SEMICONDUCTOR PHYSICS

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OBJECTIVE OF THE LECTURE:

- ✓ Define a semiconductor – no. of electrons in outer shell, location on periodic table, most commonly used ones etc.

- ✓ Know the crystal structure of silicon

- ✓ Understand intrinsic and extrinsic semiconductor behaviour, know how to affect this behaviour through doping.

- ✓ Explain in detail what depletion regions are and how they are formed.

- ✓ P-N junction

WHY SEMICONDUCTORS?

- **SEMICONDUCTORS: They are here, there, and everywhere**

- **Computers, palm pilots,** Silicon (Si) MOSFETs, ICs, CMOS

  laptops, anything "intelligent"

- **Cell phones, pagers** Si ICs, GaAs FETs, BJTs

- **CD players** AlGaAs and InGaP laser diodes, Si photodiodes

- **TV remotes, mobile terminals** Light emitting diodes (LEDs)

- **Satellite dishes** InGaAs MMICs (Monolithic Microwave ICs)

- **Fiber networks** InGaAsP laser diodes, pin photodiodes

- **Traffic signals, car** GaN LEDs (**green**, **blue**)

  taillights InGaAsP LEDs (**red**, **amber**)

- **Air bags** Si MEMs, Si ICs

- **and, they are important, especially to Elec. Eng. & Computer Sciences**

INTRODUCTION

Semiconductors are materials whose electrical properties lie between Conductors and Insulators.

Ex : Silicon and Germanium

The interesting feature about semiconductors is that they are bipolar and current is transported by two charge carriers of opposite sign (electrons and holes).

■ Their intermediate properties are determined by

1.Crystal Structure bonding Characteristics.

2. Electronic Energy bands.

Difference in conductivity

Insulators   Semiconductors   Conductors

| 10^{-12} S/m | 10^4 to 10^{-4} S/m | 10^8 S/m |
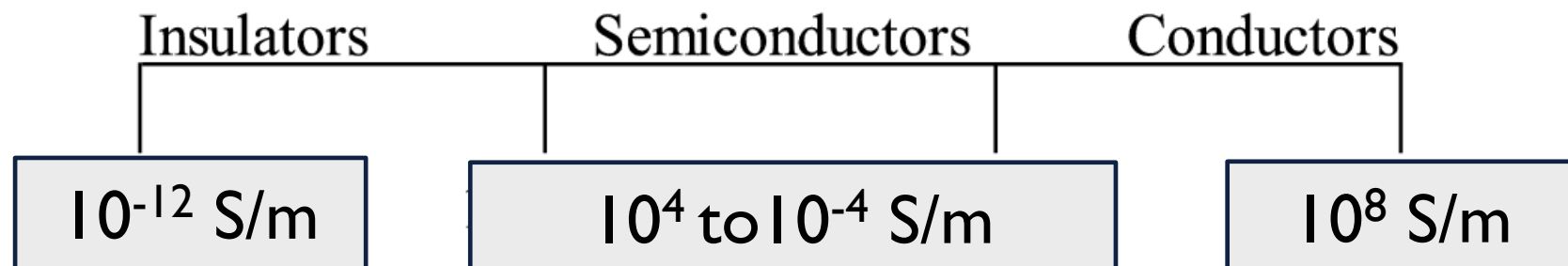
Semiconductor Materials

- **Elemental semiconductors** – Si and Ge (group IV of periodic table) –compose of single species of atoms

- **Compound semiconductors** – combinations of atoms of group III and group V and some atoms from group II and VI. (combination of two atoms results in binary compounds).

- There are also three-element (ternary) compounds (GaAsP) and

- four-elements (quaternary) compounds such as InGaAsP.

Si and Ge are **indirect band** semiconductors

where as Semiconductors like GaAs, InP, ZnS are examples of **direct band gap** semiconductors.

(a)	II	III	IV	V	VI
		B	C		
		Al	Si	P	S
	Zn	Ga	Ge	As	Se
	Cd	In		Sb	Te

(b)	Elemental	IV compounds	Binary III-V compounds	Binary II-VI compounds
	Si	SiC	AlP	ZnS
	Ge	SiGe	AlAs	ZnSe
			AlSb	ZnTe
			GaP	CdS
			GaAs	CdSe
			GaSb	CdTe
			InP	
			InAS	
			InSb	

SEMICONDUCTOR MATERIALS

The wide variety of electronic and optical properties of these semiconductors provides the device engineer with great flexibility in the design of electronic and opto-electronic functions.

- **Ge** was widely used in the early days of semiconductor development for transistors and diodes.

- **Si** is now used for the majority of rectifiers, transistors and integrated circuits.

- **Compounds** are widely used in high-speed devices and devices requiring the emission or absorption of light.

- The electronic and optical properties of semiconductors are strongly affected by impurities, which may be added in precisely controlled amounts (e.g. an impurity concentration of one part per million can change a sample of Si from a poor conductor to a good conductor of electric current). This process called doping.

Semiconductors have **negative temperature co-efficient.** The reason for this is, when the temperature is increased, a large number of charge carriers are produced due to the breaking of covalent bonds and these electrons move freely and gives rise to conductivity and hence the resistivity decreases.

- Silicon and Germanium are elemental semiconductors and they have four valence electrons which are distributed among the outermost s and p orbitals.

- They form strong covalent bonds with 4 neighbors.

- These outer most s and p orbitals of Semiconductors involve in Sp3 hybridization.

- These Sp3 orbitals form four covalent bonds of equal angular separation leading to a tetrahedral arrangement of atoms in space results tetrahedron shape, resulting crystal structure is known as Diamond cubic crystal structure.

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)
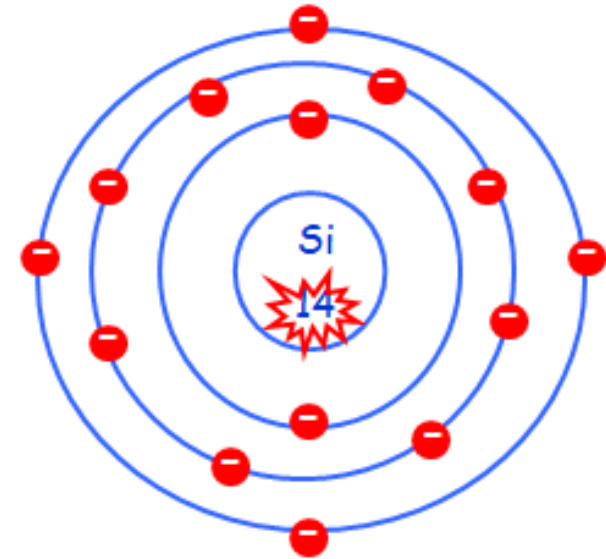
Silicon Atomic Structure

Silicon : It's a Group 4 element which means it has 4 electrons in outer shell

However, like all other elements it would prefer to have 8 electrons in its outer shell.
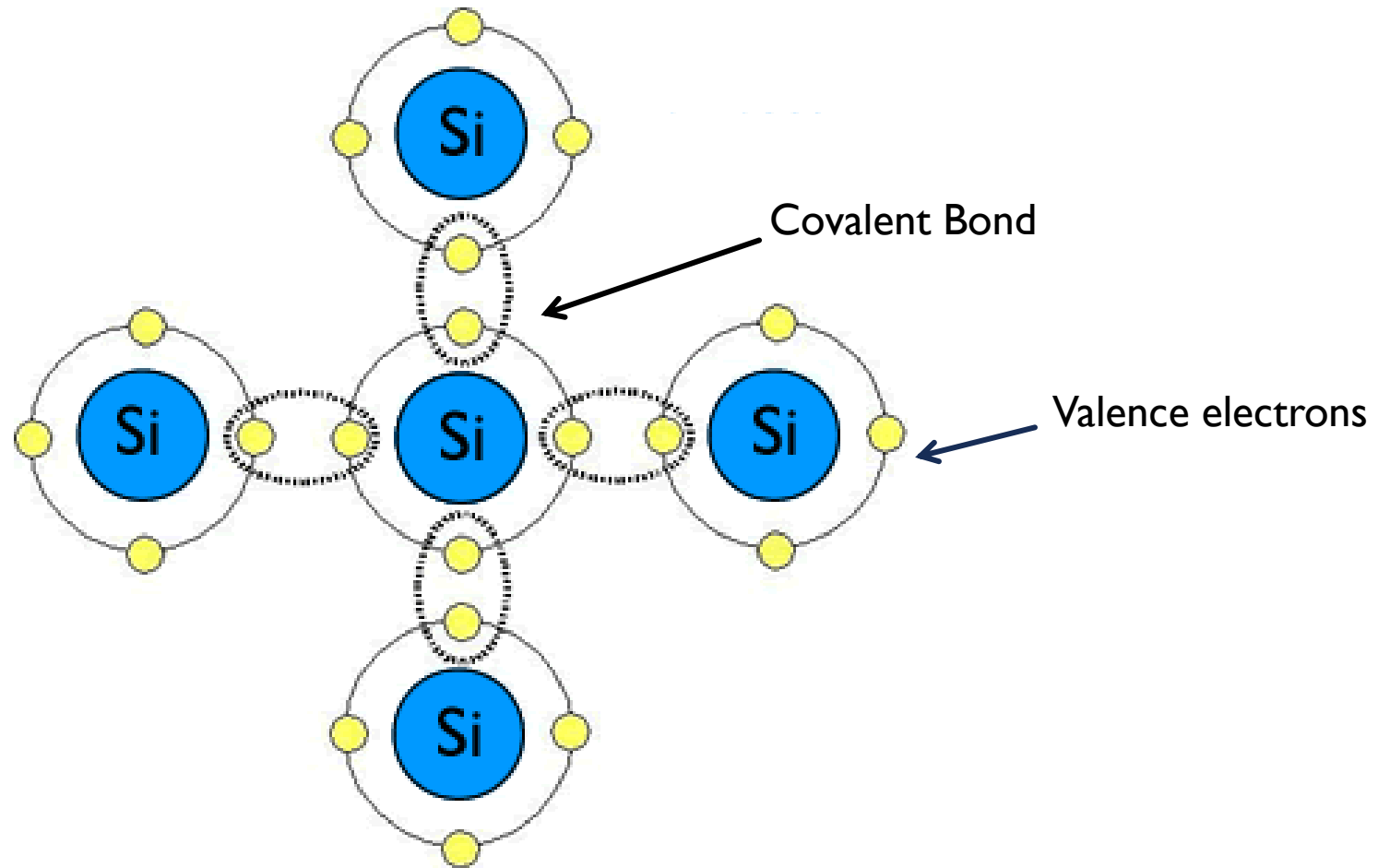
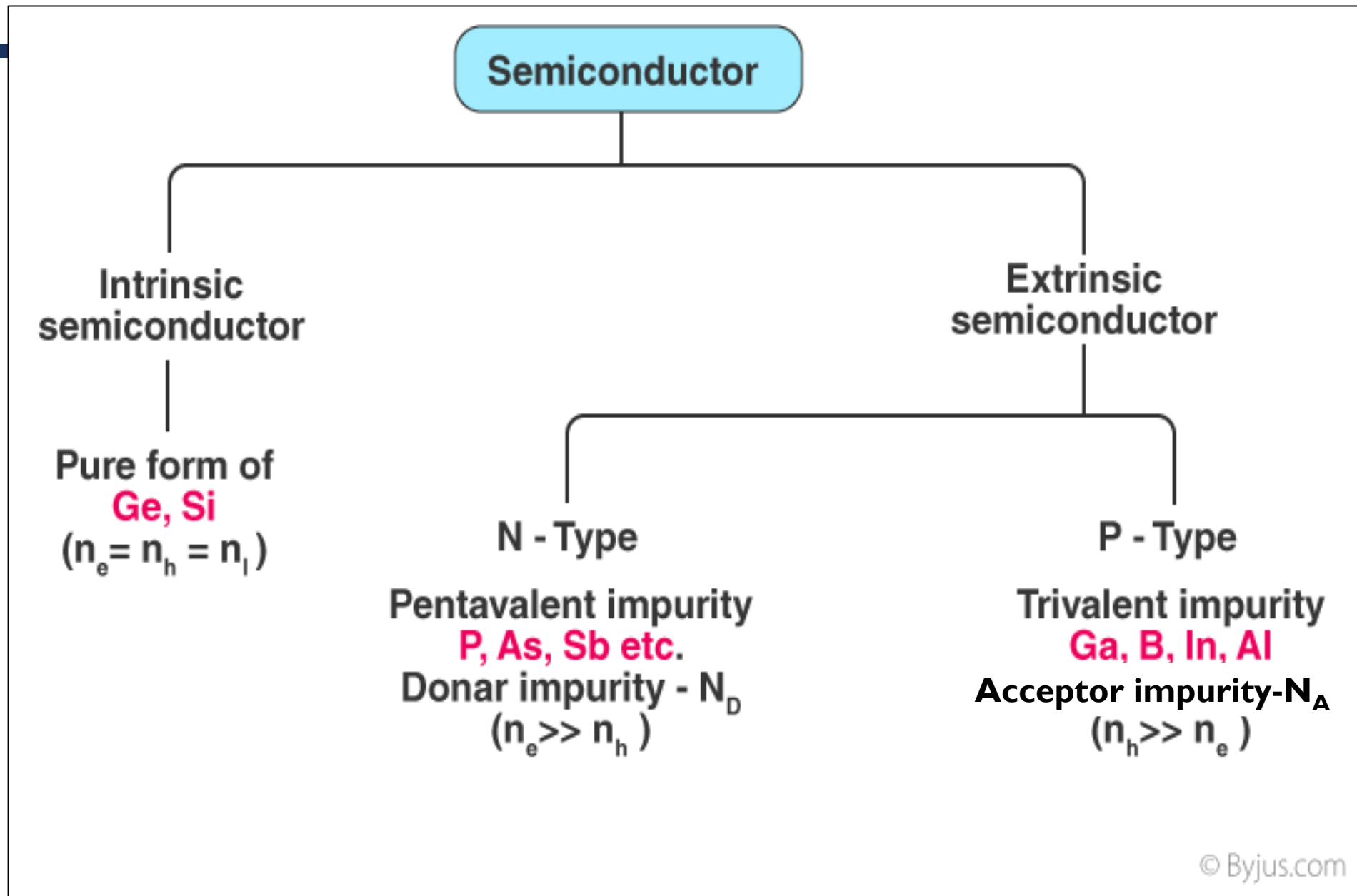This results in the covalent bonding of Si atoms in the crystal matrix

A Covalent Bond Formed by the Sharing of Electrons in an Outer Energy Level

The Silicon Atomic Structure

SILICON

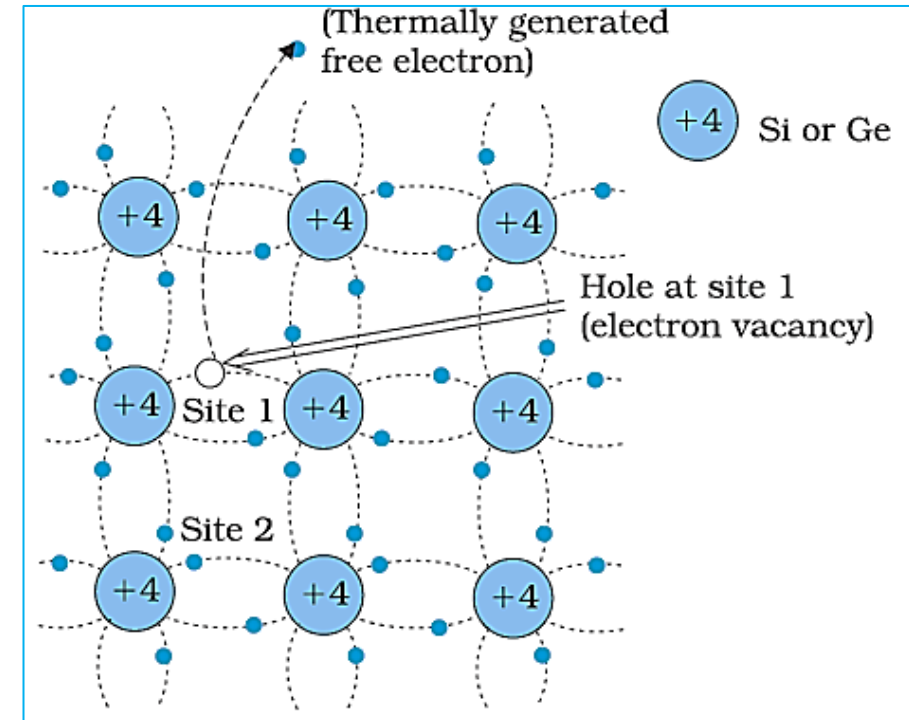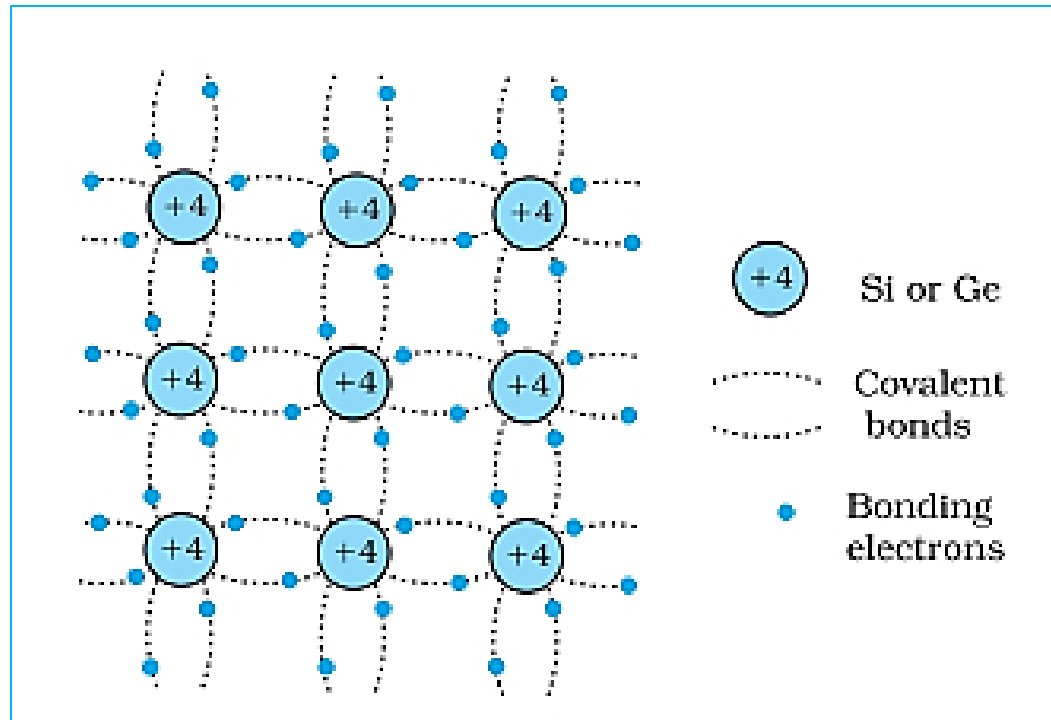
Covalent Bond

Valence electrons

Intrinsic Semiconductors

A chemically pure semiconductor is known as an intrinsic semiconductor. Intrinsic semiconductors have less than one impurity atom in a billion host atoms.

- Fermi level lies exactly at the center of the energy gap.

- At 0 K, an intrinsic semiconductor behaves as a perfect insulator.

- At higher temperature, electrons get thermally excited from the valence band to the conduction band.

- Examples: Germanium and Silicon.

