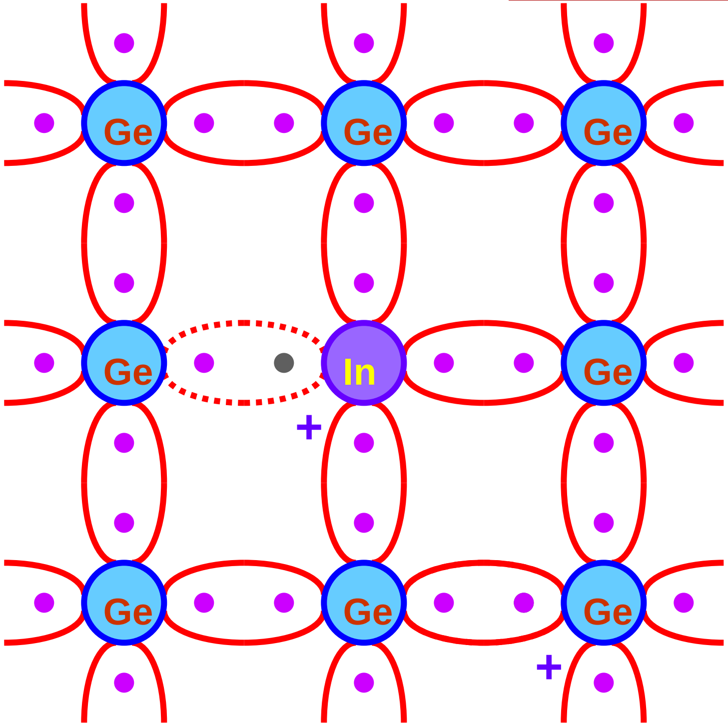
$$\boxed{n\,p = n_i\,p_i = n_i^2}$$

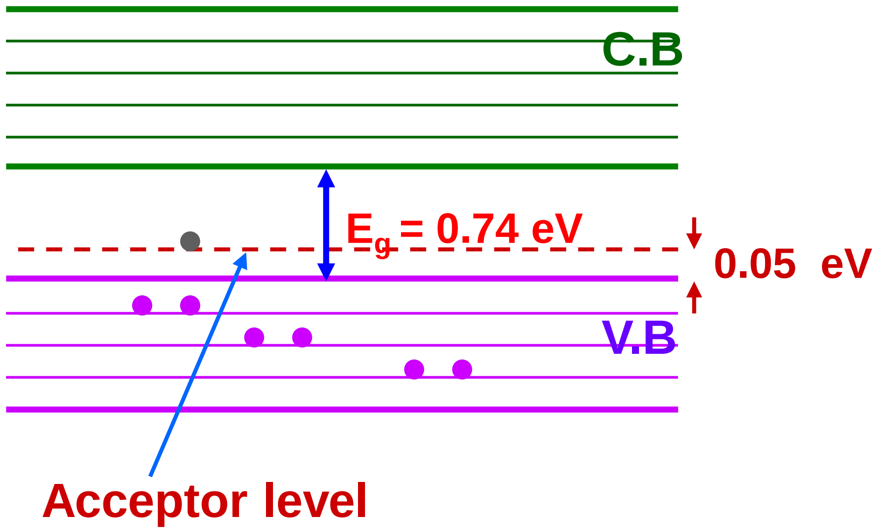
where n_i and p_i are the intrinsic carrier concentrations.

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 neighboring 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

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

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

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

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

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

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

Refer Class notes

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 $\frac{E_c + E_v - 2E_F}{kT} = 0 \Rightarrow \boxed{E_F = \frac{E_C + E_V}{2}}$

$\therefore$ Fermi level in an intrinsic SC → at the centre of the band gap.

Important formulae and definitions related to Conductors

Refer Class notes

CONDUCTIVITY IN INTRINSIC SC

- The conductivity of a conductor is given by

$$\sigma = (e)(n)(\mu)$$

- For semiconductor, there are two types of charge carriers, electrons and holes
- let n and p are electron and hole density respectively
- μ_e *and* μ_h are mobility of electron and holes respectively
- Therefore, the conductivity of semiconductor is given by

$$\sigma = (\sigma_{electron}) + (\sigma_{holes})$$

$$\sigma = (e)(n)(\mu_e) + (e)(p)(\mu_h)$$

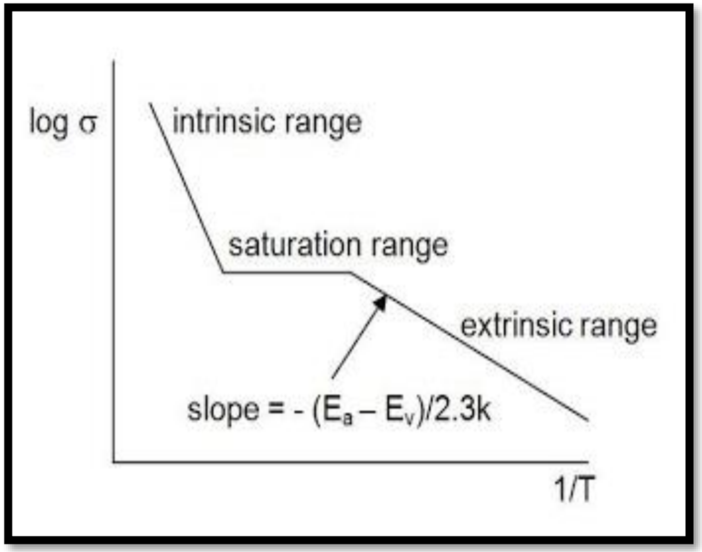
$$\sigma = e(n\mu_e + p\mu_h)$$

- For Intrinsic semiconductors, n = p = n_i

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

CONDUCTIVITY IN EXTRINSIC SC

- Low temperature → frozen charge carriers → resistivity is extremely high.
- Moderate increase in temperature → Rapid decrease in resistivity with the increase of ionized charges.
- At sufficiently high temperature → dopants are completely ionized → conductivity decreases and the resistivity increases again.
- At still higher temperature → resistivity decreases sharply due to appreciable excitation of all carriers and crossing the energy gap.



- **In doped semiconductor (Extrinsic), majority carriers greatly outnumbers the minority carriers, so that the equation can be reduced to a single term involving the majority carrier.**

- **For n-type semiconductor**

$$\boldsymbol{\sigma_n = (n)(e)(\mu_e)}$$

- **For p-type semiconductor**

$$\boldsymbol{\sigma_p = (p)(e)(\mu_h)}$$

- **Conductivity of a material is determined by two factors:**

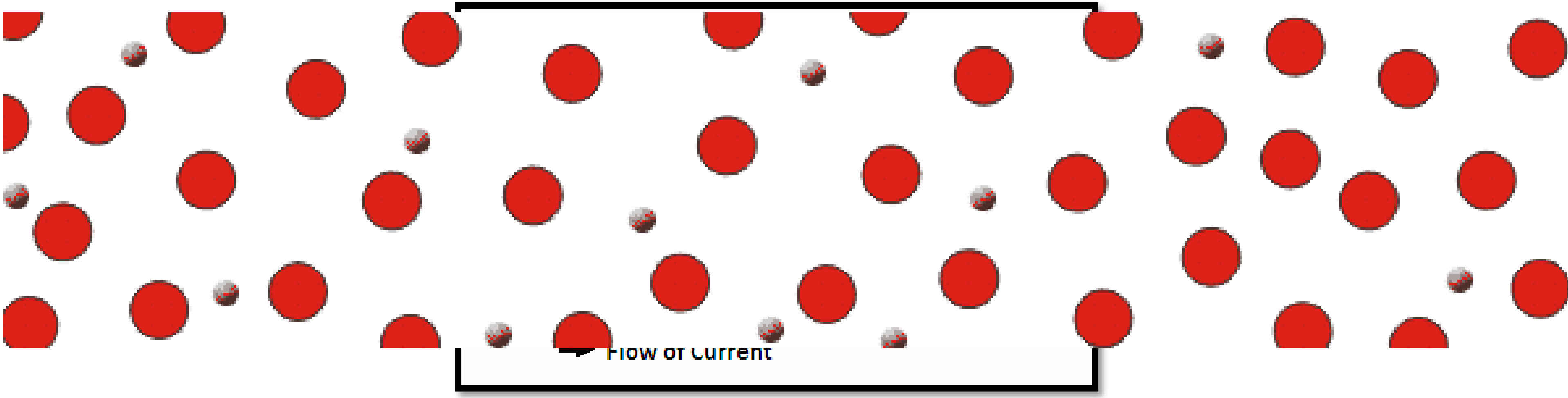
(i) concentration of free carriers available to conduct current

(ii) their mobility (or freedom to move).

In a semiconductor, both mobility and carrier concentration are temperature dependent.

DRIFT CURRENT

- Absence of field: free electrons move in a conductor with random velocities and random directions.
- Presence of field: the randomly moving electrons experience an electrical force in the opposite direction of the field.
- Electrons shift towards higher potential with their random motion.
- The electrons will drift towards higher potential along with their random motions.



https://web2.ph.utexas.edu/~coker2/index.files/current.htm

- Electrons have a net velocity towards the higher potential end of the conductor known as the drift velocity of electrons.
- The drift movement of electrons inside an electrically stressed conductor, is known as drift current.
- For conductor drift current density is given by $J_{(drift)} = (n)(e)(\mu)(\mathrm{E})$
- The drift current density for electron and hole are given by

$$J_{(drift)electron} = -(n)(e)(\mu_e)(\mathrm{E})$$

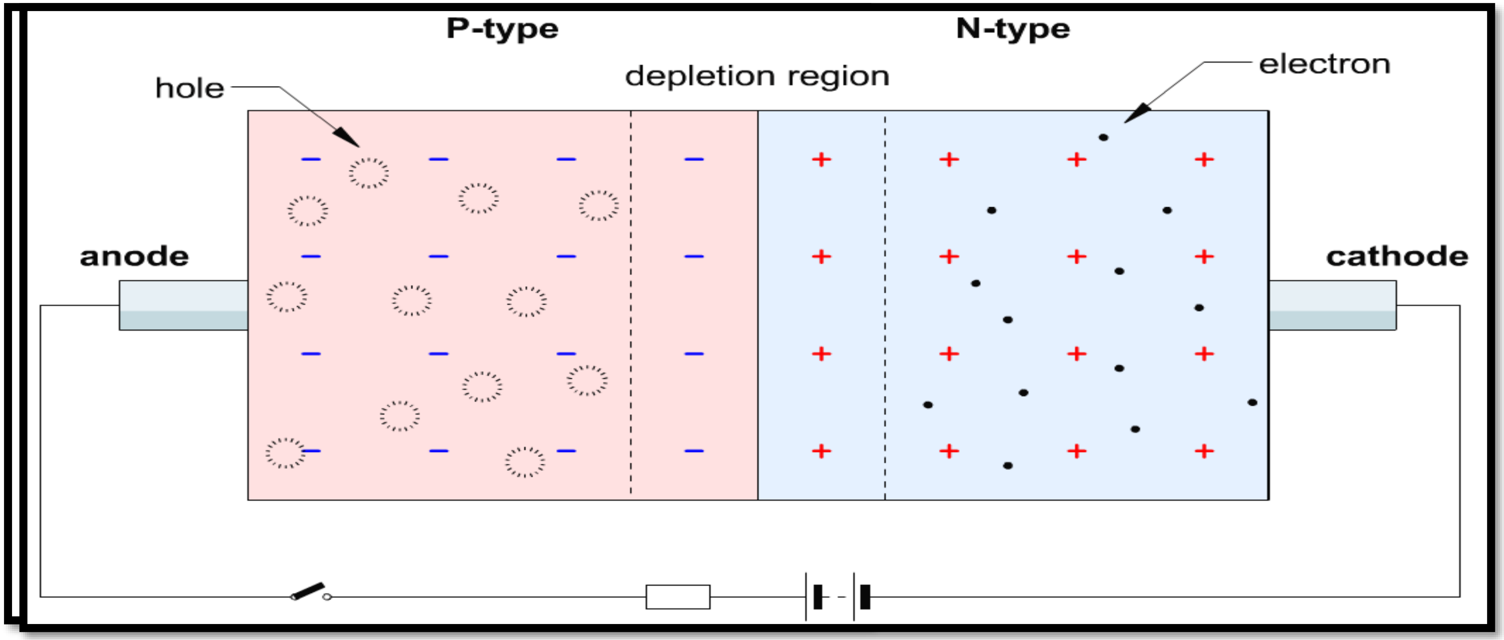
$$J_{(drift)hole} = (p)(e)(\mu_h)(\mathrm{E})$$