Intrinsic Semiconductors
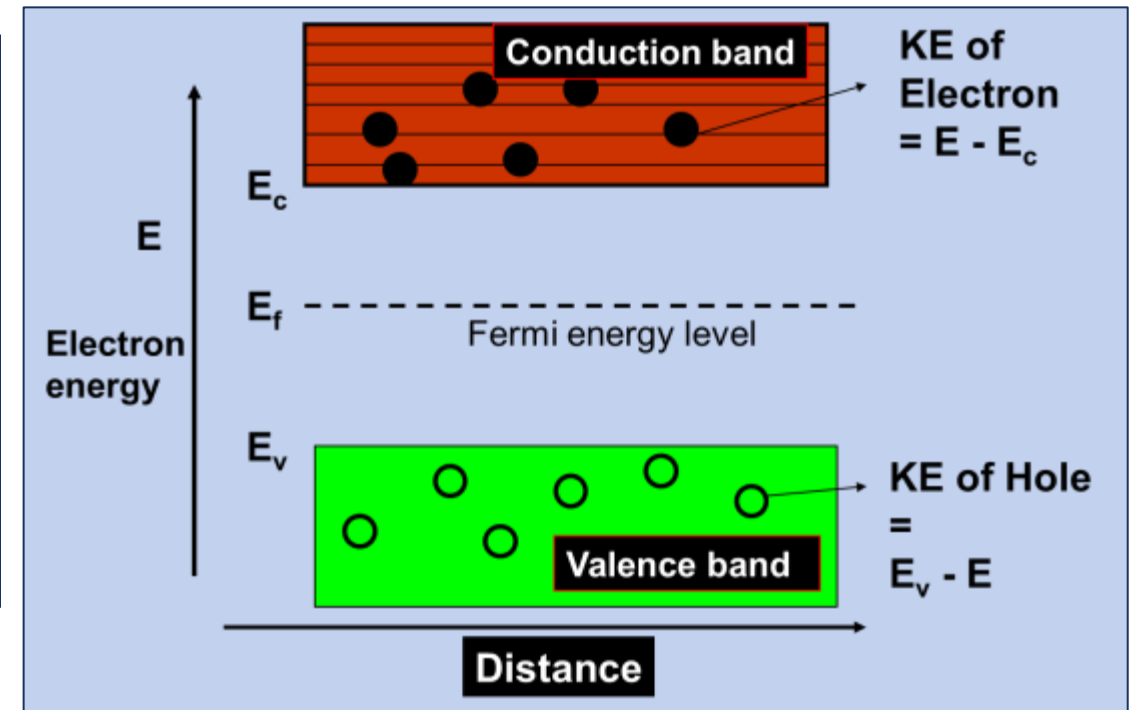
Explanation: Pure Ge or Si which are intrinsic semiconductors, their each atom has four valence electrons in outer most orbits.

➢ At 0 K, all the valence electrons of Si atoms are bounded by the covalent bonds.
• The energy available at 0 K is not sufficient to break the covalent bonds.
• Thus, there are no free electrons in the material at absolute zero. So, valence band is completely filled & conduction band is totally empty.
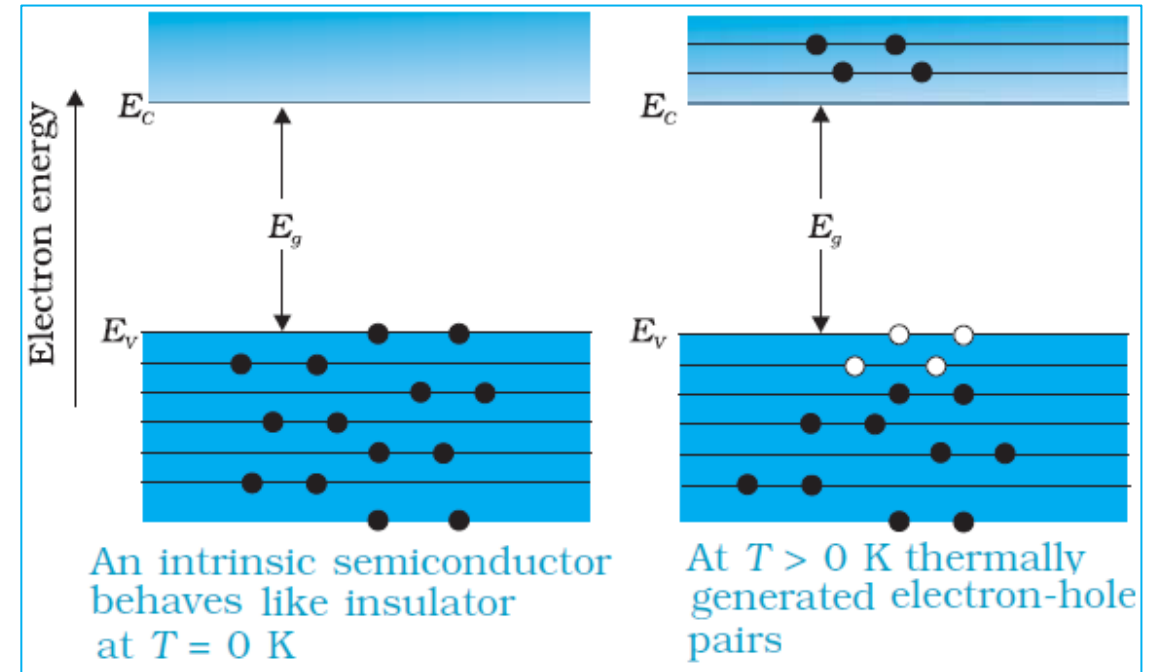
➤ At T > 0 K, some of the electrons which are bounded by covalent bonds, acquire sufficient energy and break the bonds.

• Hence, they become free and jump from valence band to conduction band and a vacancy (hole) is created in the valence band.

The energy required to break a covalent bond should be greater than the energy gap of the given semiconductor (E > E_g). The electron vacancy created in valence band is called a hole.

As temperature increases, the number of free electrons and holes created increases exponentially.

An intrinsic semiconductor behaves like insulator at $T = 0$ K

At $T > 0$ K thermally generated electron-hole pairs

If the conduction band electron and the hole are created by the excitation of a valence band electron to the conduction band, they are called an **_electron-hole pair_** (EHP).

The bottom of the conduction band is denoted as E_c and the top of the valence band is denoted as E_v.
The difference between the bottom of the conduction band and the top of the valence band is called energy gap or band gap energy.

Intrinsic Semiconductors

In intrinsic semiconductors, all the charge carriers i.e. free electrons and holes are generated from the thermally ruptured bonds, and these charge carriers result in the electrical conduction in the semiconductor.

Definition: An intrinsic semiconductor is a semiconductor crystal in which electrical conduction is caused by the thermally generated electrons and holes.

Band gap E_g:
- It is the minimum amount of energy required to excite an electron from valence band to the conduction band.
- It is the minimum amount of energy required to convert a bound electron into a free electron.

E_g (Si) = 1.12 eV, E_g (Ge) = 0.72 eV at 300K.

Limitations of Intrinsic Semiconductor:

- They have low conductivity.

- Conductivity in Intrinsic semiconductor is temperature dependent and increase exponentially with temperature.

- In intrinsic semiconductors, conductivity cannot be controlled from outside.

- Because of these reasons, intrinsic semiconductors are not useful for device fabrication.

The concentration (#/cm³) of conduction electrons & holes in a semiconductor can be modulated in several ways:

1. by adding special impurity atoms (*dopants*)
2. by applying an electric field
3. by changing the temperature
4. by irradiation

Extrinsic Semiconductors

The extrinsic semiconductors are the one in which impurities are present. These added impurities can be either group-III elements or group-V elements. Based on the impurities present in the extrinsic semiconductors, they are classifies into two categories:

- n-type semiconductors

- p-type semiconductors

The process of adding a controlled amount of impurity in an intrinsic semiconductor is called *doping* and the impurity added is called *dopant.*

*Extrinsic semiconductors = intrinsic semiconductor + impurities*

| n-type	p-type
Phosphorous (P)	Aluminium (Al)
Arsenic (As)	Boron (B)
Antimony (Sb)	Gallium (Ga)
	Indium (In)

Advantages Of Extrinsic Semiconductors

- They possess high conductivity.

- Conductivity can be altered via controlling the amount of doping.

- Conductivity is no more temperature dependent.

1. n-type Semiconductor:

- Doped with **pentavalent atom** (5 valence electrons) such as like P, As, Sb etc.

- four electrons participate in the bonding with Si atoms and the fifth electron is left free.

- this free electron contributes to the conductivity.

- No. of electrons >> No. of holes

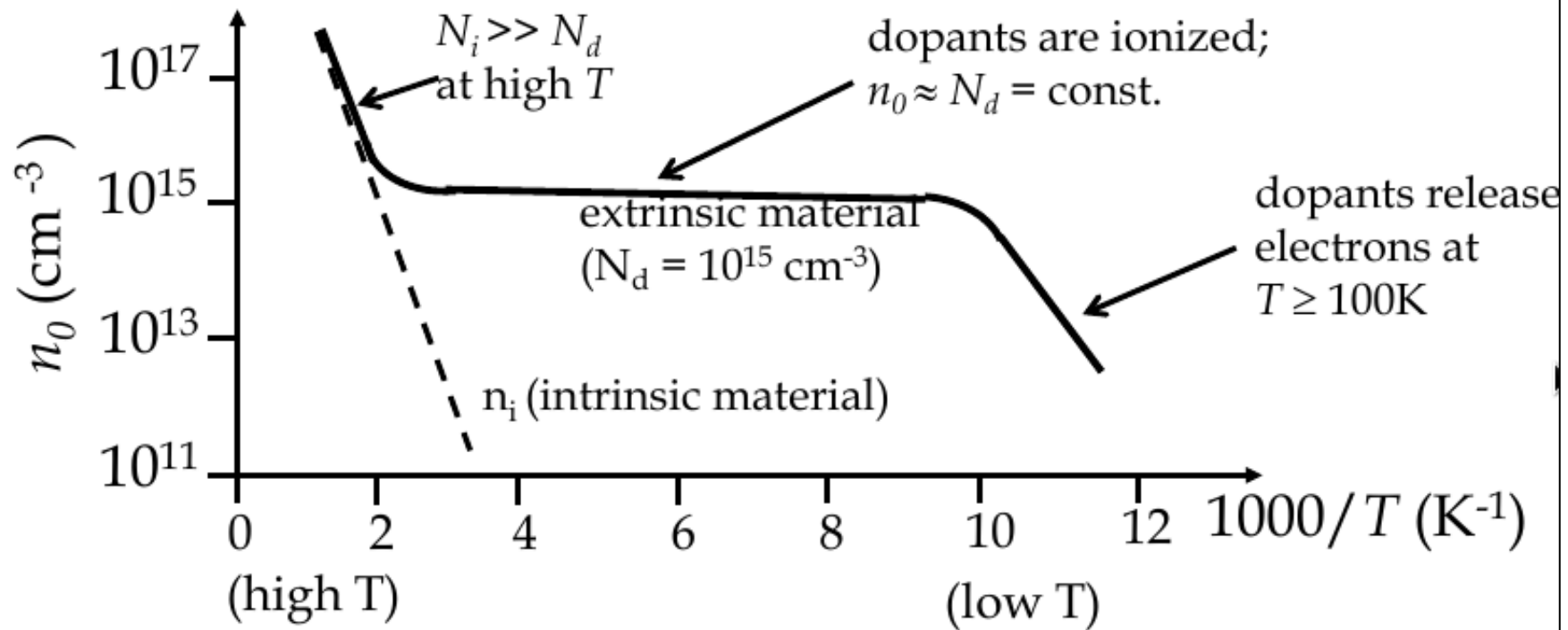Image source: kimiq.com

Energy level diagram of
N type semiconductor
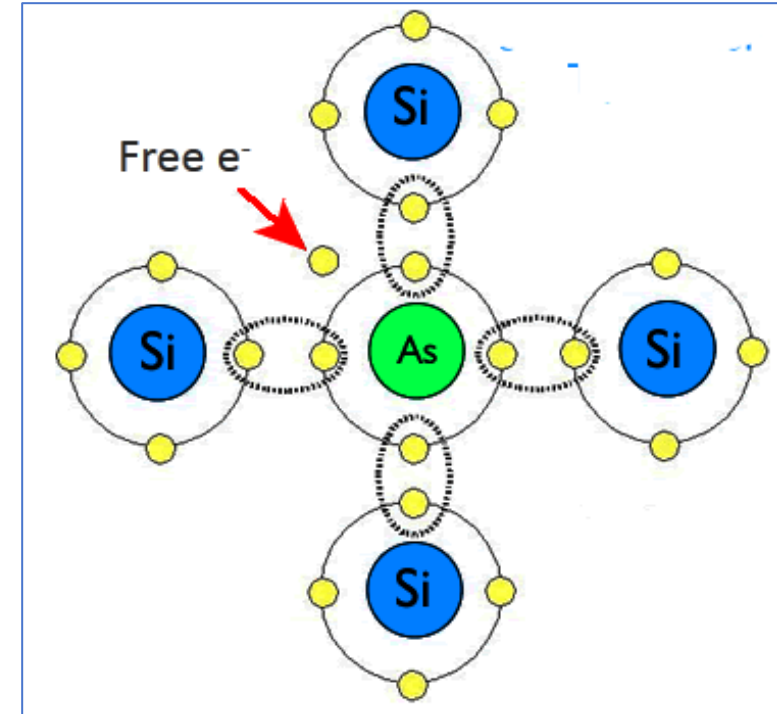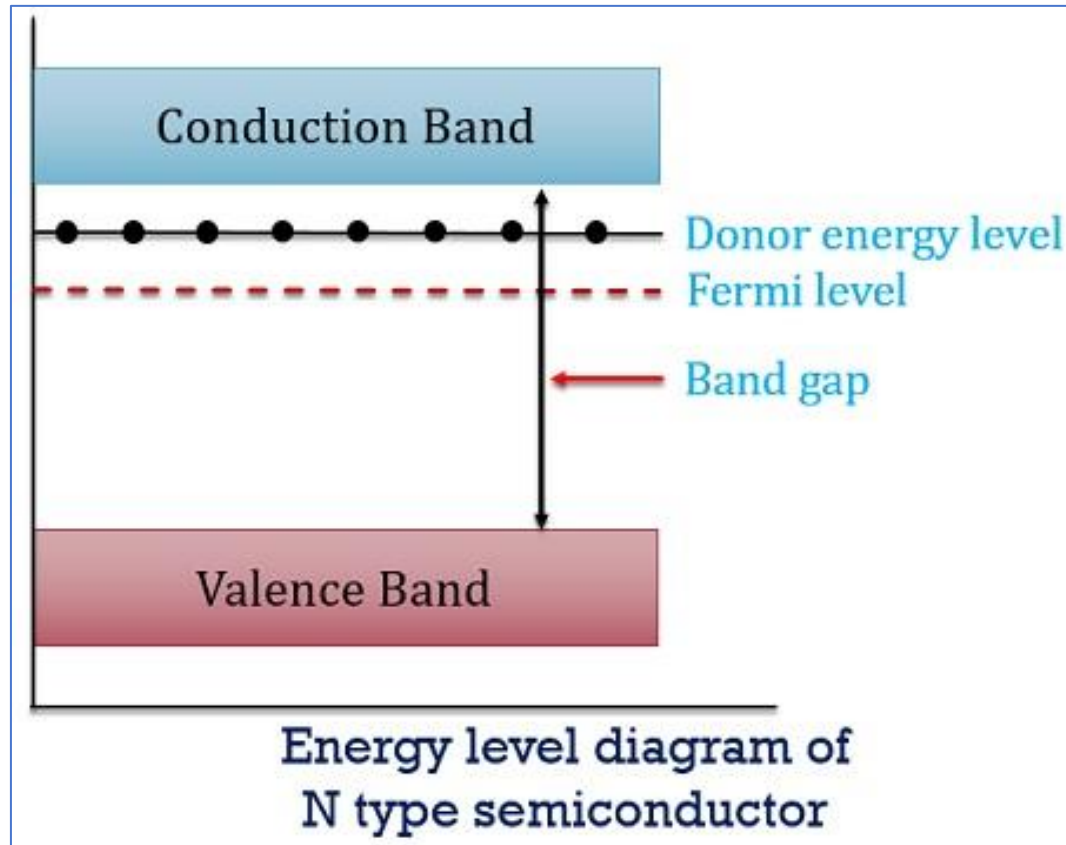
- The pentavalent impurity added in these semiconductors is known as donor impurities, as they donate a free electron.

- The ionization energy of 5th electron is very small ≈0.045eV.

- Fermi level (E_{Fn}) is located between conduction band and donor level at lower temperatures.

- but as the temperature increases, the Fermi level (E_{fn}) shifts towards the intrinsic Fermi level (E_i).
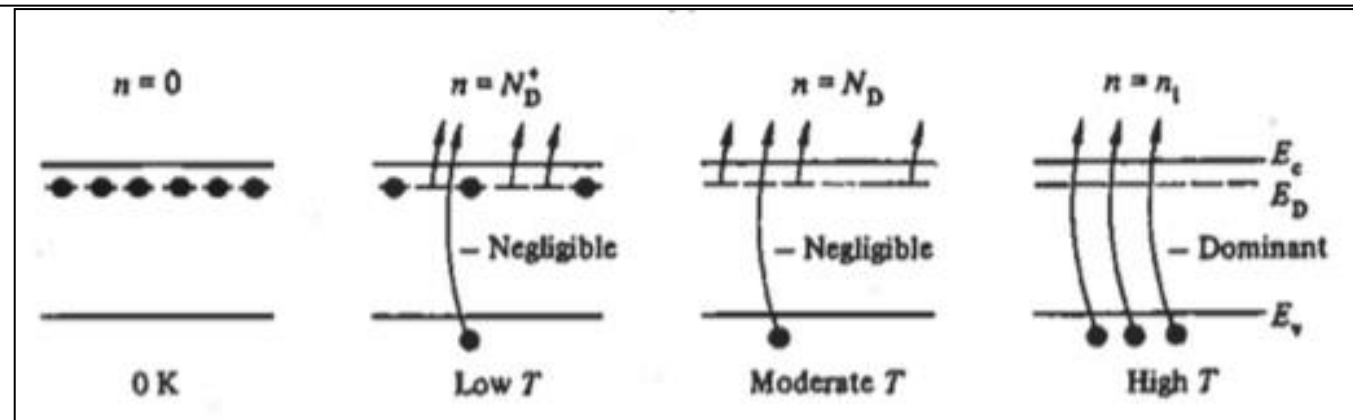
: Energy band diagram of n-type semiconductor
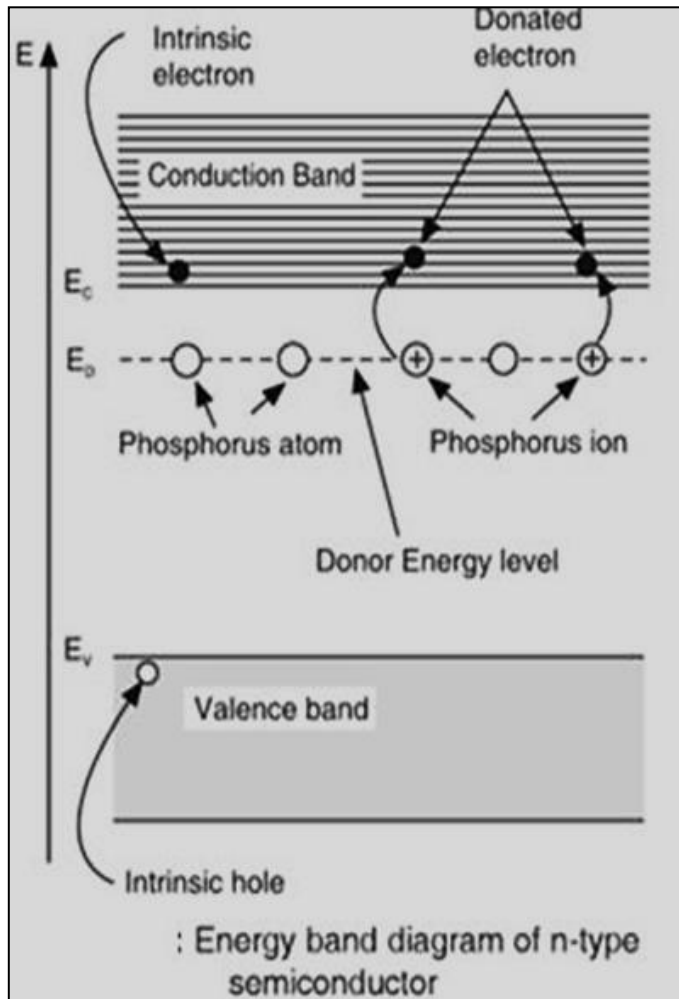
- The donor energy level (E_d) exists which is close to conduction band as shown in the fig.
- At 0K the donor energy level is filled with electrons. Fermi level lies close to conduction band.
- At T K the electrons move to conduction band by leaving a positive donor ions. The number electrons in the conduction band is equal to number of positive ions in the donor energy level.
- As the temperature raises the covalent bond breaks and electrons move from valence band to conduction band.
- Hence the current is due to electrons which are called majority charge carriers. Hence, number of electrons are greater than number of holes i.e., n>>p
- At high temperatures N-type semiconductor will act as intrinsic semiconductor.