- where n, p are the electron and hole densities, μ_e and μ_h are mobility of electron and holes respectively.
- Negative sign indicates that the electrons having -ve charge move in direction opposite to the applied field.
- Total drift current density : $J_{(drift)Total} = J_{(drift)electron} + J_{(drift)hole}$

$$J_{(drift)Total} = -(n)(e)(\mu_e)(\mathrm{E}) + (p)(e)(\mu_h)(\mathrm{E})$$

DIFFUSION CURRENT

- In semiconducting material → Dopants are introduced to some region → even distribution of carriers takes place to maintain the uniformity → known as diffusion process
- Movement of the mobile charge carriers are responsible for the flow of diffusion current from one region to the other.
- No source of energy is required for the diffusion current.



http://semesters.in/v-i-characteristics-of-p-n-junction-diode-notes-for-electronics-engineering

DIFFUSION CURRENT

- Non-uniformity of charge carriers (electrons/holes) → gives the diffusion current (is independent of the electric field) → depends on the concentration gradient.
- Concentration of electrons (*n*) and holes(*p*) varies with the distance (*x*) .
- Diffusion current density for electrons is $J_{(diff)electron} = eD_e \frac{dn}{dx}$, where D_e is the diffusion coefficient for electrons and (dn/dx) is the concentration gradient of electrons.
- Diffusion current density for holes is $J_{(diff)holes} = -pD_h \frac{dp}{dx}$, where D_h is the diffusion coefficient for holes and (dp/dx) is the concentration gradient of holes.
- Resultant diffusion current density for both holes and electrons is given as $J_{(diff)Total} = eD_e \frac{dn}{dx} - pD_h \frac{dp}{dx}$

The total current density in semiconductor is the sum of drift current and diffusion current is given by

$$J_{Total} = J_{drift} + J_{diffusion}$$

$$J_{Total} = J_{(drift)electron} + J_{(drift)hole} + J_{(diffusion)electron} + J_{(diffusion)hole}$$

$$J_{Total} = -(\mathrm{n})(e)(\mu_e)(\mathrm{E}) + (\mathrm{p})(e)(\mu_h)(\mathrm{E}) + eD_e\frac{dn}{dx} - pD_h\frac{dp}{dx}$$

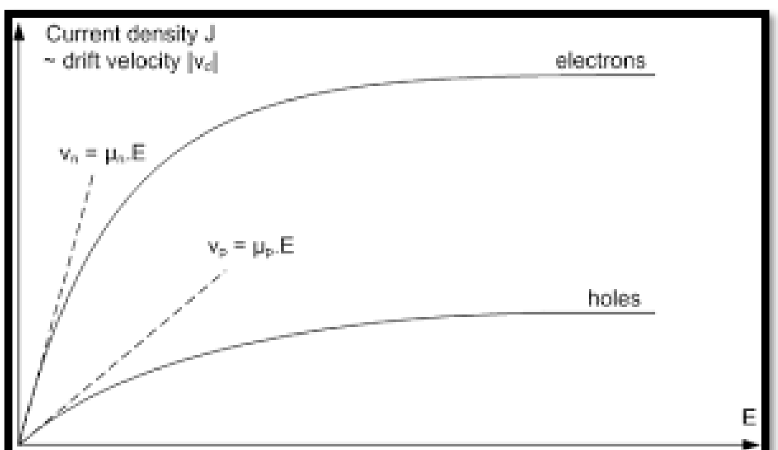


Figure shows the plot for the current density J_{drift} and the absolute value of the drift velocity, over the electric field E. The mobility of holes and electrons can be evaluated using the tangential of the drift velocity.

http://lamp.tu-graz.ac.at/~hadley/psd/problems/diffusioncurrent2/s.pdf

FERMI DIRAC DISTRIBUTION FUNCTION

- **The probability density functions describes the probability that particles occupy the available energy levels in a given system.**

- **Fermions : half-integer spin particles- Electrons are Fermions- obeys Pauli exclusion principle → one Fermion occupies a single quantum state → fills the available states in an energy band.**

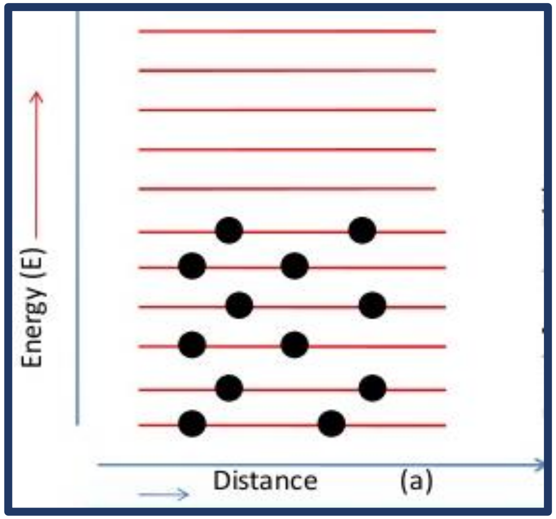
- **Fermi function : The probability that an energy level at energy, *E*, in thermal equilibrium with a large system, is occupied by an electron.**

- **Fermi Dirac distribution function is given as:**

$$f(E) = \frac{1}{1 + exp^{(E-E_F)/kT}}$$

- **E_F : Fermi energy; k : Boltzmann constant; T: Temperature**

FERMI LEVEL IN A CONDUCTOR

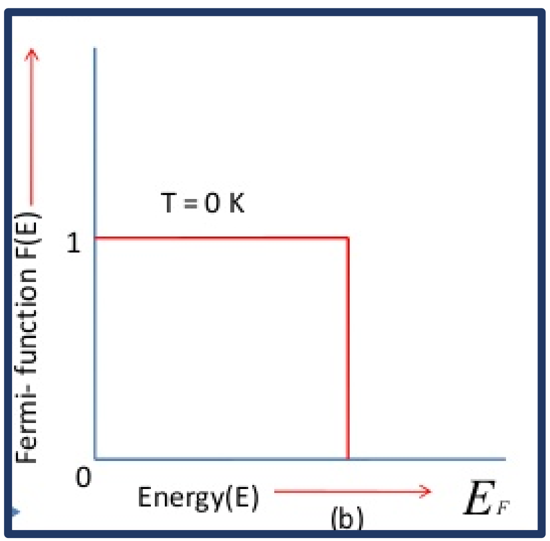


Fermi function is $f(E) = \frac{1}{1+exp^{(E-E_F)/kT}}$

Case 1: At T= 0 K; E< E_F => (E-E_F) is negative

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

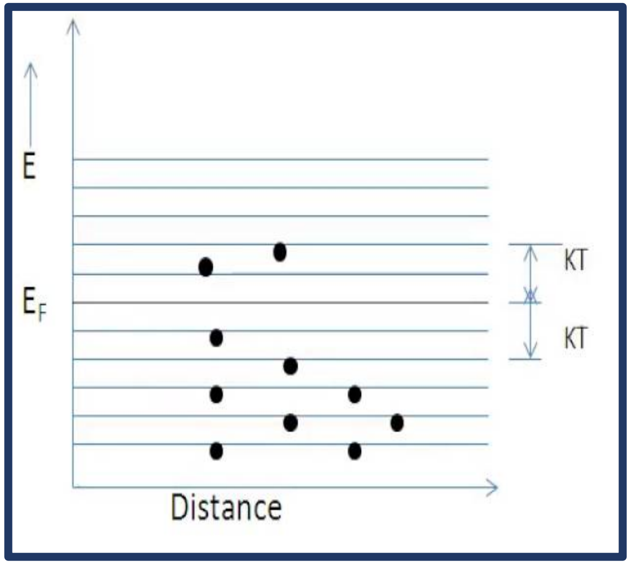
All *levels lying below* E_F are occupied.



Case 2: At T= 0 K; E> E_F => (E-E_F) is positive

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

All energy levels lying above E_F are vacant

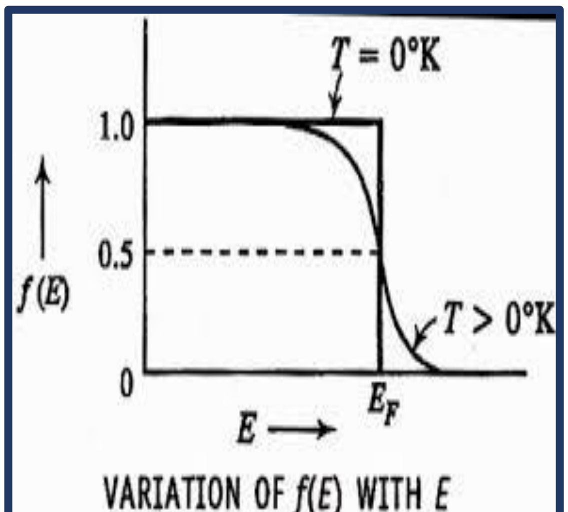


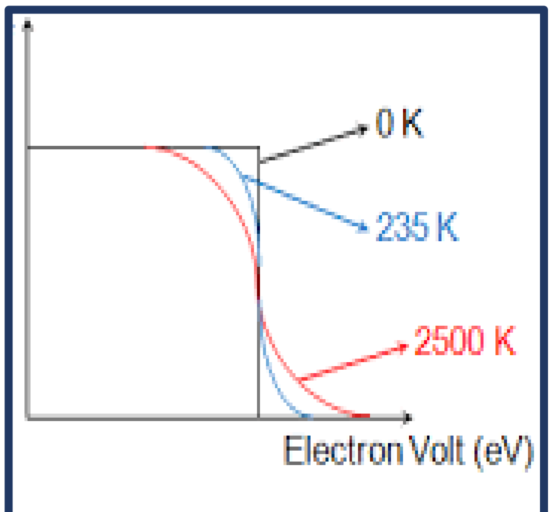
Case 3: At T > 0 K; E=E_F

$$\therefore f(E) = \frac{1}{1+e^{\left(\frac{0}{kT}\right)}} = \frac{1}{1+e^{0}} = \frac{1}{1+1} = \frac{1}{2}$$

The probability of occupancy at any temperature T > 0 K is 50 %.

Fermi energy: Average energy possessed by electrons participating in conduction at temperature above 0K.





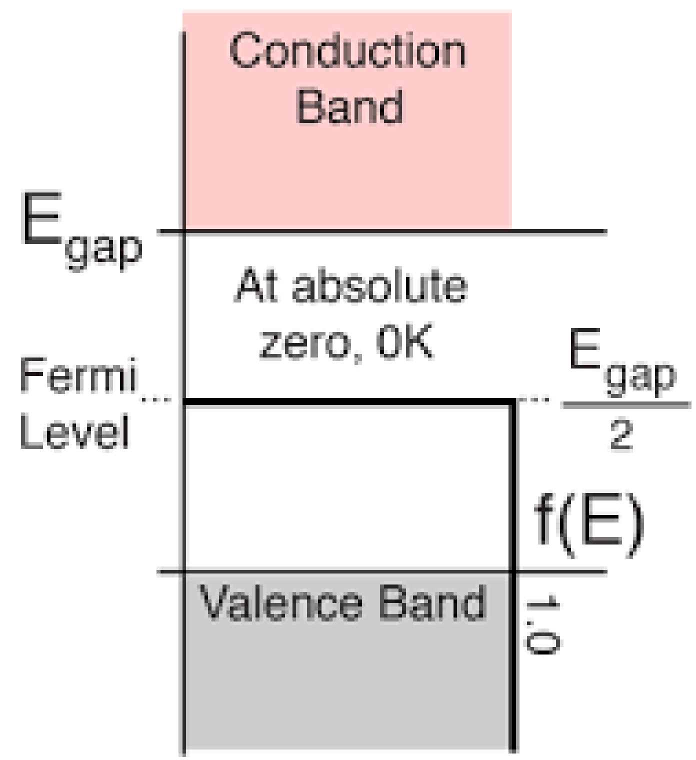
$\mathit{Fermi\ velocity}: v_F$: It is the velocity of the electrons in the highest occupied states in metals at zero temperature.