$N_i \gg N_d$ at high T

dopants are ionized;
$n_0 \approx N_d$ = const.

extrinsic material
$(N_d = 10^{15}$ cm$^{-3})$

dopants release electrons at $T \geq 100$K

n_i (intrinsic material)

n_0 (cm^{-3})

10^{17}

10^{15}

10^{13}

10^{11}

0   2   4   6   8   10   12 $1000/T$ (K^{-1})

(high T)   (low T)

Temperature dependence of carrier concentration has 3 regions.

$n = 0$ $n = N_D^+$ $n = N_D$ $n = n_i$

— Negligible   — Negligible   — Dominant

E_c
E_D
E_v

0 K   Low T Moderate T High T
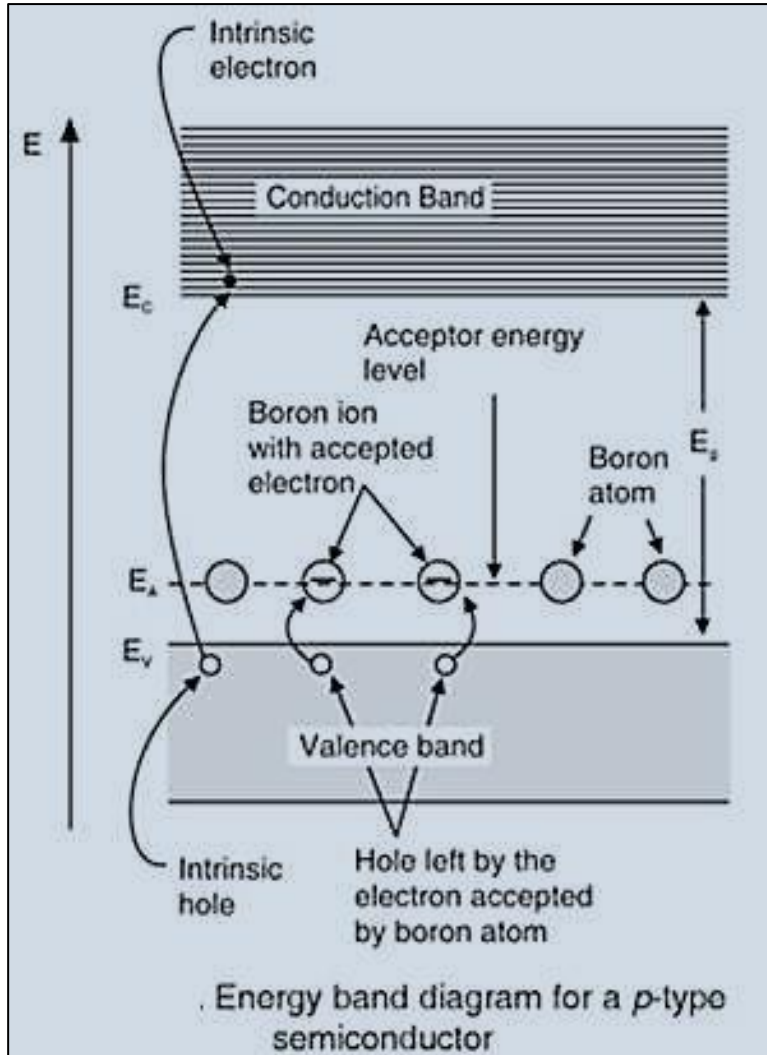
2. p-type Semiconductor:

- Doped with trivalent atom (3 valence electrons)

- only three complete covalent bonds are formed and the fourth bond cannot be formed as it is short of one electron.

- When an adjoin electron acquires sufficient energy it jumps into the vacancy to form the fourth bond and it leaves behind a hole.

- This hole can move freely in the lattice.

- No. of holes >> No. of electrons

- As the Boron atom accepts an electron, it is called *acceptor atom.*

Image source: electronicsdesk.com

Energy level diagram of
P type semiconductor
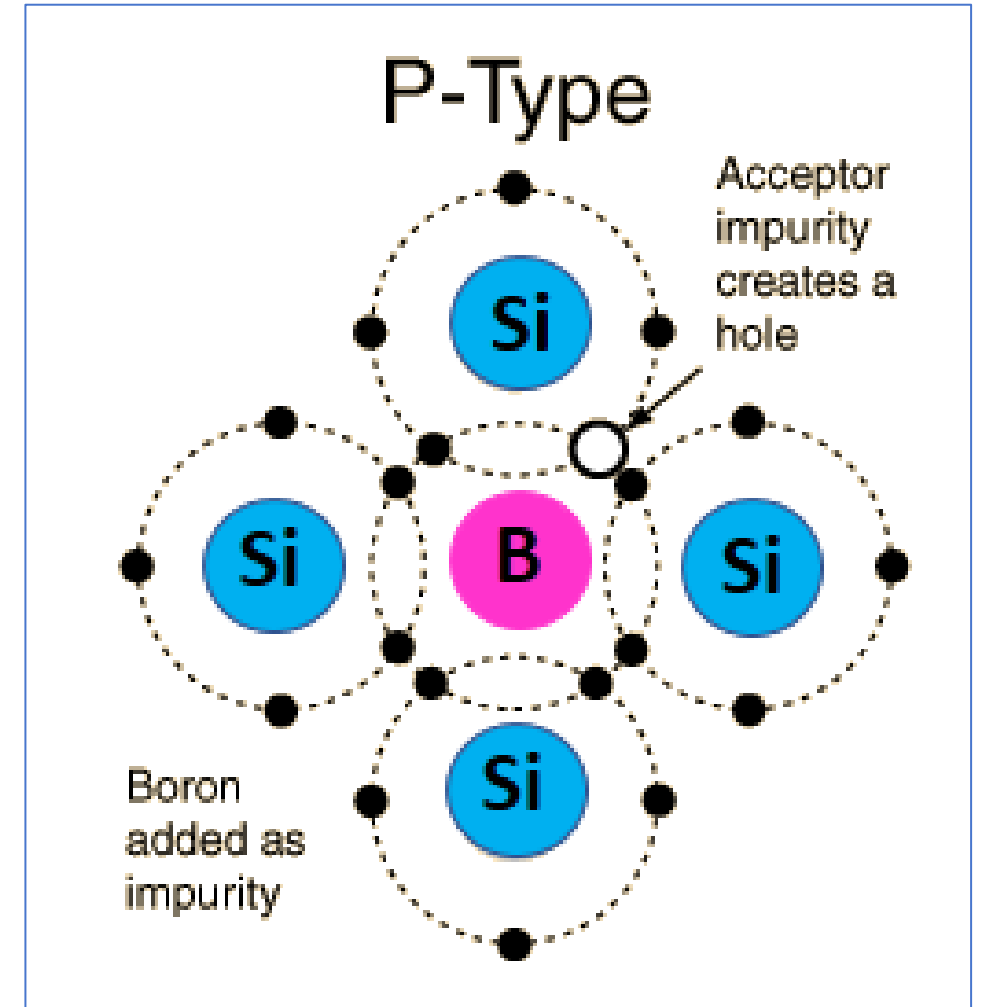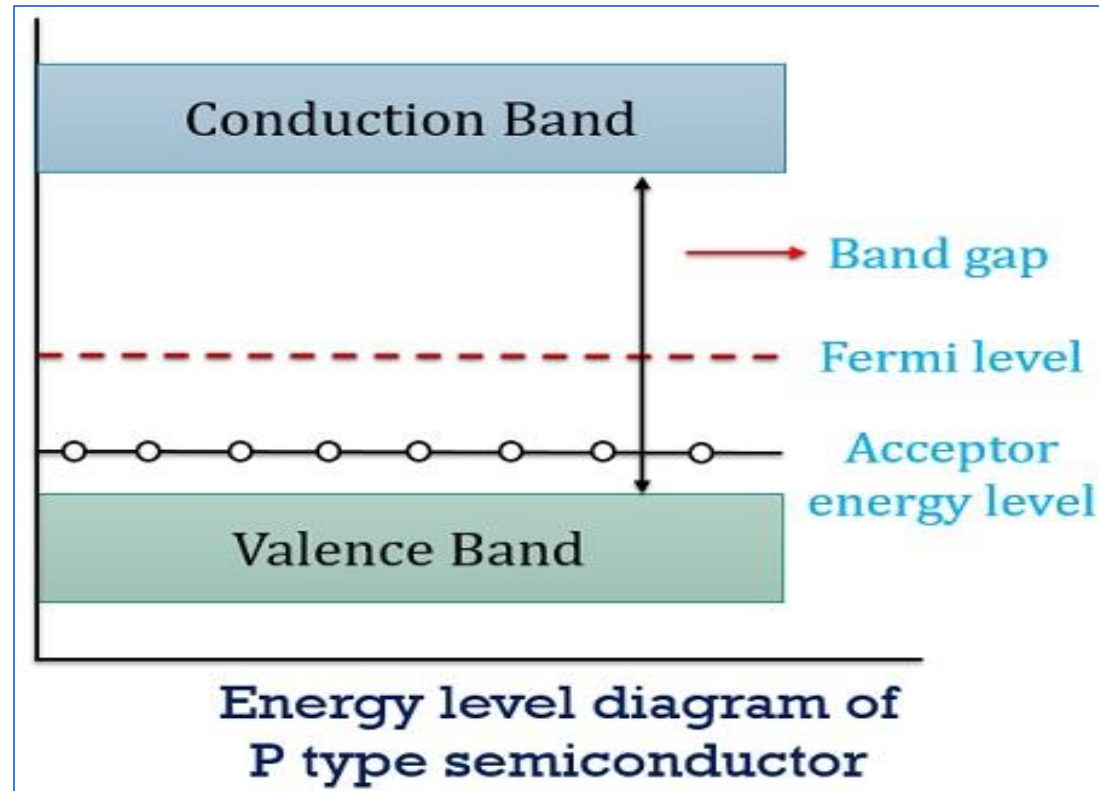
- the Fermi level (E_F) is located between valence band and acceptor level at lower temperatures

- but as temperature increases, the Fermi level (E_f) moves towards the intrinsic Fermi level (E_i).

Energy band diagram for a p-type semiconductor

- In p-type semiconductors an acceptor energy level (E_a) exists which is close to valence band as shown in the fig.
- At 0K the acceptor energy level is filled with hole. Fermi level lies close to valence band.
- At TK the electrons move to acceptor energy level by leaving a hole in the valence band. The number holes in the valence band is equal to number of negative ions in the acceptor energy level.
- As the temperature raises the covalent bond breaks and electrons move from valence band to conduction band.
- Hence the current is due to holes which are called majority charge carriers. Hence, number of holes are greater than number of electrons i.e., p>>n
- At high temperatures P-type semiconductor will act as intrinsic semiconductor.
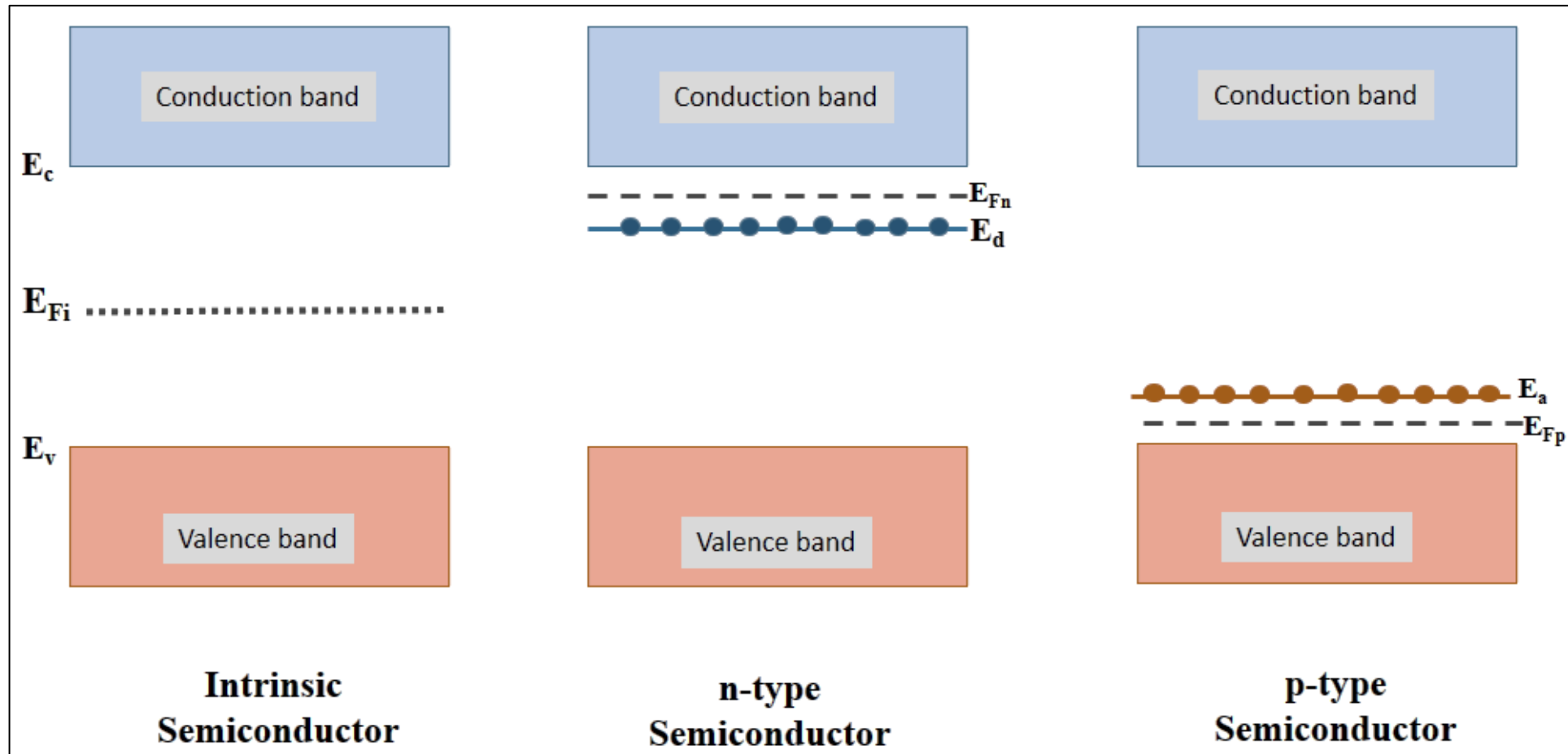
Fermi Energy And Fermi Level- Important Points

- Electrons are **Fermions** i.e. they have spin half and they obey Pauli's exclusion principle.

- Each energy level can accommodate only two electrons at most.

- The highest energy level occupied by the electron at 0 K is known as Fermi energy level.

- **At 0 K** all the energy levels below the Fermi level are completely filled and all energy levels above Fermi level are totally empty.

- At T > 0 K, the probability of occupation of electrons at Fermi level is half.

- At T > 0 K, probability of finding the electrons above Fermi level increases.

- At T > 0 K, probability of finding the electrons below Fermi level decreases

Fermi-Dirac Statistical Distribution

The probability that an electron occupies an energy level E, at thermal equilibrium is given by

$$f(E) = \frac{1}{1 + e^{(E - E_F)/k_B T}}$$

where, $f(E)$ is called the Fermi factor or Fermi function

k_B = Boltzmann constant = 1.38×10^{-23} JK^{-1}

T = is the absolute temperature in Kelvin

E_F = Fermi level or the Fermi energy.

The above equation is known as Fermi-Dirac equation or Fermi-Dirac distribution function.

- *Note: the probability of the electron to occupy the energy level E increases with temperature.

Effect of Temperature on Fermi-Dirac Distribution Function

> **At temperature 0 K:**

i. when $E < E_F$,

$$f(E) = \frac{1}{1+e^{-\infty}} = \frac{1}{0+1} = 1$$
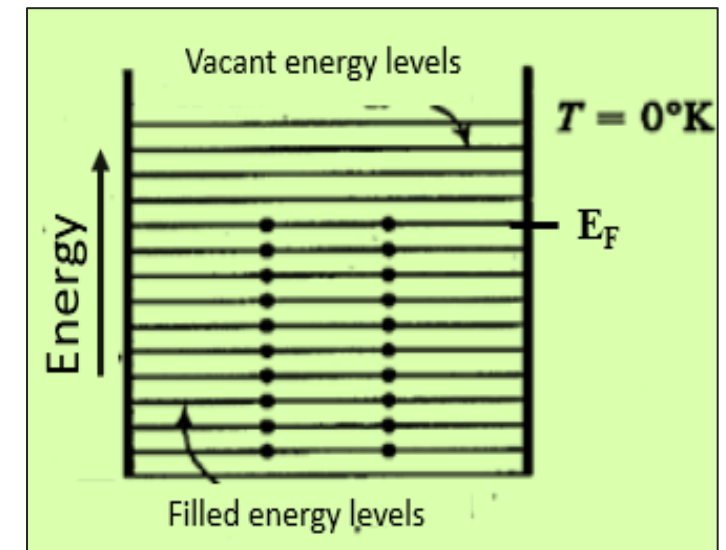
which implies that at T=0 K,

all the energy levels below the Fermi level are occupied.

ii. when $E > E_F$,

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

which implies that at T=0K,

all the energy levels above Fermi levels are empty.

iii. For $E = E_F$,

$$f(E) = \frac{1}{1+e^{\frac{0}{0}}} = \text{indeterminate}$$

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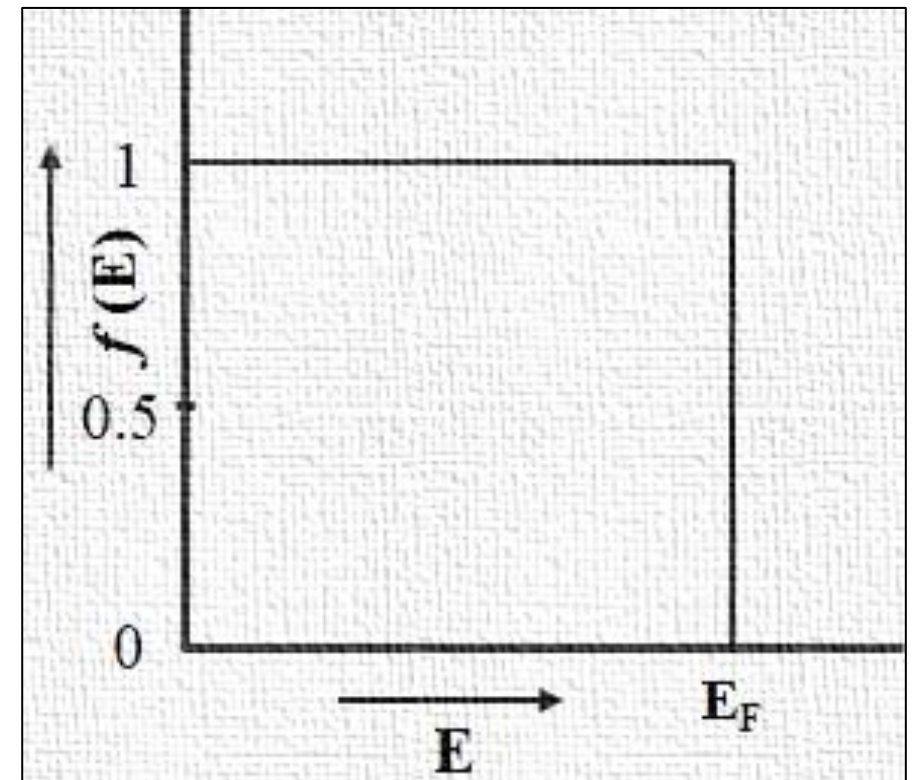
The curve has step-like character with

- $f(E) = 1$ for energies below E_F and

- $f(E) = 0$ for energies above E_F, shown in the figure.

This represents that at absolute zero, all the energy states below E_F are filled with electrons and all those above it are empty.

➢ At temperature T > 0 K

On heating the conductor, electrons are excited to higher energy levels. In general, $E_F \gg kT$.

- At normal temperatures, only the electrons occupying the energy levels near the Fermi level can be thermally excited to the energy level somewhat above E_F.

- Thus, as a result of thermal excitation

✓ the probability of finding electrons in the levels immediately below E_F will decrease and
✓ the probability of finding electrons in the levels immediately above E_F will increase.
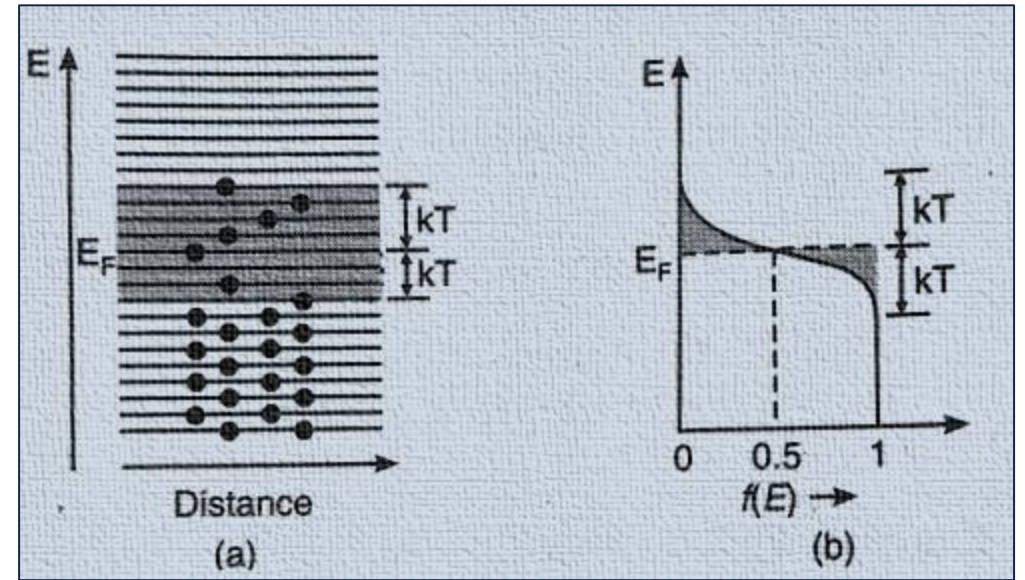
Fermi level can be defined as the energy level which has the probability of occupancy of 0.5.

$$f(E) = \frac{1}{1+\exp(E-E_F)/K_B T} < 1 \text{ for } E < E_F$$
$$> 0 \text{ for } E > E_F$$
$$= \frac{1}{2} \text{ for } E = E_F$$

At T > 0K, if we consider electron at Fermi level i.e. $E = E_F$

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

This implies that the probability of occupancy of Fermi level at any temperature above 0K is 0.5 or 50%.

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.

Variation of Fermi Function With Temperature

- From figure shown, we can see that as the temperature is raised from absolute zero to $T_1 K$, the distribution curve begins to depart from step-like function and tails off smoothly to zero.

A graph has been plotted between $f(E)$ and E, at different temperatures 0 K, T_1, T_2, T_3 is shown in Figure.

From the figure, it is clear that,

- at $T = 0 K$, there is an *abrupt jump* in value of $f(E)$ from 1 to 0 at E_F.

- At $T > 0K$ the change is *gradual.*
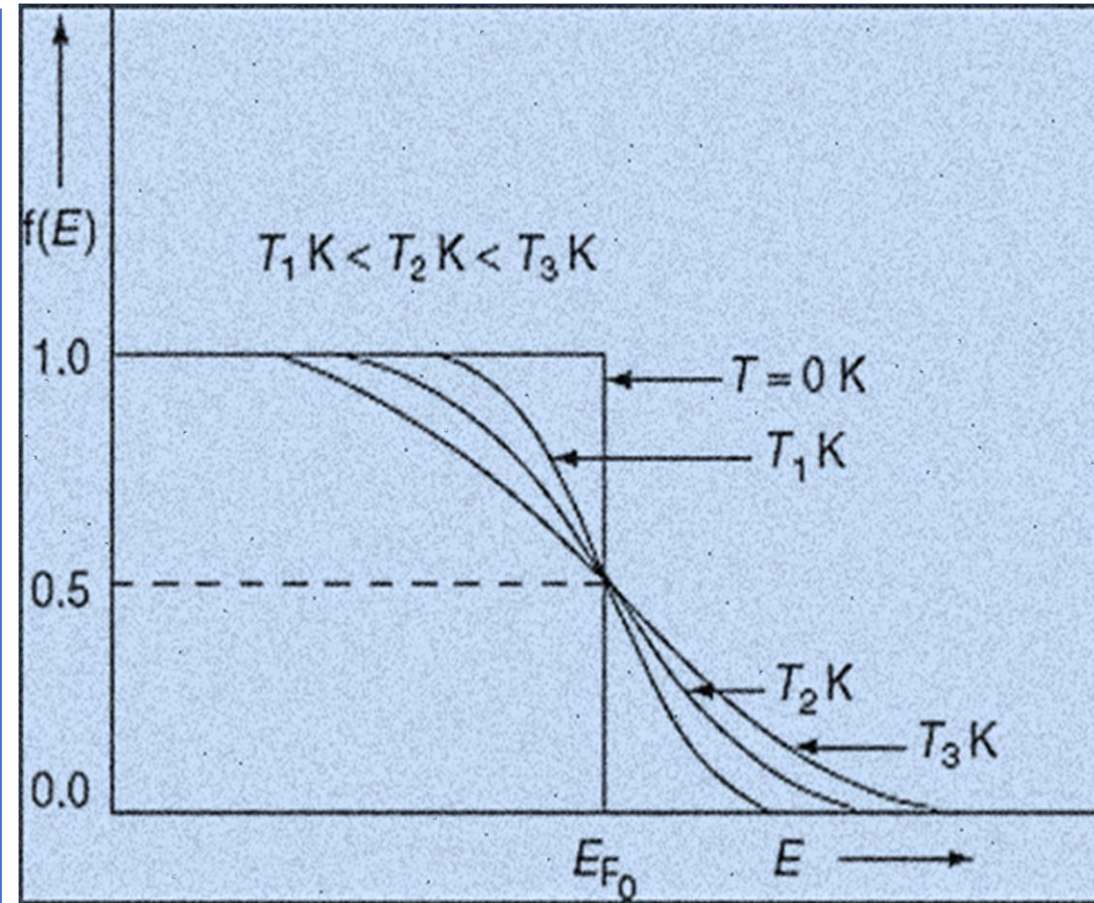
Comparison between Distributions

Boltzmann	Bose Einstein	Fermi Dirac
$$f_{MB}(\varepsilon) = A e^{-\frac{\varepsilon}{kT}}$$	$$f_{BE}(\varepsilon) = \frac{1}{e^{\alpha} e^{\varepsilon/kT} - 1}$$	$$f_{FD}(\varepsilon) = \frac{1}{\exp\left(\dfrac{\varepsilon - \varepsilon_F}{k_B T}\right) + 1}$$
Identical and distinguishable	Identical and indistinguishable	Identical and indistinguishable
spin doesn't matter	integer spin 0,1,2 …	half-integer spin 1/2,3/2,5/2 …
localized particles Ψ don't overlap	bosons	fermions
gas molecules at low densities	wave functions overlap total Ψ symmetric	wave functions overlap total Ψ anti-symmetric
"unlimited" number of particles per state $n_K \ll 1$	photons ^{4}He atoms	free electrons in metals electrons in white dwarfs
	unlimited number of particles per state	never more than 1 particle per state

Difference between Intrinsic and Extrinsic Semiconductor

S.No	Intrinsic Semiconductor	Extrinsic Semiconductor
1.	Semiconductor in a pure form is called intrinsic semiconductor.	Semiconductor which are doped with impurity is called extrinsic semiconductor
2.	Here the change carriers are produced only due to thermal agitation.	Here the change carriers are produced due to impurities and may also be produced due to thermal agitation.
3.	They have low electrical conductivity.	They have high electrical conductivity.
4.	They have low operating temperature.	They have high operating temperature.
5.	At 0K, Fermi level exactly lies between conduction band and valence band.	At 0K, Fermi level exactly lies closer to conduction band in "n" type semiconductor and lies near valence band in "p" type semiconductor.
	Examples: Si,Ge,etc.	**Examples:** Si and Ge doped with Al, In,P,As etc

Difference between the P and N type semiconductors

Sl No	P-type Semi conductor	N-type semi conductor
1	P-type semiconductor is formed due to the dopping of III group elements i.e. Boron, Aluminium, Thallium.	N-type semi conductor is formed due to dopping of Nitrogen, Phosporus, Arsenic, Antimony, Bismoth.
2	These are also known as Trivalent semi conductors.	These are also known pentavalent semiconductor.
3	P-type semiconductors is positive type semiconductor it means it deficiency of 1 electron is required.	N-type semiconductor is negative type semi-conductor it means excess of 1 electron is required.
4	In P-type semiconductor majority charge carries are holes and minority charge carries are electrons.	In N-type semiconductor majority charge carries are electrons and minority charge carries are hole.
5	A hole indicates a missing electron. In this no. of holes is more than the no. of electrons.	In N-type semiconductor the no. of holes is less than the no. of free electron.

DENSITY OF STATES (DOS)

The density of states (DOS) is defined as the number of various states at a particular energy level that electrons are allowed to occupy, i.e. the number of electron states available per unit volume per unit energy. Bulk properties such as specific heat, paramagnetic susceptibility and other transport phenomena of conductive solids depend on this function.

- *Density of states in 3-D (Bulk)*

$$g(E) = \frac{1}{2\pi^2}\left(\frac{2m^*}{\hbar^2}\right)^{3/2}\sqrt{E_g - E}$$

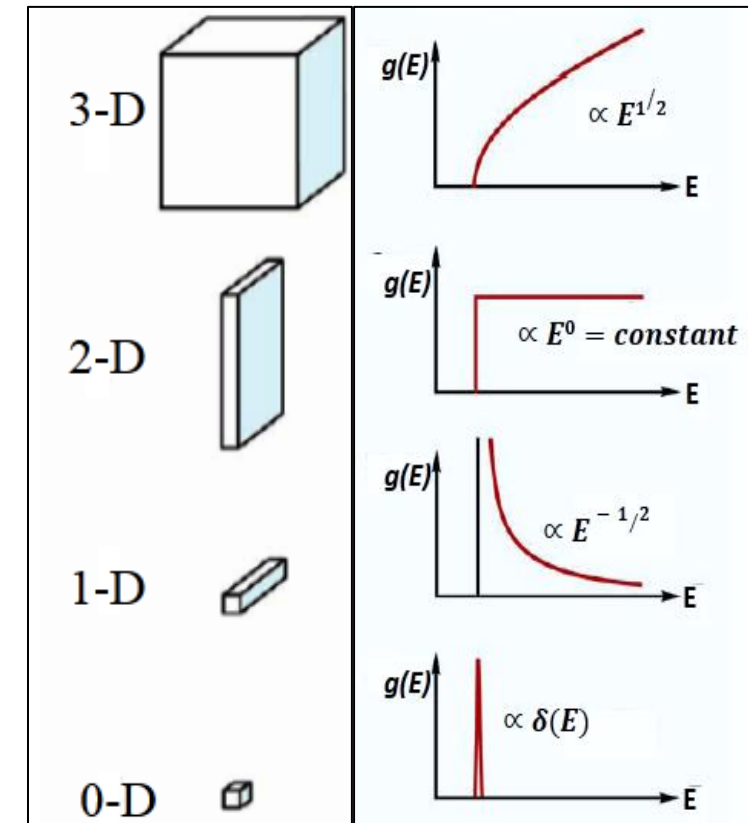- *Density of states in 2-D (Quantum Well)*

$$g(E) = \frac{m^*}{\pi\hbar^2}$$

- *Density of states in 1-D (Quantum Wire)*

$$g(E) = \frac{m^*}{\pi\hbar}\sqrt{\frac{m^*}{2\,(E_g - E)}}$$

- *Density of states in 0-D (Quantum dot)*

$$g(E) = 2\delta(E_g - E)$$

Expression For Carrier Concentration of Intrinsic Semiconductors

i.e. Expression For Electron Concentration And Hole Concentration

Carrier Concentration in Intrinsic Semiconductor

- When a suitable form of Energy is supplied to a Semiconductor then electrons take transition from Valence band to Conduction band.

- Hence a free electron in Conduction band and simultaneously free hole in Valence band is formed. This phenomenon is known as Electron - Hole pair generation.

- In Intrinsic Semiconductor the Number of Conduction electrons will be equal to the Number of Vacant sites or holes in the valence band.

Carrier concentration is the no. of electrons in conduction band per unit volume (n) and the no. of holes in valence band per unit volume (p) of the material.

➤ Calculation of electron density

Let $dn \rightarrow$ number of electrons whose energy lie in the energy interval E and $E + dE$ in the conduction band. Then,

$$dn = Z(E)\, f(E)\, dE \qquad \text{------ (1)}$$

where $Z(E)\, dE \rightarrow$ is the density of state in the energy interval E and $E + dE$

$f(E) \rightarrow$ probability that a state of energy is occupied by an electron.

$$n = \int_{E_c}^{\infty} Z(E)\, f(E)\, dE \qquad \text{------- (2)}$$

The density of state in the conduction band is given by

$$Z(E)\, dE = \frac{4\pi}{h^3}\, (2m_e^*)^{3/2}\, E^{1/2}\, dE \qquad for\ E > E_c$$

The bottom level of conduction band (E_c) corresponds to the P.E of electron at rest. Thus, ($E-E_c$) is the K.E of electron in the higher levels of the conduction band.

Therefore, above equation can be written as

$$Z(E)\, dE = \frac{4\pi}{h^3}\, (2m_e^*)^{3/2}\, (E - Ec)^{1/2}\, dE \qquad \text{------(3)}$$

The probability of an electron occupying an energy level is given by

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

When number of available energy states >> number of electrons, the Fermi-Dirac distribution function can be approximated to the Boltzmann function.

$$f(E) = exp.[\,-(E - E_F)/\ kT]\qquad\text{------ (4)}$$

Substituting values (3) and (4) in equation (2), we get

$$n = \frac{4\pi}{h^3}\,(2m_e^*)^{3/2}\int_{E_c}^{\infty}(E - Ec)^{1/2}\,e^{-(E - E_F)/\ kT}\,dE$$

$$n = \frac{4\pi}{h^3}\,(2m_e^*)^{3/2}\int_{E_c}^{\infty}(E - E_c)^{1/2}\,e^{-(E - E_F + E_c - E_c)/\ kT}\,dE$$

$$n = \frac{4\pi}{h^3}\,(2m_e^*)^{3/2}e^{(E_F - E_c)/\ kT}\int_{E_c}^{\infty}(E - E_c)^{1/2}\,e^{-(E - E_c)/\ kT}\,dE\qquad\text{-------(5)}$$

The above integral is of the standard form whose solution is given by

$$\int_0^{\infty} x^{1/2}\,e^{-ax}\,dx = \frac{\sqrt{\pi}}{2a^{3/2}}$$

where $a = 1/kT$ and $x = (E - E_c)$

So, equation (5) becomes

$$n = = \frac{4\pi}{h^3}(2m_e^*)^{3/2}e^{(E_F - E_c)/kT}\left[\frac{\sqrt{\pi}}{2}(kT)^{3/2}\right]$$

$$n = 2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{3/2}e^{-(E_c - E_F)/kT}$$

Put

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

and it is known as **_effective density of states_** in the conduction band and its is temperature dependent. In Si, at 300K, $N_c = 2.8 \times 10^{25}/m^3$

Thus, we get

$$n = N_c e^{-(E_c - E_F)/kT}$$

This is the expression for the electrons concentration in the conduction band of intrinsic semiconductor.

➢ Calculation of hole density

Let $dp \rightarrow$ number of holes whose energy lie in the energy interval E and $E + dE$ in the valence band. Then,

$$dp = Z(E) \, [1 - f(E)] \, dE \; \text{------ (1)}$$

$$p = \int_{-\infty}^{E_v} Z(E) \, f(E) \, dE \qquad \text{--------- (2)}$$

where $Z(E) \, dE \rightarrow$ is the density of state in the energy interval E and $E + dE$

$[1 - f(E)] \rightarrow$ Probability that a state of energy is vacant i.e. is not occupied by an electron.

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

$$[1 - f(E)] = e^{-(E_F - E)/kT} \qquad \text{---- (3)}$$

The density of state in the valence band is given by

$$Z(E) \, dE = \frac{4\pi}{h^3} \, (2m_h^*)^{3/2} E^{1/2} \, dE$$

The topmost level of valence band (E_v) corresponds to the P.E of a hole at rest. Thus, (E_v -E) is the K.E of hole in the lower energy levels of the valence band.

Therefore, above equation can be written as

$$Z(E) \, dE = \frac{4\pi}{h^3} \, (2m_h^*)^{3/2} \, (E_v - E)^{1/2} \, dE \qquad \text{------(4)}$$

Substituting values (3) and (4) in equation (2), we get

$$p = \frac{4\pi}{h^3} \, (2m_h^*)^{3/2} \int_{-\infty}^{E_v} (E_V - E)^{1/2} \, e^{-(E_F - E)/kT} \, dE$$

$$p = \frac{4\pi}{h^3} \, (2m_h^*)^{3/2} \int_{-\infty}^{E_v} (E_V - E)^{1/2} \, e^{-(E - E_F + E_v - E_v)/kT} \, dE$$

$$\boldsymbol{p} = \frac{4\pi}{h^3} \, (2m_h^*)^{3/2} e^{-(E_F - E_v)/kT} \int_{-\infty}^{E_v} (E_V - E)^{1/2} \, e^{-(E_v - E)/kT} \, dE \qquad \text{------(5)}$$

The above integral is of the standard form whose solution is given by

$$\int_0^\infty x^{1/2} \, e^{-ax} \, dx = \frac{\sqrt{\pi}}{2a^{3/2}}$$

where $a = 1/kT$ and $x = (E_v - E)$

So, equation (5) becomes

$$p = \frac{4\pi}{h^3}(2m_h^*)^{3/2} e^{-(E_F-E_v)/kT} \left[\frac{\sqrt{\pi}}{2}(kT)^{3/2}\right]$$

$$p = 2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{3/2} e^{-(E_F-E_v)/kT}$$

Put

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

and it is known as **effective density of states** in the valence band.

Thus, we get

$$p = N_v\, e^{-(E_F-E_v)/kT}$$

This is the expression for the hole concentration in the valence band of intrinsic semiconductor.