$$v_F = \sqrt{2E_F/m}$$

https://www.electrical4u.com/fermi-dirac-distribution-function/

WHAT IS FERMI LEVEL

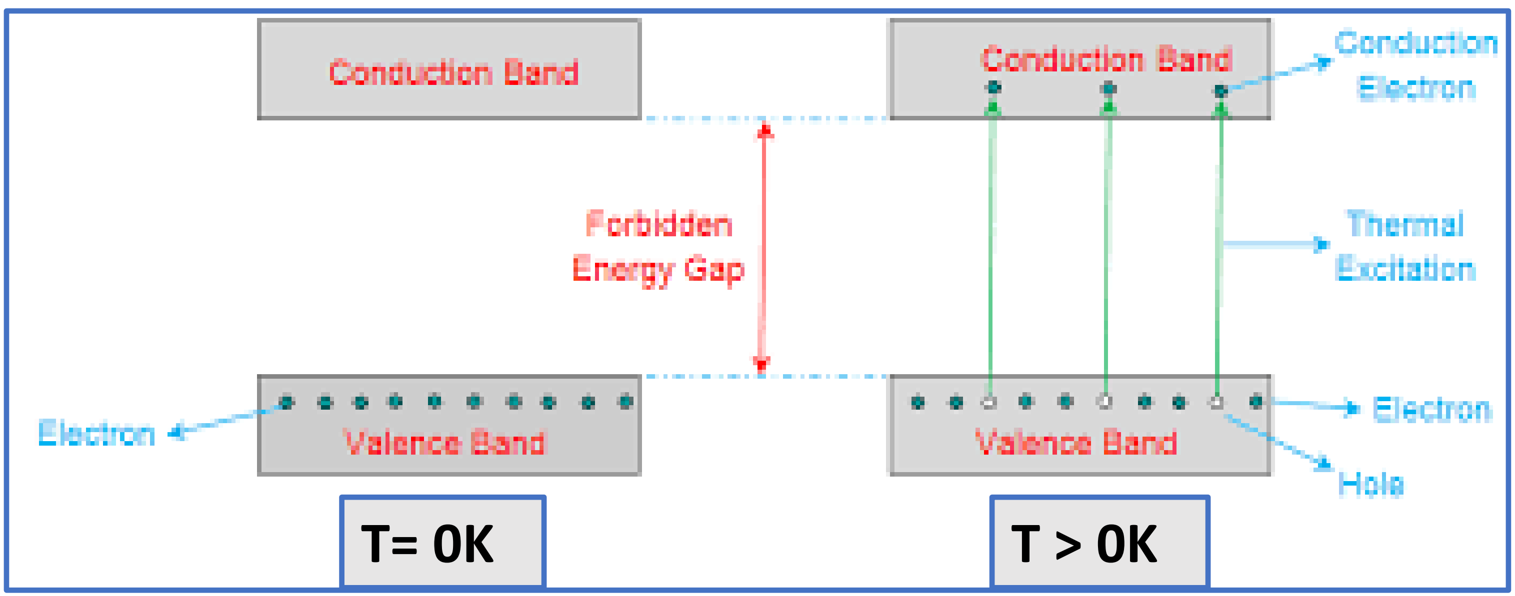
- The highest energy level that an electron occupies at the absolute zero temperature is known as the Fermi Level.
- The Fermi level lies between the valence band and conduction band. At T=0 K, the electrons are all in the lowest energy state → Fermi level can be considered as the sea of fermions (or electrons) above which no electrons exist.
- The Fermi level changes as the temperature increases or electrons are added to or withdrawn from the solids.



Context of Fermi level for a semiconductor

FERMI LEVEL IN INTRINSIC SC

- At T=0 K, the valence band will be full of electrons → impossible to cross the energy barrier → acts as an insulator.
- At T > 0 K → the electron movement from the valence band to the conduction band increases → create holes in the valence band in place of electrons.
- The electron concentration '*n*' is equal to hole concentration '*p*'.