➤ Intrinsic carrier concentration

In intrinsic semiconductor, the concentration of both the charge carriers i.e. electrons and holes is equal, and therefore they both are denoted as n_i.

$$n = p = n_i$$

$$n_i^2 = np$$

$$n_i^2 = (N_c e^{-(E_c - E_F)/kT})(N_v e^{-(E_F - E_v)/kT})$$

$$n_i^2 = (N_c N_v) e^{-(E_c - E_v)/kT}$$

$$But\ (E_c - E_v) = E_g$$

$$n_i^2 = (N_c N_v) e^{-E_g/kT}$$

Substituting the values of N_c and N_v, we get

$$n_i^2 = 4 \left[\frac{2\pi\ kT}{h^2}\right]^3 (m_e^* m_h^*)^{3/2} e^{-E_g/kT}$$

$$n_i = 2 \left[\frac{2\pi\ kT}{h^2}\right]^{3/2} (m_e^* m_h^*)^{3/4} e^{-E_g/2\ kT}$$

$$n = N_c\, e^{-(E_c - E_F)/\, kT}$$

$$p = N_v\, e^{-(E_F - E_v)/\, kT}$$

Since n = p,

$$N_c\, e^{-(E_c - E_F)/\, kT} = N_v\, e^{-(E_F - E_v)/\, kT}$$

Taking log on both sides

$$-\frac{(E_c - E_F)}{kT} = ln\frac{N_v}{N_c} - \frac{(E_F - E_v)}{kT}$$

$$-E_c + E_F = kT\, ln\frac{N_v}{N_c} - E_F + E_v$$

$$2E_F = kT\, ln\frac{N_v}{N_c} + (E_c + E_v)$$

$$E_F = \frac{1}{2}kT\, ln\frac{N_v}{N_c} + \frac{1}{2}(E_c + E_v)$$

$$N_c = 2 \left[\frac{2\pi m_e^* kT}{h^2}\right]^{3/2} \quad \text{and} \quad N_v = 2 \left[\frac{2\pi m_h^* kT}{h^2}\right]^{3/2}$$

Therefore, $\quad \dfrac{N_v}{N_c} = \left(\dfrac{m_h^*}{m_e^*}\right)^{3/2}$

$$ln \frac{N_v}{N_c} = \frac{3}{2} \, ln \left(\frac{m_h^*}{m_e^*}\right)$$

$$E_F = \frac{1}{2}(E_c + E_v) + \frac{3}{4} kT \, ln \left(\frac{m_h^*}{m_e^*}\right)$$

If $m_e^* = m_h^*$, then $\quad ln\left(\dfrac{m_h^*}{m_e^*}\right) = 0$

$$E_F = \frac{1}{2}(E_c + E_v)$$

$$E_F = \frac{1}{2}(E_c - E_v) + E_v$$

$$E_F = \frac{1}{2} E_g + E_v$$

If we denote top of valence band as zero level, $E_v = 0$

$$\textcolor{red}{E_F = \frac{1}{2} E_g}$$

Then

Variation of Fermi Level (E_F) with Temperature

> **For Intrinsic semiconductors**

It is found that with an increase in temperature the Fermi level

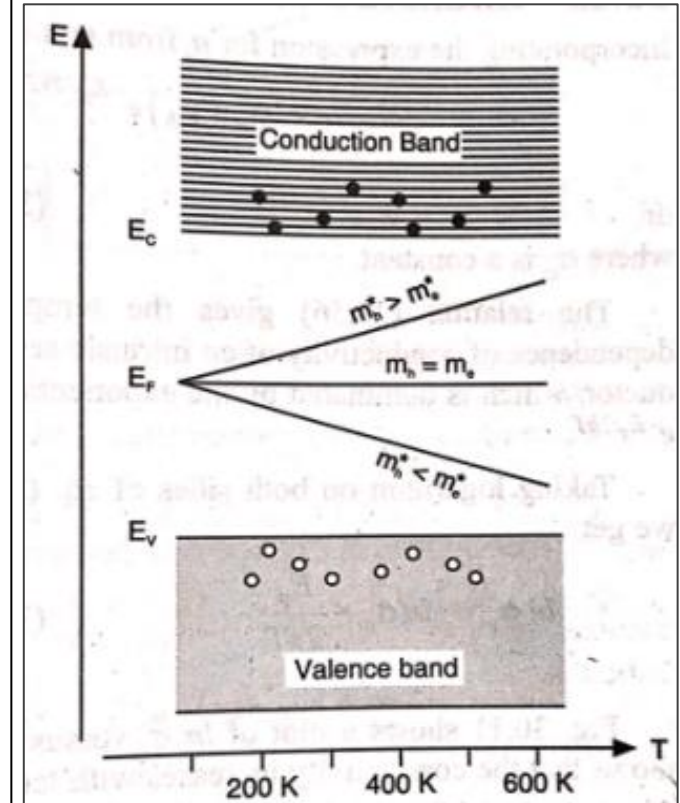- **shifts *up*** towards the lowermost level of conduction band if

$$m^*_h > m^*_e$$

- **shifts *downwards*** to the topmost level of valence band

$$m^*_h < m^*_e$$

In general, for intrinsic semiconductors,

the Fermi level is considered to be independent of temperature and thus, lies in the mid of band gap irrespective of the temperature.

Carrier Concentration in N-type Semiconductor

- Let $N_d \rightarrow$ number of donor atoms in the semiconductor

When temperature is increased above 0 K, the donor atoms get ionized and the electrons start moving from donor levels to the conduction band.

- $E_d \rightarrow$ energy required by electrons to move from donor levels to the conduction band

- If $n \rightarrow$ electron concentration in conduction band

we assume that

$$n = N_d^+$$

$$n = N_d - N_d^0$$

where $N_d^+ \rightarrow$ is the number of ionized donor atoms

$N_d^0 \rightarrow$ is the number of unionized donor atom left at energy level E_d

$$n = N_d - N_d \, f\,(E_d)$$

$$n = N_d\,[1 - f\,(E_d)] = N_d\,[1 - \frac{1}{1+e^{(E_d - E_F)/\,kT}}\,]$$

$$n = N_d\,[\frac{1}{1+e^{-(E_d - E_F)/\,kT}}]$$

or, $\qquad \boldsymbol{n = N_d\,e^{(E_d - E_F)/\,kT}}$ ------- (1)

But, electron concentration in conduction band is given as,

$$\boldsymbol{n = N_c\,e^{-(E_c - E_F)/\,kT}} \qquad \text{------- (2)}$$

Equating (1) and (2)

$$N_d\,e^{(E_d - E_F)/\,kT} = N_c\,e^{-(E_c - E_F)/\,kT}$$

Taking log on both sides and rearranging the terms, we get

$$\left(\frac{E_d - E_F}{kT}\right) + \left(\frac{E_c - E_F}{kT}\right) = ln\,\frac{N_c}{N_d}$$

$$(E_d + E_c) - 2\,E_F = (kT)\,ln\,\frac{N_c}{N_d}$$

$$E_F = \frac{(E_d + E_c)}{2} - \left(\frac{kT}{2}\right) \ln \frac{N_c}{N_d}$$

$$E_F = \frac{(E_d + E_c)}{2} + \left(\frac{kT}{2}\right) \ln \frac{N_d}{N_c}$$

$$E_F = \frac{(E_d + E_c)}{2} + \left(\frac{kT}{2}\right) \ln \frac{N_d}{2\left(2\pi m_e^* kT / h^2\right)^{3/2}} \qquad \text{--------- (3)}$$

at T = 0 K, above equation gives

$$E_F = \frac{(E_d + E_c)}{2}$$

i.e. the Fermi level lies between the bottom of conduction band and donor levels.

Rewriting equation (2)

$$n = N_c\, e^{(E_F - E_c)/kT}$$

Substituting value of E_F from equation (3) in the above relation, we obtain

$$n = N_c\, exp \left[\frac{(E_d + E_c)}{2} + \left(\frac{kT}{2}\right) \ln \frac{N_d}{2\left(2\pi m_e^* kT / h^2\right)^{3/2}} - E_c \right] / kT$$

$$n = N_c\, exp \left[\frac{(E_d - E_c)}{2kT} + \left(\frac{1}{2}\right) \ln \frac{N_d}{2\left(2\pi m_e^* kT / h^2\right)^{3/2}} \right]$$

$$n = N_c \, exp \left[\frac{(E_d - E_c)}{2kT} + ln \sqrt{\frac{N_d}{2\left(2\pi m_e^* kT / h^2\right)^{3/2}}} \right] \qquad \left[\because \frac{1}{2} ln \, x = ln \sqrt{x}\right]$$

$$n = N_c \, exp \left(\frac{E_d - E_c}{2kT}\right) . \, exp \left[ln \sqrt{\frac{N_d}{2\left(2\pi m_e^* kT / h^2\right)^{3/2}}} \right] \qquad [\because exp(a + b) = exp \, a . exp \, b]$$

$$n = N_c \, exp \left(\frac{E_d - E_c}{2kT}\right) \sqrt{\frac{N_d}{2\left(2\pi m_e^* kT / h^2\right)^{3/2}}} \qquad [\because exp(\ln x) = x]$$

Substituting the value $N_c = 2 \left[\frac{2\pi m_e^* kT}{h^2}\right]^{3/2}$, we get

$$n = 2 \left[\frac{2\pi m_e^* kT}{h^2}\right]^{3/2} exp \left(\frac{E_d - E_c}{2kT}\right) \sqrt{\frac{N_d}{2\left(2\pi m_e^* kT / h^2\right)^{3/2}}}$$

$$n = (2N_d)^{1/2} \left[\frac{2\pi m_e^* kT}{h^2}\right]^{3/4} exp \left(\frac{E_d - E_c}{2kT}\right)$$

From this expression, it is clear that, the n-type semiconductor the electron concentration is dependent on the donor concentration (i.e. it is directly proportional to the square root of N_d).

Carrier Concentration In P-type Semiconductor

- Let $N_a \rightarrow$ number of donor atoms in the semiconductor

When temperature is increased above 0 K, the acceptor atoms get ionized and the holes start appearing in the valence band.

- $E_a \rightarrow$ energy required by electrons to move into acceptor levels from the valence band

- If $p \rightarrow$ hole concentration in valence band

we assume that, $p = N_a^-$

where $N_a^- \rightarrow$ is the number of ionized acceptor atoms

- The concentration of ionized acceptor atoms

$$N_a^- = N_a\, f\,(E_a)$$

$$p = N_a\, exp\left(\frac{E_F - E_a}{kT}\right) \qquad \text{------- (1)}$$

- But, the hole concentration in valence band is given as: $p = N_v\, e^{-(E_F - E_v)/\, kT}$

$$p = N_v\, exp\left(\frac{E_v - E_F}{kT}\right) \qquad \text{----- (2)}$$

Equating (1) and (2)

$$N_a \, exp \left(\frac{E_F - E_a}{kT} \right) = N_v \, exp \left(\frac{E_v - E_F}{kT} \right)$$

Taking log on both sides and rearranging the terms, we get

$$\left(\frac{E_F - E_a}{kT} \right) + \left(\frac{E_v - E_F}{kT} \right) = ln \frac{N_v}{N_a}$$

$$-(E_v + E_a) - 2 \, E_F = (kT) \, ln \frac{N_v}{N_a}$$

$$E_F = \frac{(E_v + E_a)}{2} + \left(\frac{kT}{2} \right) ln \frac{N_v}{N_a}$$

$$E_F = \frac{(E_v + E_a)}{2} - \left(\frac{kT}{2} \right) ln \frac{N_a}{N_v}$$

$$E_F = \frac{(E_v + E_a)}{2} - \left(\frac{kT}{2} \right) ln \frac{N_a}{2 \left(2\pi m_h^* kT / h^2 \right)^{3/2}} \qquad \text{-------- (3)}$$

at T = 0 K, $$E_F = \frac{(E_v + E_a)}{2}$$

i.e. the Fermi level lies exactly between the top level of valence band and acceptor levels.

Substituting value of E_F from equation (3) in the equation (2), we obtain

$$p = N_v \, exp \left(\frac{E_v - E_F}{kT} \right)$$

$$p = N_v \, exp \left[\frac{E_v}{kT} - \frac{(E_v + E_a)}{2kT} + \left(\frac{1}{2} \right) \, ln \, \frac{N_a}{2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2}} \right]$$

$$p = N_v \, exp \left[\frac{(E_v - E_a)}{2kT} + \left(\frac{1}{2} \right) \, ln \, \frac{N_a}{2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2}} \right]$$

$$p = N_v \, exp \left[\frac{(E_v - E_a)}{2kT} + ln \, \sqrt{ \frac{N_a}{2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2}} } \right] \qquad [\because \tfrac{1}{2} ln \, x = ln \, \sqrt{x}]$$

$$p = N_v \, exp \left(\frac{E_v - E_a}{2kT} \right) exp \left[ln \, \sqrt{ \frac{N_a}{2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2}} } \right] \qquad [\because exp(a + b) = exp \, a \, . \, exp \, b]$$

$$p = N_v \; exp\left(\frac{E_v - E_a}{2kT}\right) \left[\sqrt{\frac{N_a}{2\left(2\pi m_h^* kT / h^2\right)^{3/2}}}\right] \qquad [\because exp(\ln x) = x]$$

Substituting the value $N_v = 2 \left[\frac{2\pi m_h^* kT}{h^2}\right]^{3/2}$, we get

$$p = 2 \left[\frac{2\pi m_h^* kT}{h^2}\right]^{3/2} exp\left(\frac{E_v - E_a}{2kT}\right) \left[\sqrt{\frac{N_a}{2\left(2\pi m_h^* kT / h^2\right)^{3/2}}}\right]$$

$$p = (2N_a)^{1/2} \left[\frac{2\pi m_h^* kT}{h^2}\right]^{3/4} exp\left(\frac{E_v - E_a}{2kT}\right)$$

From above expression, it is clear that, in p-type semiconductor the hole concentration is dependent on the acceptor concentration (i.e. it is directly proportional to the square root of N_a).

INTRINSIC CONDUCTIVITY

When a potential difference is applied across a semiconductor then under the influence of electric field 'E',

➢ Electrons move opposite to electric field direction

➢ Holes move in the direction of electric field.

The net movement of electrons and holes is called **drift** and corresponding velocity is called drift velocity.

Drift motion is superimposed on random thermal motion and is directional and causes current flow.

The drift velocity is also given by $\quad v_d = \mu E$

where μ is the mobility of electrons or holes.

mobility is given as $\qquad \mu = \dfrac{v_d}{E} = \dfrac{e\tau_c}{m^*}$ $\qquad$ and is expressed in the **units m²/V-s**

where τ_c is the average time taken to travel between two collisions and is called mean free time or ***relaxation time*** τ_c

The number of electrons crossing any plane of cross-sectional area A in one second is $nv_d A$

$$\text{current } I = env_d A$$

$$\text{Current density } J = I/A = nev_d$$

- ➢ For electrons drifting in Conduction band current density J_e, is given by

$$J_e = nev_{de} = ne\mu_e E$$

- ➢ For holes drifting in valence band current density J_e, is given by

$$J_h = pev_{dh} = pe\mu_h E$$

where μ_e and μ_h are the mobility's of electrons and holes resp.

Comparing with Ohm's law, $\quad$ J = σE, we get

$$\sigma_e = ne\mu_e$$
$$\sigma_h = pe\mu_h$$

Total current density, $J = J_e + J_h$

$$J = (ne\boldsymbol{\mu_e} + pe\mu_h)E$$

Therefore,

Intrinsic conductivity

$$\boxed{\sigma = ne\boldsymbol{\mu_e} + pe\mu_h}$$

as $n = p = n_i$

$$\sigma = en_i \left(\boldsymbol{\mu_e} + \mu_h\right)$$

In general, variation of mobility with temperature is very small.

Hence, large variation in conductivity is linked to electron/hole concentration with temperature.

$$\sigma \propto n_i (T)$$

$$\rho = 1/\sigma = 1/ne\mu_n$$

Variation of Intrinsic Conductivity with Temperature

- The conductivity of a semiconductor depends on the concentration of the charge carriers (n & p)

- Similar to drift velocity of electrons under an applied field in metals in semiconductors the concept of mobility is used to calculate conductivity.

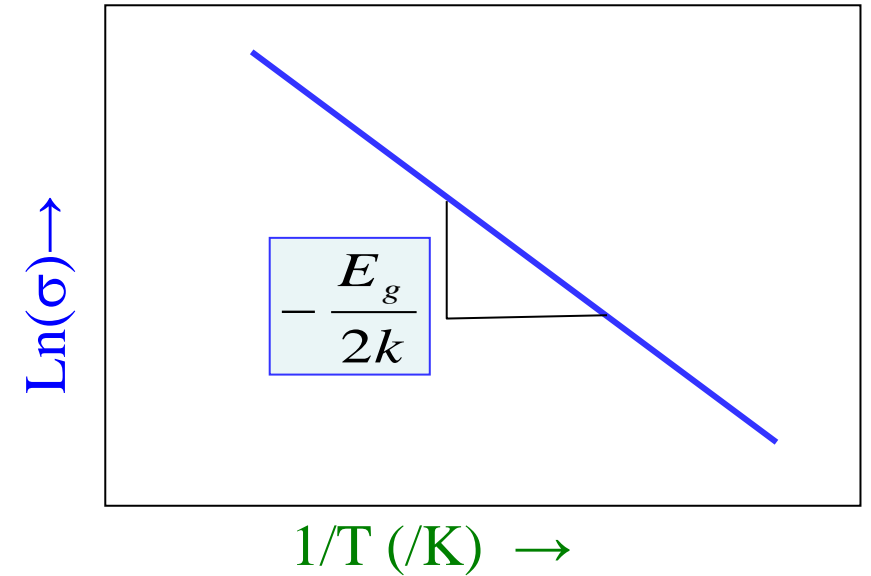$$\sigma = ne\mu_e + pe\mu_h$$

Substituting the values of n and p, we get

$$\sigma = N\,e\,(\,\mu_e + \mu_h\,)\exp\left[-\frac{E_g}{2kT}\right]$$

$$\sigma = N \, e \, (\mu_e + \mu_h)\exp\left[-\frac{E_g}{2kT} \right]$$

$$\sigma = \sigma_\circ \exp\left[-\frac{E_g}{2kT} \right]$$

$$\ln \sigma = \ln \sigma_\circ - \frac{E_g}{2kT}$$

$$-\frac{E_g}{2k}$$

Ln(σ)→

1/T (/K) →

EXTRINSIC CONDUCTIVITY

Conductivity in N-type semiconductor

$$\sigma_n = (n_n e \mu_e + p_n e \mu_h)$$

❖ As in n-type semiconductor, $p_n << n_n$

$$\sigma_n = n_n e \mu_e$$

Conductivity in p-type semiconductor

$$\sigma_p = (p_p e \mu_h + n_p e \mu_e)$$

❖ As in p-type semiconductor, $n_p << p_p$

$$\sigma_p = p_p e \mu_h$$

Addition of n-type impurities decreases the number of holes below a level. Similarly, the addition of p-type impurities decreases the number of electrons below a level.

It has been experimentally found that
"Under thermal equilibrium for any semiconductor, the product of no. of holes and the no. of electrons is constant and independent of amount of doping. This relation is known as **"mass action law"**

$$n.p = n_i^2$$

where n = electron concentration,
p = hole concentration and
n_i = intrinsic concentration
This relation is equally valid for extrinsic semiconductors also.

For N-type Semiconductor:

$$n_n = N_c\, e^{-(E_c - E_F)/kT}$$

$$p_n = N_v\, e^{-(E_F - E_v)/kT}$$

$$n_n\, p_n = N_c\, N_v\, e^{-E_g/kT}$$

$$n_n\, p_n = n_i^2 \qquad \underline{\hspace{2cm}}(1)$$

For P-type Semiconductor:

$$n_p = N_c\, e^{-(E_c - E_F)/kT}$$

$$p_p = N_v\, e^{-(E_F - E_v)/kT}$$

$$n_n\, p_n = N_c\, N_v\, e^{-E_g/kT}$$

$$n_p\, p_p = n_i^2 \qquad \underline{\hspace{2cm}}(2)$$

Equations 1 and 2 show that the product of majority and minority carrier concentration in extrinsic semiconductor at a particular temperature is constant.

Charge Carrier Concentration In N-type and P-type Semiconductors

The free electron and hole concentrations are related by the Law of Electrical Neutrality i.e.

Total positive charge density is equal to the total negative charge density

Let N_D = Concentration of donor atoms = no. of positive charges/m^3 contributed by donor ions

p = hole concentration

N_A = Concentration of acceptor atoms

n = electron concentration

By the law of electrical neutrality $\qquad\qquad N_D + p = N_A + n$

For N-Type semiconductor $N_A = 0$ i.e. Concentration of acceptor atoms and $n \gg p$, then

$$N_D + 0 = 0 + n$$

$$N_D = n$$

i.e. in N-type, concentration of donor atoms is equal to the concentration of free electrons.
According to Mass Action Law

$$n.p = n_i^2$$

$$\boxed{p = n_i^2 / n = n_i^2 / N_D}$$

For P-Type semiconductor $N_D = 0$ i.e. Concentration of donor atoms and $p \gg n$, then

$$N_A + 0 = 0 + p$$
$$N_A = p$$

i.e. in P-type, concentration of acceptor atoms is equal to the concentration of holes.
According to Mass Action Law, $n.p = n_i^2$

$$\boxed{n = n_i^2 / p = n_i^2 / N_A}$$

Variation of Fermi Level (E_F) with Temperature

➤ **For n-type semiconductors**

At low temperatures, some of the donor atoms get ionized and provide electrons to the conduction band.

✓ At 0 K, the Fermi level (E_{Fn}) lies between the donor level and bottom level of the conduction band.

$$E_{Fn} = \frac{E_c + E_d}{2}$$

✓ As the temperature increases, the donor level gets depleted and Fermi level shifts downwards. At the temperature of total depletion ($T = T_d$), the Fermi level coincides with the donor level (E_d).

$$E_{Fn} = E_d \quad \text{at } T = T_d$$

✓ At $T > T_d$, the Fermi level moves downward in a linear manner.

✓ At $T = T_i$, when there are no more donor atoms, intrinsic process contributes to the electron concentration. So, at further higher temperatures, the n-type semiconductor loses its extrinsic behavior and acts as an intrinsic semiconductor. Thus, the Fermi level approaches the intrinsic value.

$$E_{Fn} = E_{Fi} = \frac{E_g}{2} \quad \text{at } T \geq T_i$$
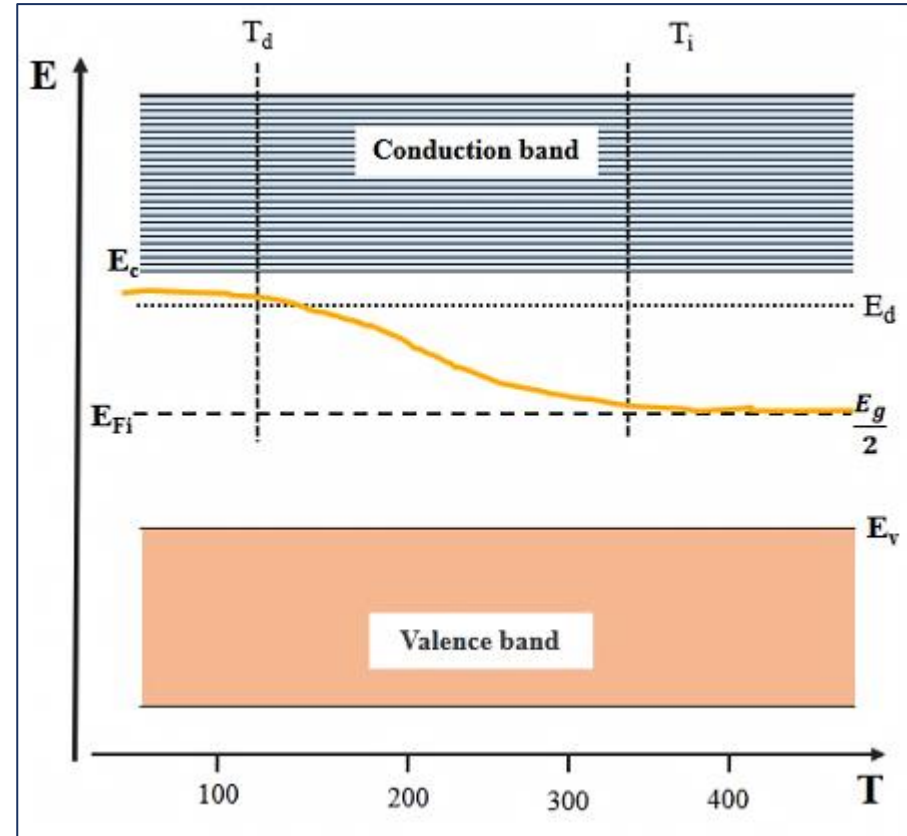
Variation of Fermi Level (E_F) with Temperature

> ## For p-type semiconductors

At low temperatures, holes in the valence band are only because of movement of electrons from the valence band to the acceptor level.
- ✓ At 0 K, the Fermi level (E_{FP}) lies in the mid of acceptor levels and top level of the valence band.

$$E_{Fp} = \frac{E_v + E_a}{2}$$

- ✓ As the temperature increases, the acceptor levels get filled up gradually and Fermi level shifts upwards. At the saturation temperature T_s (when acceptor level is totally filled) the Fermi level coincides with the acceptor level (E_a).
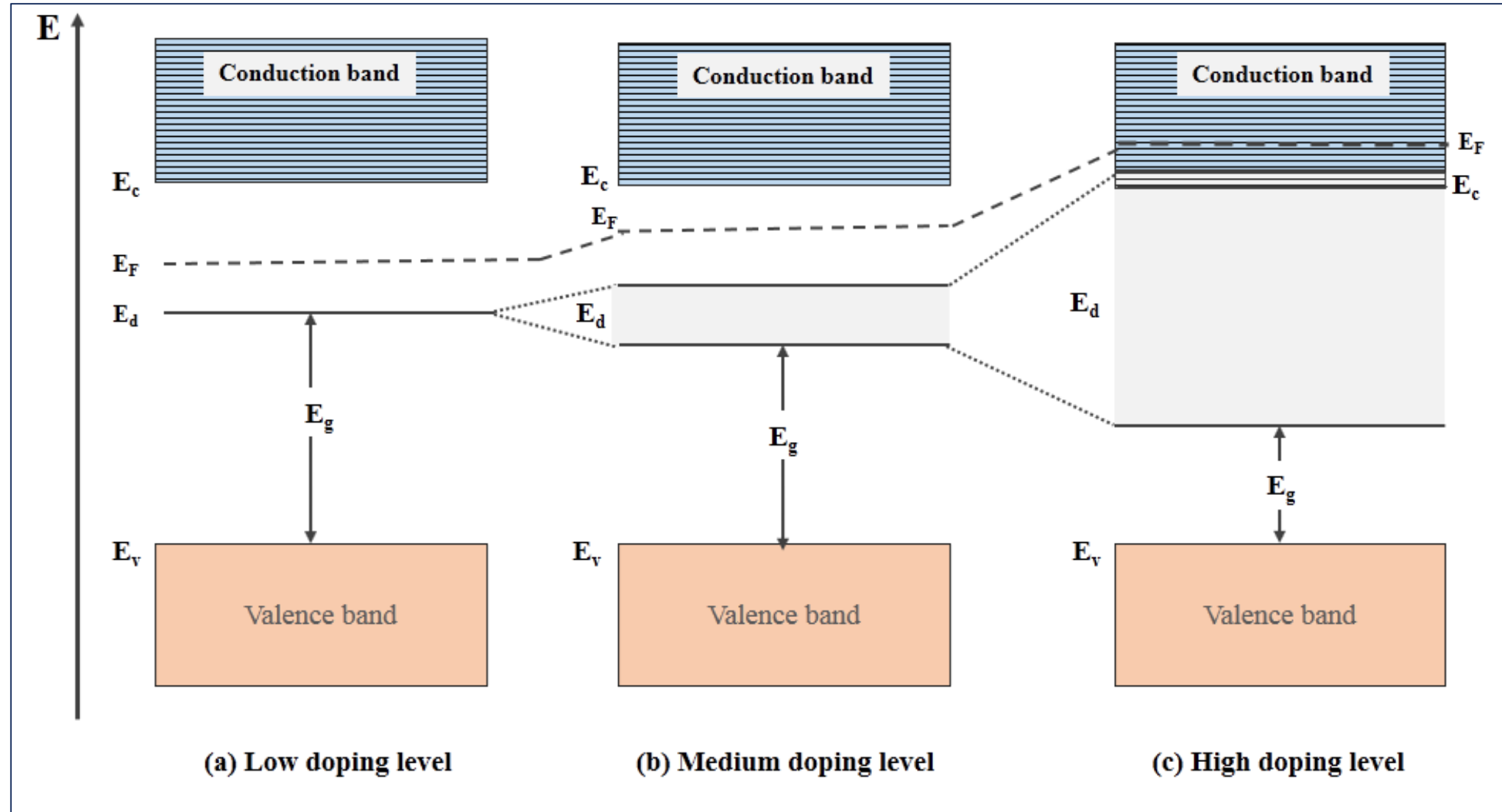
$$E_{Fp} = E_a \qquad at\ T = T_s$$

- ✓ As temperature goes above T_s i.e. $T > T_s$, the Fermi level **moves upward** in a **linear manner** somehow.

- ✓ At $T = T_i$, intrinsic behavior is established. At further higher temperatures, the p-type semiconductor loses its extrinsic behavior and acts as an intrinsic semiconductor. Thus, the Fermi level approaches the intrinsic value.

$$E_{Fp} = E_{Fi} = \frac{E_g}{2} \quad at\ T \geq T_i$$
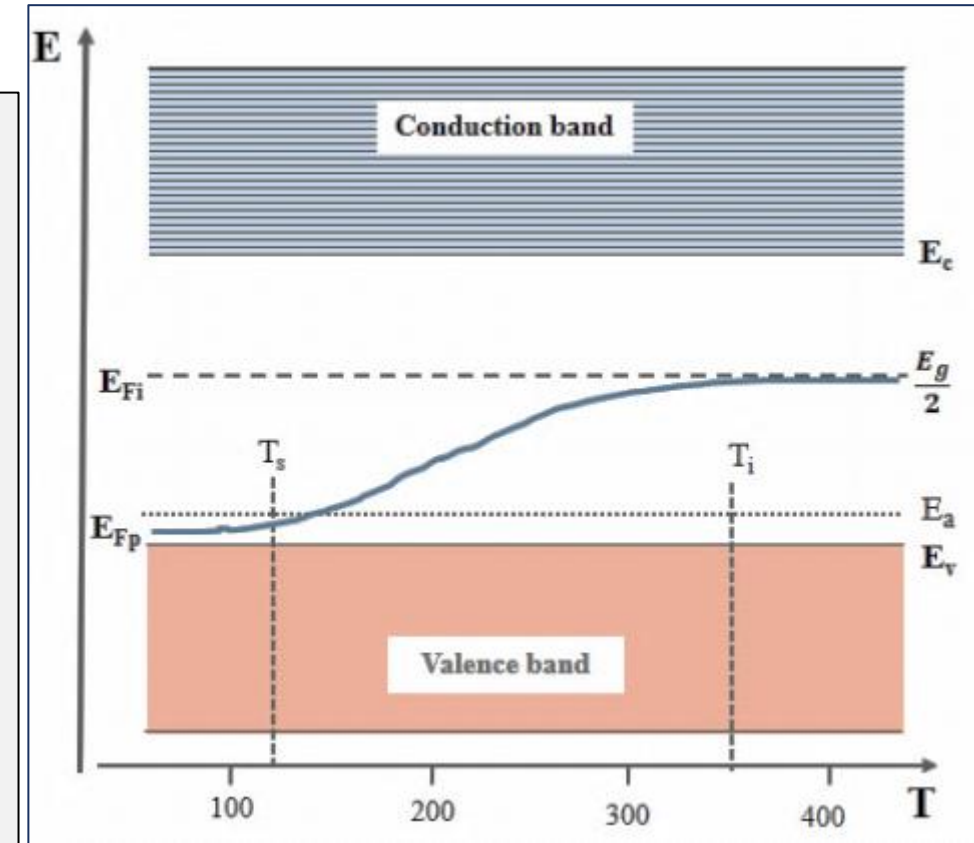
(a) Low doping level (b) Medium doping level (c) High doping level
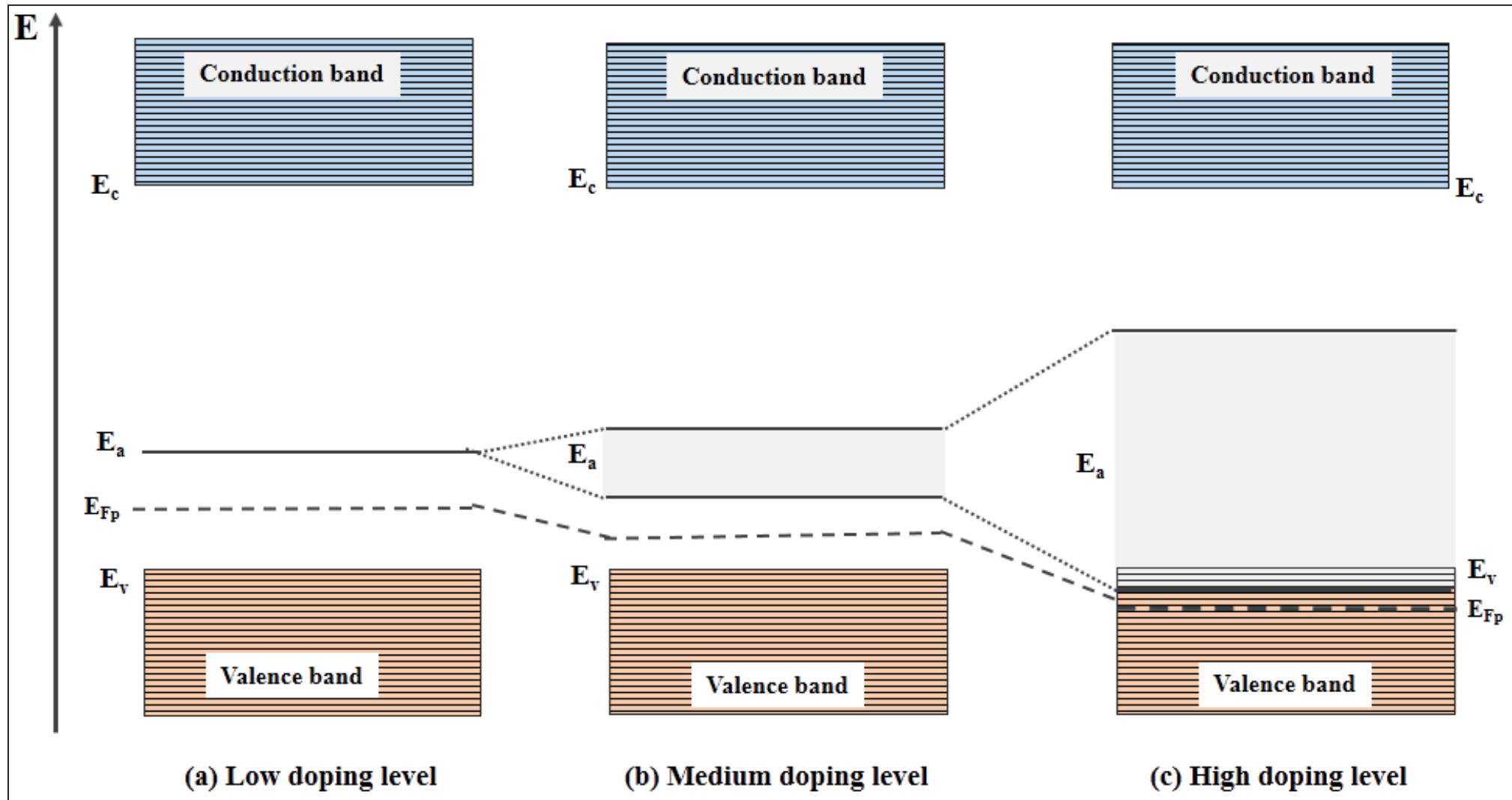
Variation of Fermi Energy Level With Doping Concentration

> ### For n-type semiconductors

- At low impurity concentration, there are <u>discrete donor energy levels.</u>

- With an increase in the impurity concentration, *donor level undergoes splitting* and it *results in the formation of formation of donor band* below the conduction band.

- With further increase in impurity concentration the width of the donor band increases.

- At one point, donor band overlaps with the conduction band

- In the process the Fermi level also shifts upwards, closer to the conduction band (with increase in impurity concentration) and finally enters the conduction band.

- With the widening of the acceptor band the width of forbidden gap decreases.

(a) Low doping level   (b) Medium doping level   (c) High doping level
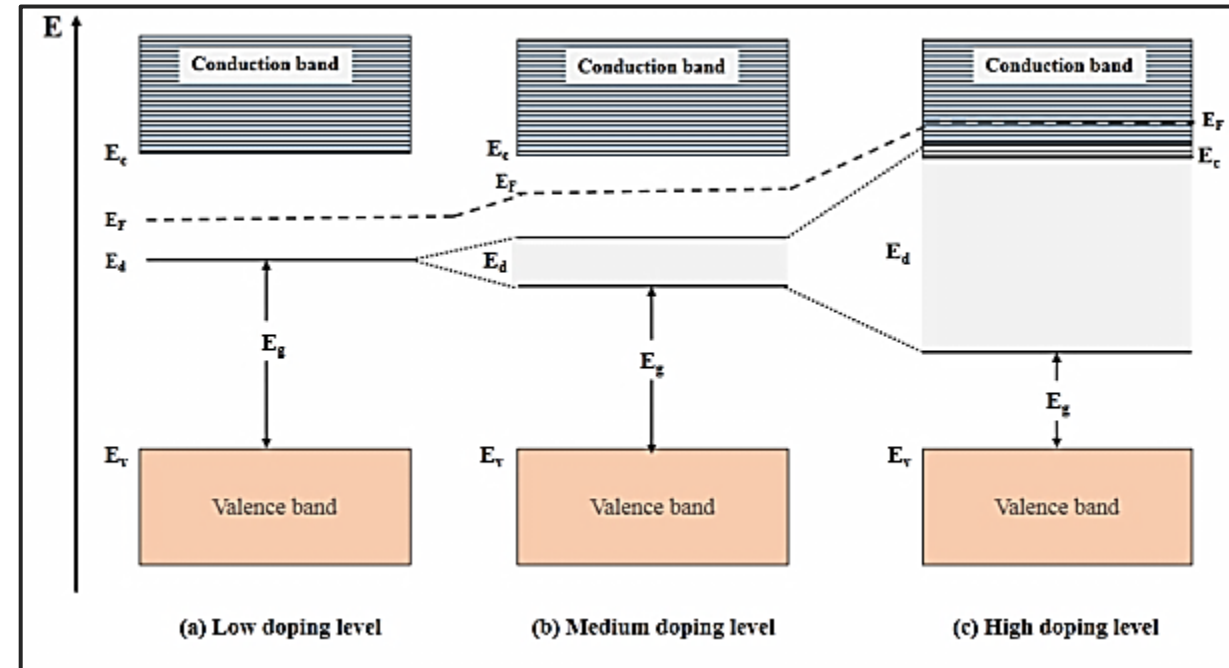
Variation of Fermi Energy Level With Doping Concentration (P-Type)

(a) Low doping level (b) Medium doping level (c) High doping level

For p-type semiconductors

- At low impurity concentration, there are <u>discrete acceptor energy levels.</u>

- With the increase in the impurity concentration the acceptor atoms interact. As a result the acceptor level broadens and splits into the band.

- acceptor band gradually broadens with increasing doping concentration.