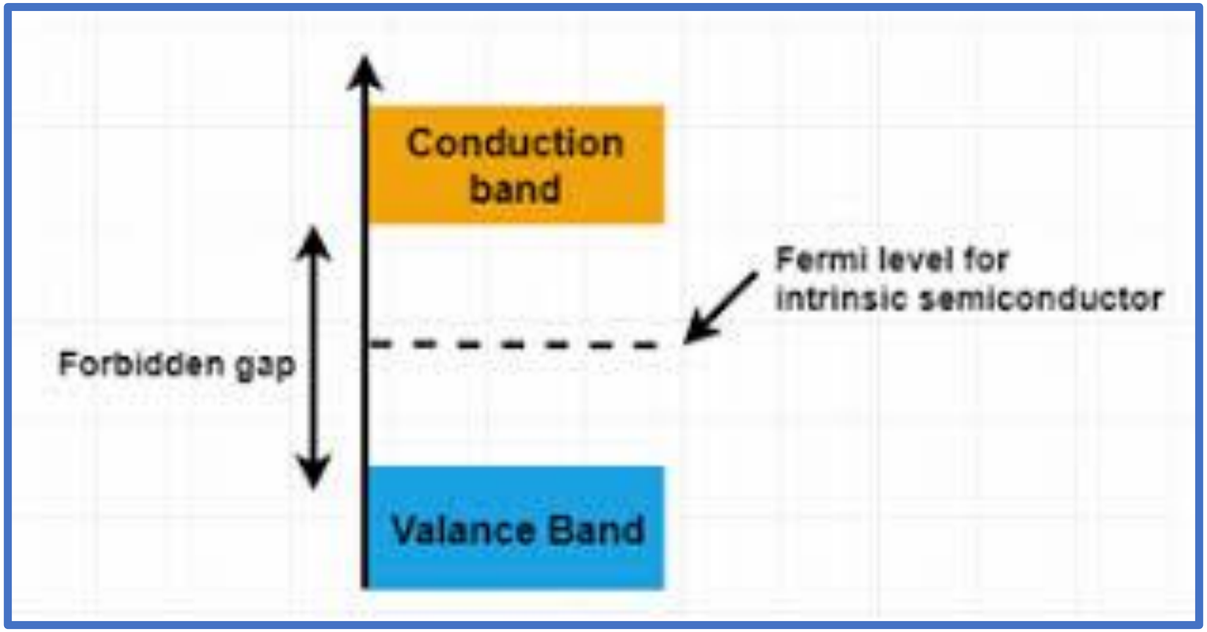


POSITION OF FERMI LEVEL IN INTRINSIC SC

We have already proved

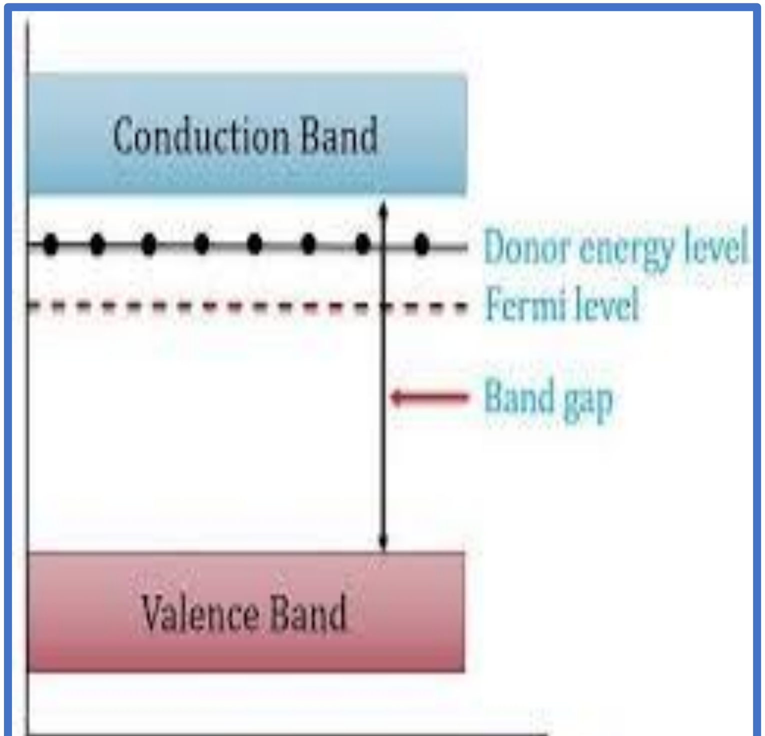
$$\boxed{E_F = \frac{E_C + E_V}{2}}$$

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

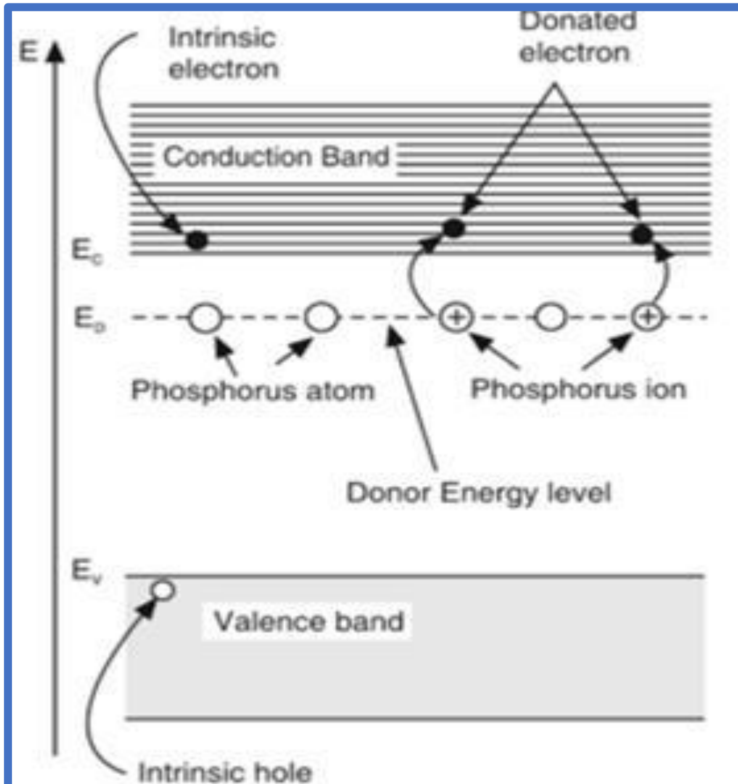


FERMI LEVEL IN EXTRINSIC SC

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



Energy level diagram of N type semiconductor

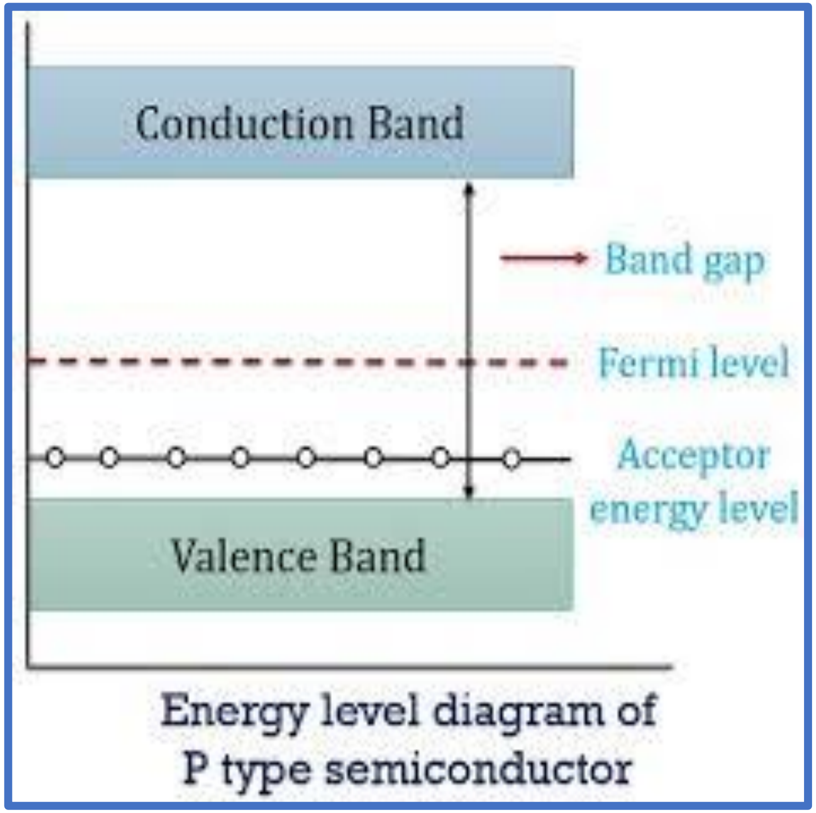


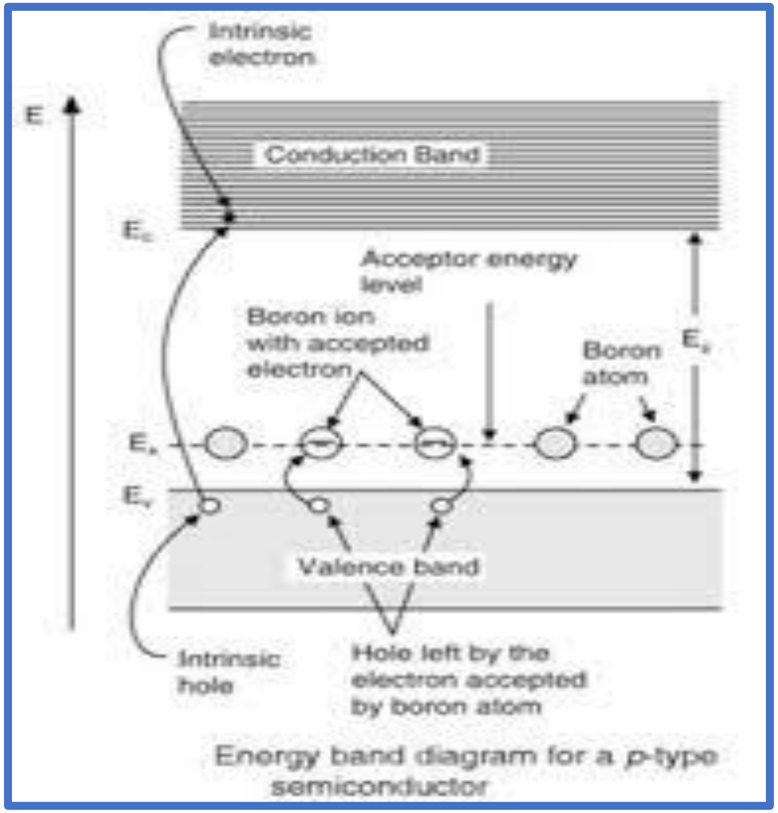
: Energy band diagram of n-type semiconductor

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

FERMI LEVEL IN EXTRINSIC SC

P-type SC- trivalent impurity : holes as majority charge carriers: acceptor impurities