- At one point the acceptor band overlaps with the valence band

- In this process the Fermi level also shifts downwards and at higher doping concentration it enters the valence band.

- With the widening of the acceptor band the width of forbidden gap decreases.

(a) Low doping level   (b) Medium doping level   (c) High doping level
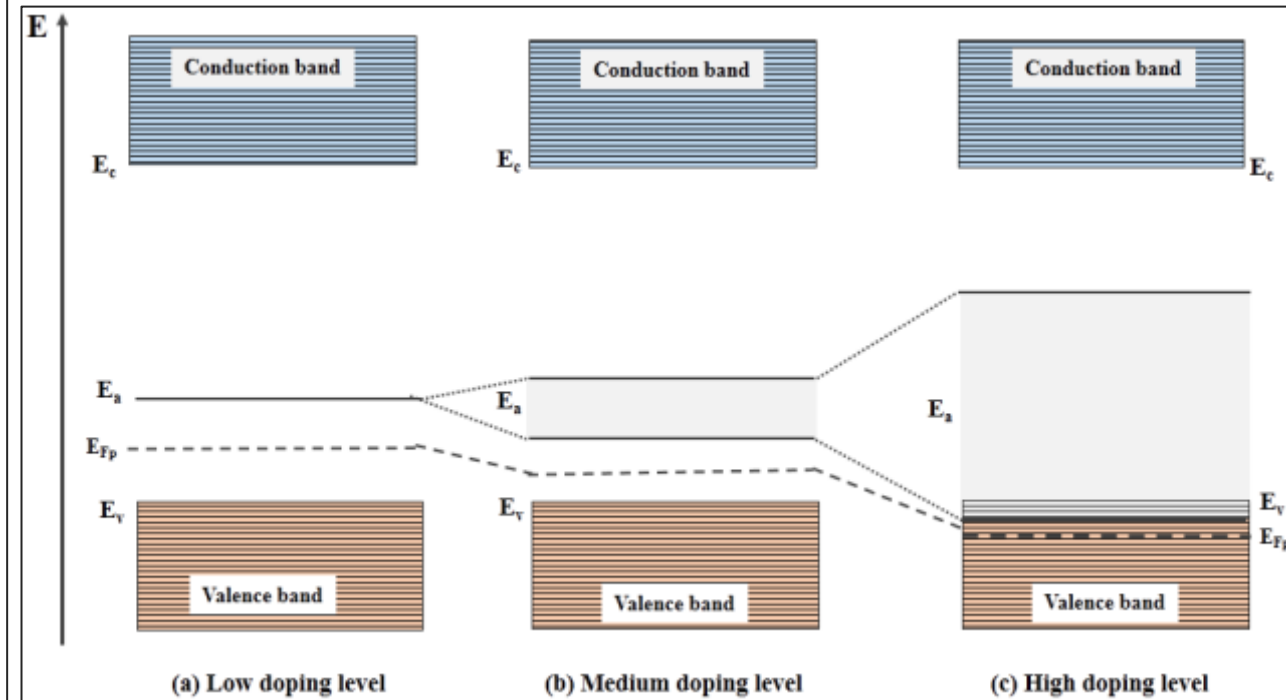
Direct Band Gap Semiconductors

In few crystals like gallium arsenide, the maximum of the valence band occurs at the same value of k as the minimum of the conduction band i.e. the minimum of the conduction band lies directly above the maximum of the valence band.

This is called direct band gap semiconductor.

Example: GaAs, Pbs, PbTe, InP etc.

✓ Here the direct recombination of hole–electron takes place.

✓ Due to hole–electron recombination the emitted energy is in the form of Electromagnetic radiation (radiative transitions)

✓ The band gap depends on doping materials, it varies from 1.4 eV to 2eV. Ex: GaAs ≈ 1.4 eV

✓ Such type of band gap materials are used in fabrication of Laser diodes and LED's

✓ In direct band gap semiconductors the direction of motion of an electron during a transition across the energy gap remains unchanged. Hence the efficiency of transition of charge carriers across the band gap is more in direct band gap than in indirect band gap semiconductors.
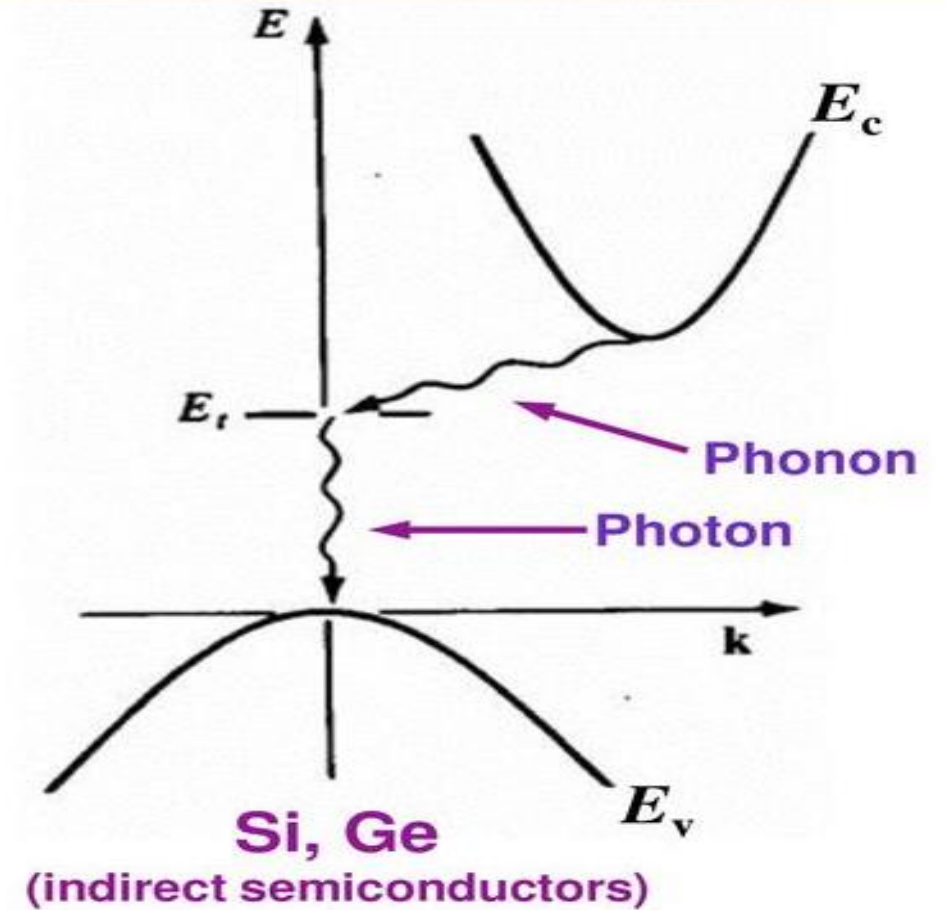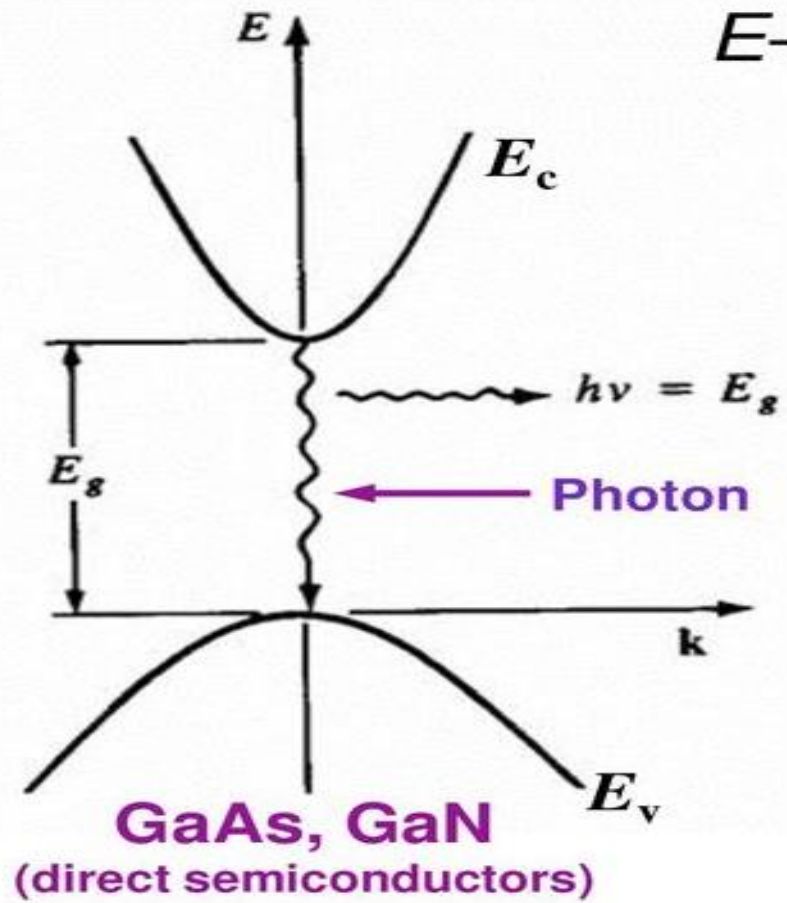
INDIRECT BAND GAP SEMICONDUCTORS

- These are also called as conventional semiconductors

- Semiconductors like Si and Ge in which the maximum of the valence band does not occur at the same k value as the minimum of the conduction band i.e. maximum of the valence band and the minimum of the conduction band are located at different momentum positions .

- An elecgron in C.B can not fall directly to V.B. It must undergo a momentum and energy change.

This we call indirect band gap semiconductors.

- Example: Ge, Si etc

✓ For the recombination of electrons and holes. The participation of a phonon needed to conserve momentum.

✓ Here the direct recombination of hole–electron is not possible, it is possible through the traps. (Hence, non-radiative transitions takes place)

✓ These can not be used to produce visible radiations.

✓ These are used in electronic devices & microwave communication.

*Phonon is the quanta of crystal lattice vibrations

BY: DR. VANITA THAKUR

E-k Diagrams

GaAs, GaN
(direct semiconductors)

Si, Ge
(indirect 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.

Generation

- **When a suitable form of energy is supplied to a semiconductor then electrons take transition from valence band to conduction band. Hence, a free electron in conduction band and a free hole in valence band is formed.**

- **This phenomenon is known as _electron – hole pair production or generation._**

E

$E_{ph} > E_g$

generation due to
light absorption
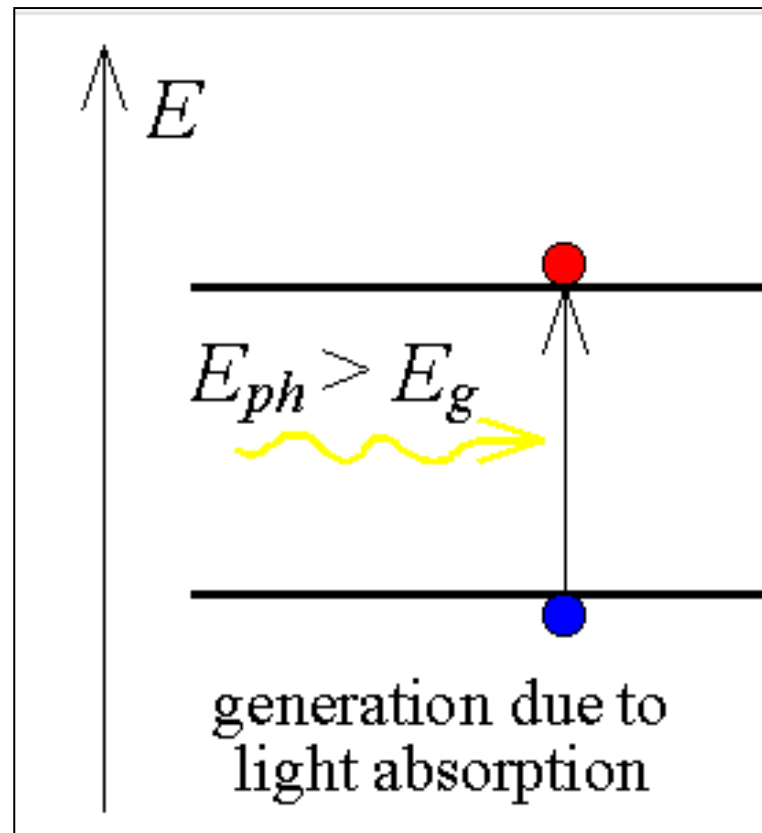
Recombination

The process of combination of a conduction electron with a hole in valence band is known as recombination. During this process, some energy, which is equal to energy gap of a semiconductor is released. Recombination is aid to occur when one of the conducting/free electron is bound again on a normal covalent tetrahedral site.

- **There is a *band to band recombination* in which excess energy is released in the form of photons (e.g. in GaAs).**

- **Another mechanism is via recombination centers and is known as Trap-assisted recombination. It occurs when an electron falls into a "trap" (or recombination center), an energy level within the bandgap caused by the presence of a foreign atom or a structural defect. Once the trap is filled it cannot accept another electron.**

It is a two-step process:

- First the electron occupy the trap,

- in a second step, it moves into an empty valence band state, thereby completing the recombination process.

band-to-band recombination   trap-assisted recombination   Auger recombination

78
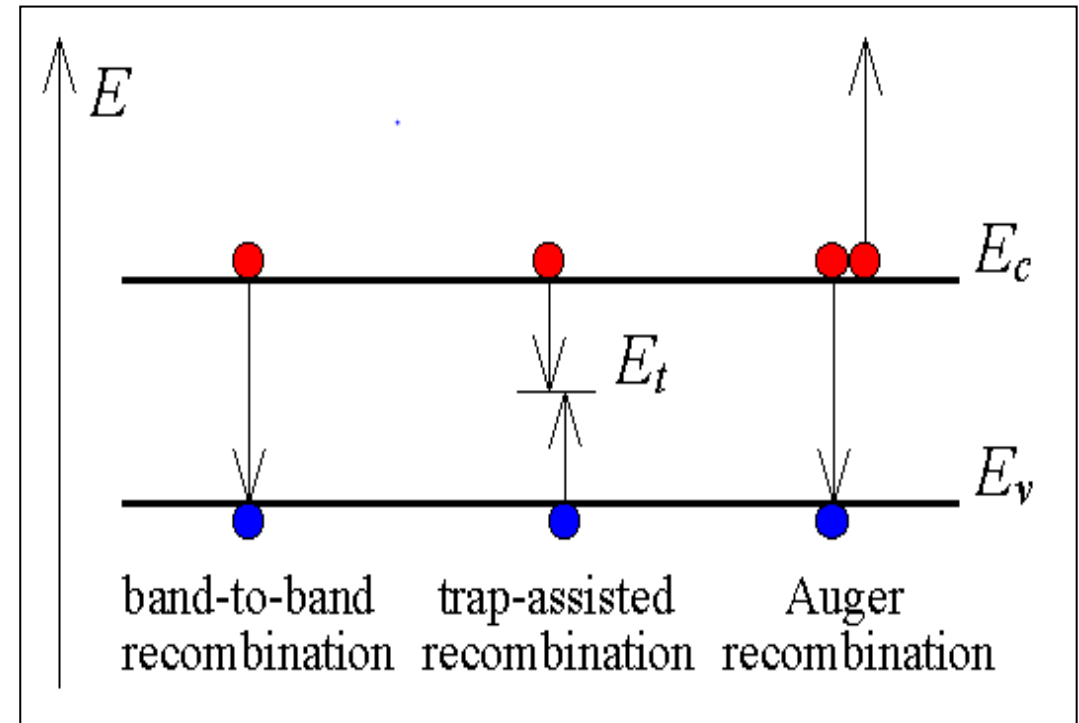
RECOMBINATION MECHANISMS IN SEMICONDUCTORS

Recombination mechanisms can in general be classified into two groups:

1. *Radiative recombination*
2. *Non-Radiative recombination*

Radiative recombination occurs when an electron in the conduction band recombines with a hole in the valence band and the excess energy is emitted in the form of a **photon.** This is also known as band to band recombination.

LED's work on this mechanism.

Radiative recombination is significant in direct band gap materials and it is a form of spontaneous emission.

Non- Radiative recombination: In this process, charge carriers recombine releasing **phonons instead of photons**. During the non-radiative recombination, the electron energy is converted to vibrational energy of lattice atoms, i.e. phonons. Thus, the excess electron energy is converted to **heat**.

Most common cause for non-radiative recombination events are defects in the crystal structure.

HALL EFFECT

- Hall Effect was discovered by Edwin Hall in 1879.

- Hall Effect is a Galvano magnetic effect.

When a metal or semiconductor carrying current is placed in a transverse magnetic field, a voltage is developed across the specimen in a direction perpendicular to both the current and the magnetic field.

This phenomenon is called the **Hall effect** and voltage so developed is called the **Hall voltage**.

Hall Effect in P-type semiconductor
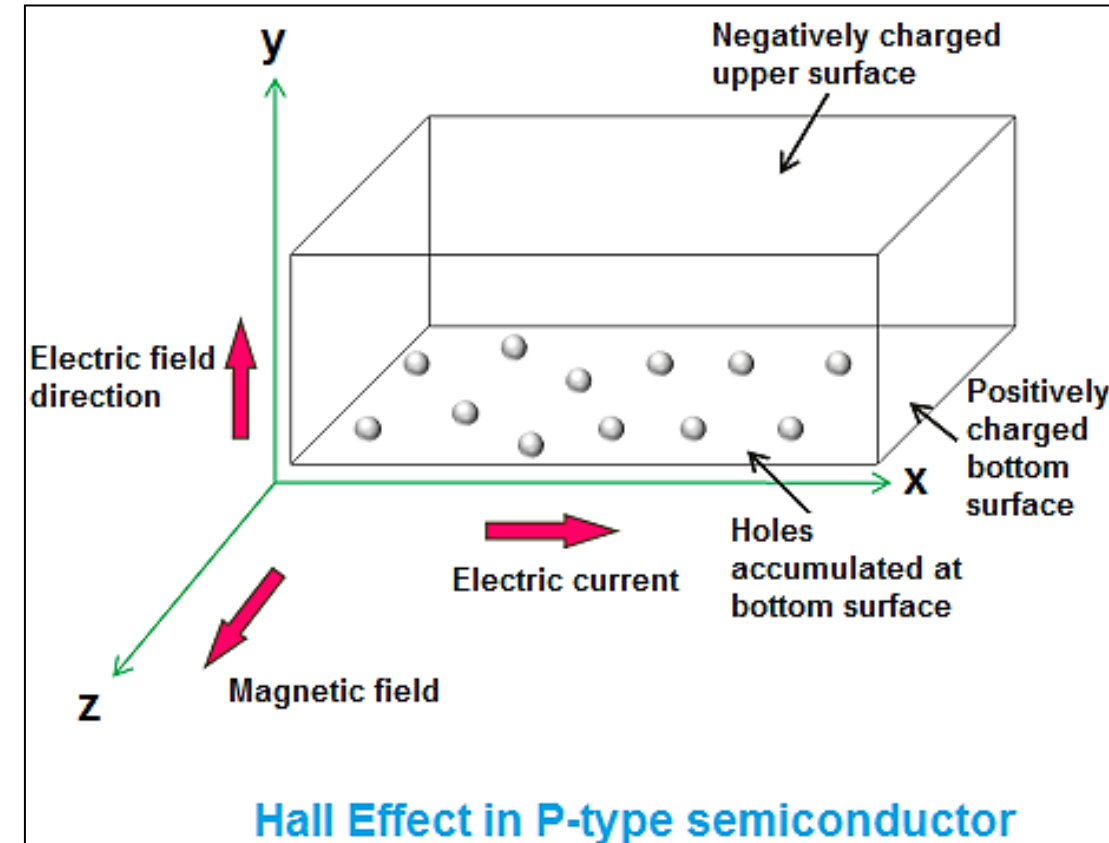
Consider a p-type semiconductor, carrying a current I_x in the x-direction. When a uniform magnetic field B_z is applied along the z-axis.

Current through the wafer is given by

$$I = peAv_d$$

Current density,

$$J_x = \frac{I}{A} = p\,e\,v_d \qquad \underline{\hspace{2cm}}(1)$$

On the application of magnetic field, holes experience a deflection because of Lorentz force (F_L), given by

$$F_L = e\,(\vec{v_d} \times \vec{B}) = e\,v_d\,B\,sin\,90^o = e\,v_d\,B \qquad \underline{\hspace{1cm}}(2)$$

The holes are deflected towards the lower surface and get accumulated there producing a net positive charge. Simultaneously, a net negative charge appears on the upper surface. This creates an upward electric field called Hall field (E_H).

Due to action of electric field E_H, holes experience an electric force F_E in addition to Lorentz force.

$$F_E = e\,E_H \qquad \underline{\hspace{2cm}}(3)$$

When an equilibrium is reached, the magnetic deflecting force on the charge carriers are balanced by the electric forces due to electric Field.

$$F_E = F_H$$
$$e\ E_H = e\ v_d B$$

If w = width of semiconductor wafer,

$$E_H = \frac{V_H}{w}$$

So, above relation becomes,

$$e\ \frac{V_H}{w} = e\ v_d B$$

$$\frac{V_H}{w} = v_d B \qquad \underline{\qquad} (4)$$

From equation (1),

$$v_d = \frac{J_x}{pe}$$

Equation (4) becomes

$$\frac{V_H}{w} = \frac{J_x}{pe}B$$

$$V_H = \frac{wBJ_x}{pe} = \frac{wBI}{pe\ A}$$

If t = thickness of Semiconductor wafer, $\quad A = wt$

$$V_H = \frac{wBJ_x}{pe} = \frac{BI}{pe\ t} \qquad \underline{\qquad}(5)$$

Hall Coefficient (R_H) is defined as Hall field per unit current density per unit magnetic induction.

Thus,
$$R_H = \frac{E_H}{J_x B} = \frac{V_H/w}{J_x B}$$

Using relation (4) i.e. $\quad \frac{V_H}{w} = v_d B$, *we get*

$$R_H = \frac{v_d B}{J_x B} = \frac{v_d}{J_x}$$

From eqn. (1), $\quad v_d = \frac{J_x}{pe}$

$$R_H = \frac{J_x}{pe}\frac{1}{J_x} = \frac{1}{pe}$$

$$R_H = \frac{1}{pe}$$

Using this value, eqn. (5) can be rewritten as

$$V_H = \frac{BI\,R_H}{t}$$
or
$$R_H = \frac{t\,V_H}{BI}$$

Drift Velocity

Acc. to equilibrium condition,

$$F_E = F_H$$

$$e\, E_H = e\, v_d\, B$$

$$e\, \frac{V_H}{w} = e\, v_d\, B$$

$$v_d = \frac{V_H}{Bw}$$

Carrier Concentration

$$R_H = \frac{1}{pe}$$

$$p = \frac{1}{R_H e}$$

In case of conductors and n-type semiconductor, $\quad R_H = \frac{-1}{ne}$

$$n = \frac{-1}{R_H e}$$

where n is concentration of electrons

Hall Mobility

Mobility is defined as the drift velocty acquired in unit electric field.

Since, $J = p e v_d$

Also

$$J = \sigma E$$

So, $p e v_d = \sigma E$

$$\frac{v_d}{E} = \frac{\sigma}{pe}$$

$$\boldsymbol{\mu_h = R_H \, \sigma}$$

APPLICATIONS OF HALL EFFECT

- Hall Effect is used to find whether a semiconductor is N-type or P-type.

- Hall Effect is used to find carrier concentration.

- Hall Effect is used to calculate the mobility of charge carriers (free electrons and holes).

- Hall Effect is used to measure conductivity.

- Hall Effect is used to measure a.c. power and the strength of magnetic field.

P-N JUNCTION FORMATION
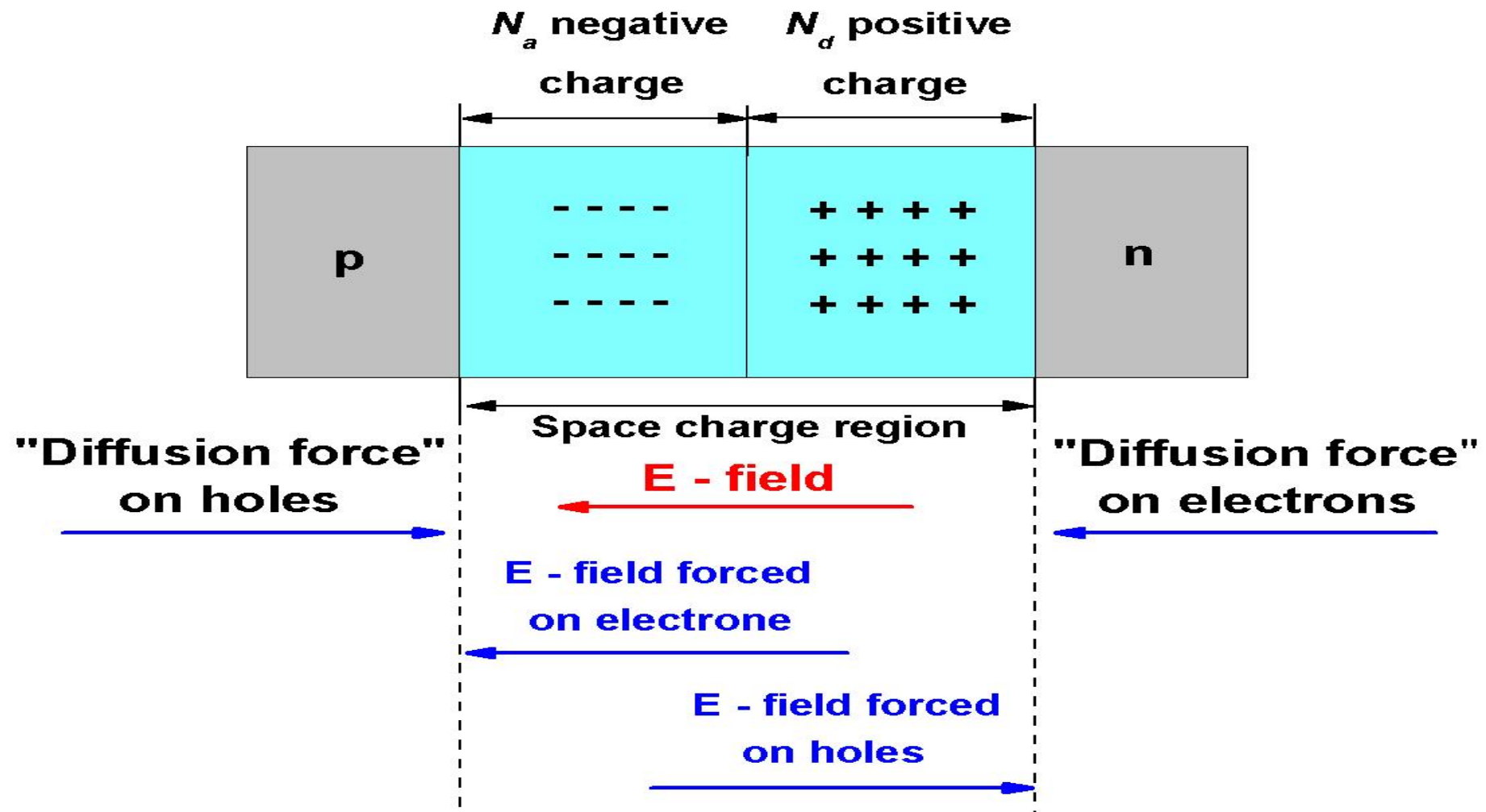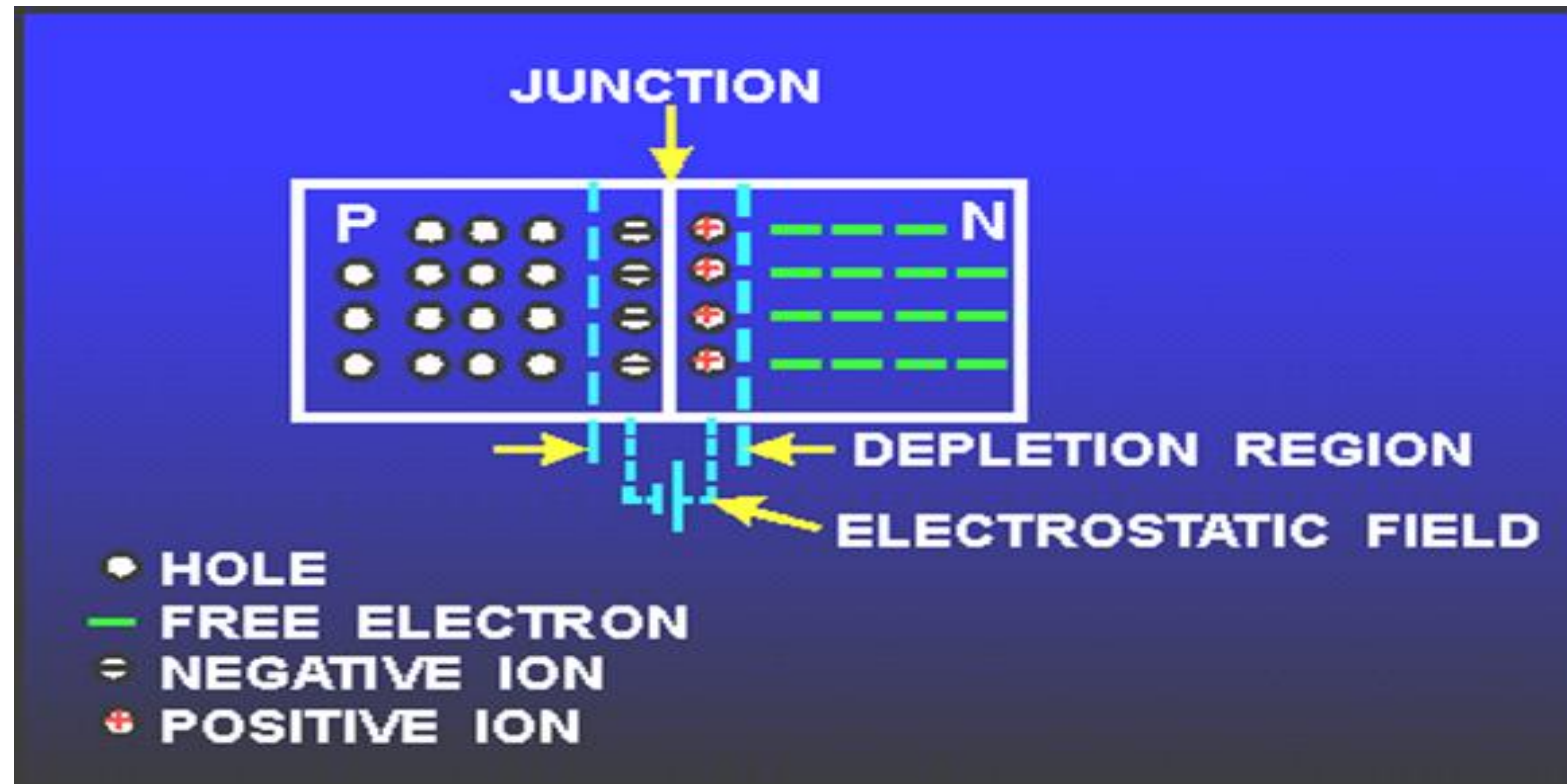
p-n junction = semiconductor in which impurity changes abruptly from p-type to n-type ;

"diffusion" = movement due to difference in concentration, from higher to lower concentration;

in absence of electric field across the junction,
➢ holes "diffuse" towards and across boundary into n-type and capture electrons;

➢ electrons diffuse across boundary, fall into holes ("*recombination of majority carriers*");
$$\Rightarrow \text{ formation of a "depletion region"}$$
Depletion region is the region without free charge carriers.

charged ions are left behind (cannot move):
negative ions left on p-side $\Rightarrow$ net negative charge on p-side of the junction;

positive ions left on n-side $\Rightarrow$ net positive charge on n-side of the junction
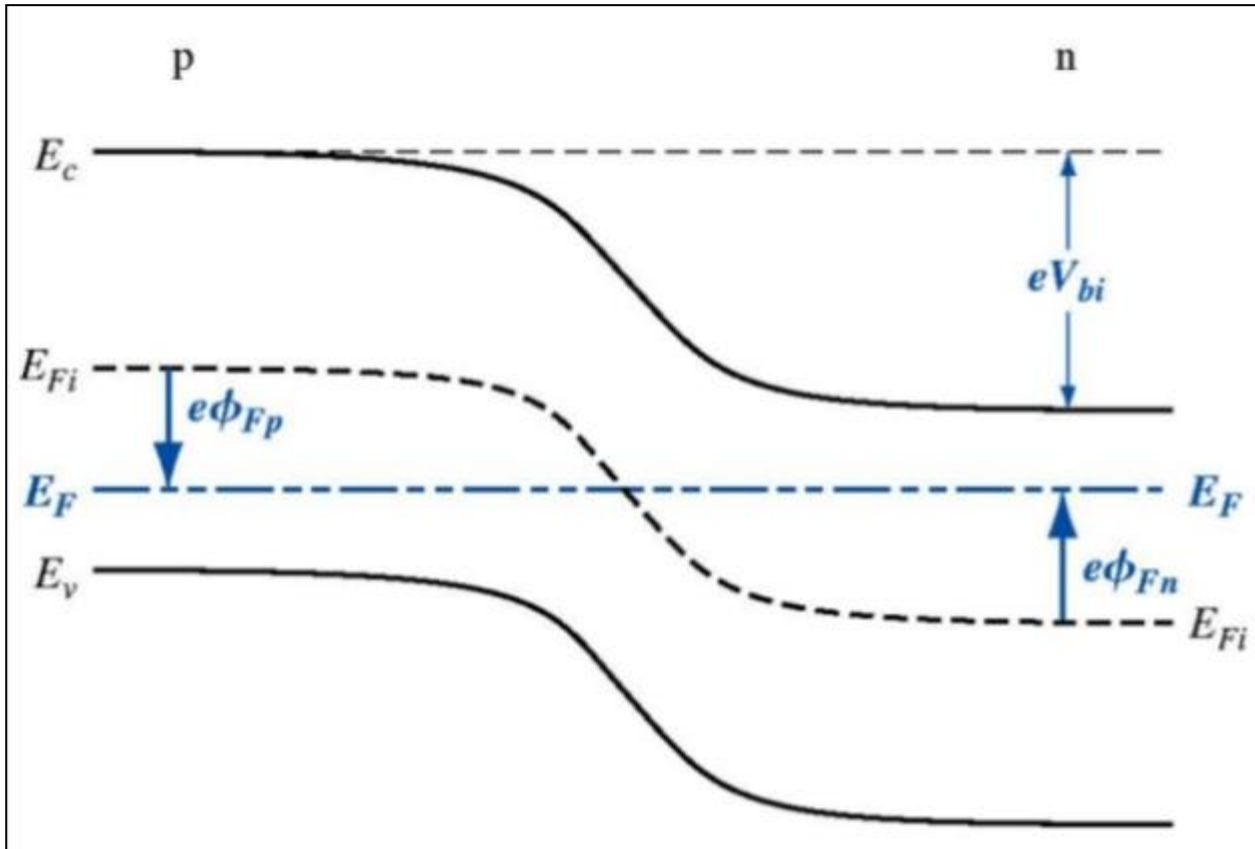
$\Rightarrow$ **electric field builds up across the junction which prevents further diffusion.**

Formation of depletion region in pn-junction:
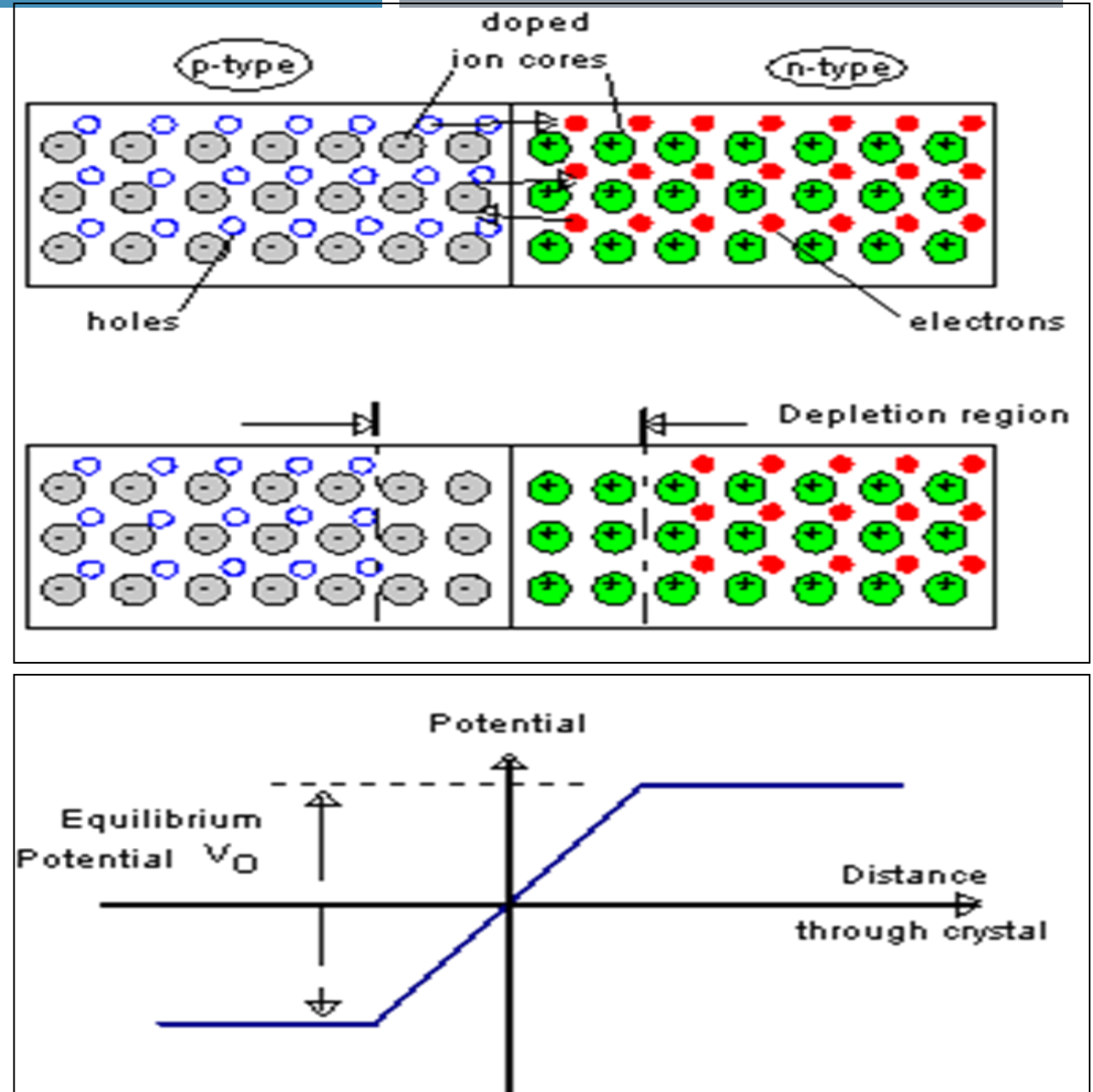
pn Junction – built-in potential barrier

No applied voltage across *pn-junction*

The junction is in thermal equilibrium —the Fermi energy level is constant throughout the entire system.

- Electrons in the conduction band of the *n* region see a potential barrier in trying to move into the conduction band of the *p* region. This potential barrier is referred to as the *built-in potential barrier* and is denoted by *Vbi (or V₀)*.
- The potential *Vbi* maintains equilibrium, so no current is produced by this voltage.

That's all!!!!

Thank You…