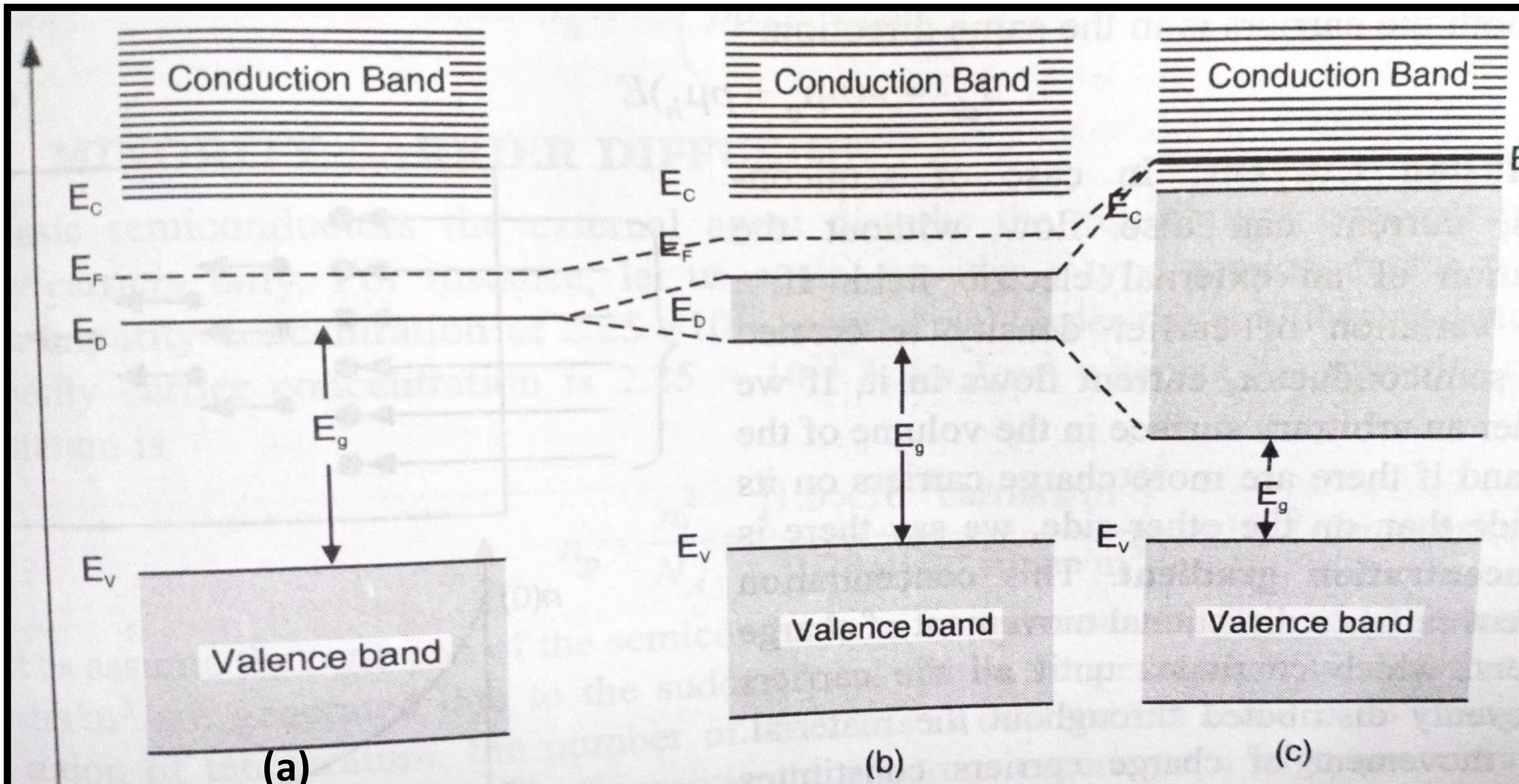




https://sites.google.com/site/puenggphysics/home/unit-5/fermi-level-of-extrinsic-semiconducto

EFFECT OF DOPING ON THE FERMI LEVEL OF N-TYPE SEMICONDUCTOR

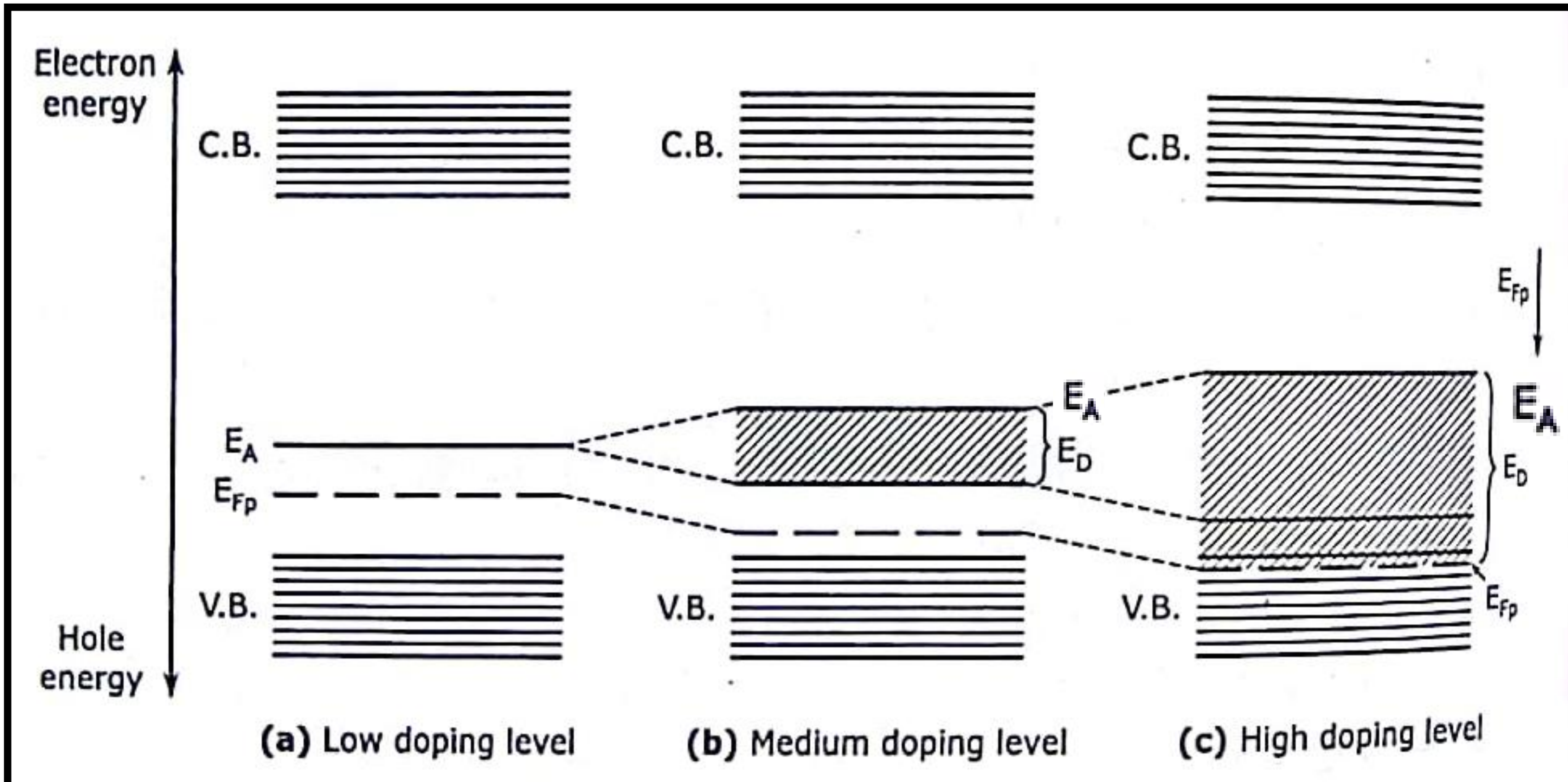
EFFECT OF IMPURITY CONCENTRATION ON E_F OF N- TYPE SC



A book of Engineering Physics by Avadhanulu and Kshirsagar

EFFECT OF DOPING ON THE FERMI LEVEL OF P-TYPE SEMICONDUCTOR

EFFECT OF IMPURITY CONCENTRATION ON E_F OF P- TYPE SC



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