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Module 3

Semiconductors and Dielectrics

Semiconductors: Energy gap in solids, Intrinsic semiconductor, Extrinsic semiconductors, Semiconductor materials, Fabrication of integrated circuits, Semiconductor devices, p-n Junction diode theory, Bipolar junction transistor.

Dielectrics: Dielectric constant, Polarization, Field vector, Clussius-Mossotti equation, ferroelectric materials, Electrostriction, Piezoelectric effect, dielectric loss.

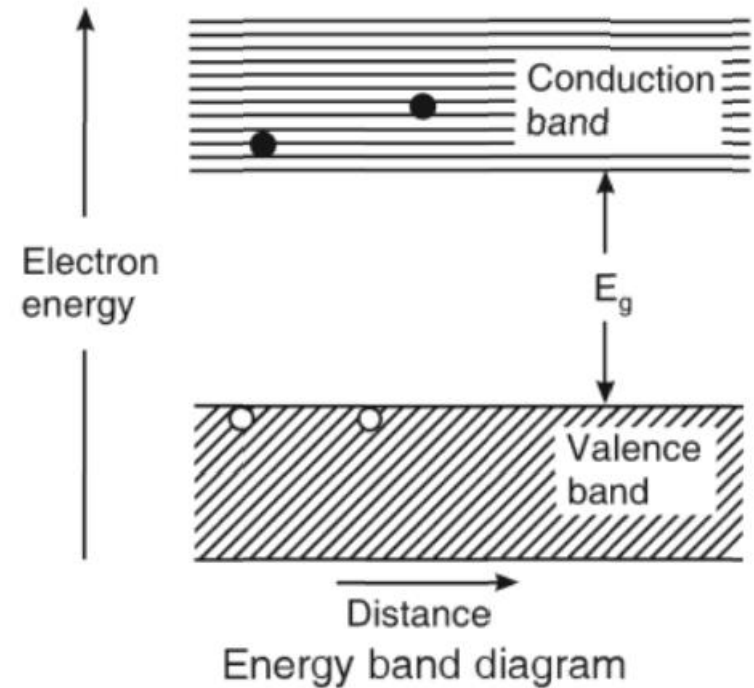
Energy gap in solids

ENERGY BAND DIAGRAM

- Energy band diagram is a graphic representation of the energy levels associated with top energy band and the next lower energy band in a solid.
- The upper band is called the **conduction band** and the lower energy band is called the **valence band**.
- These two bands are separated by a **forbidden gap/band gap (E_g)**

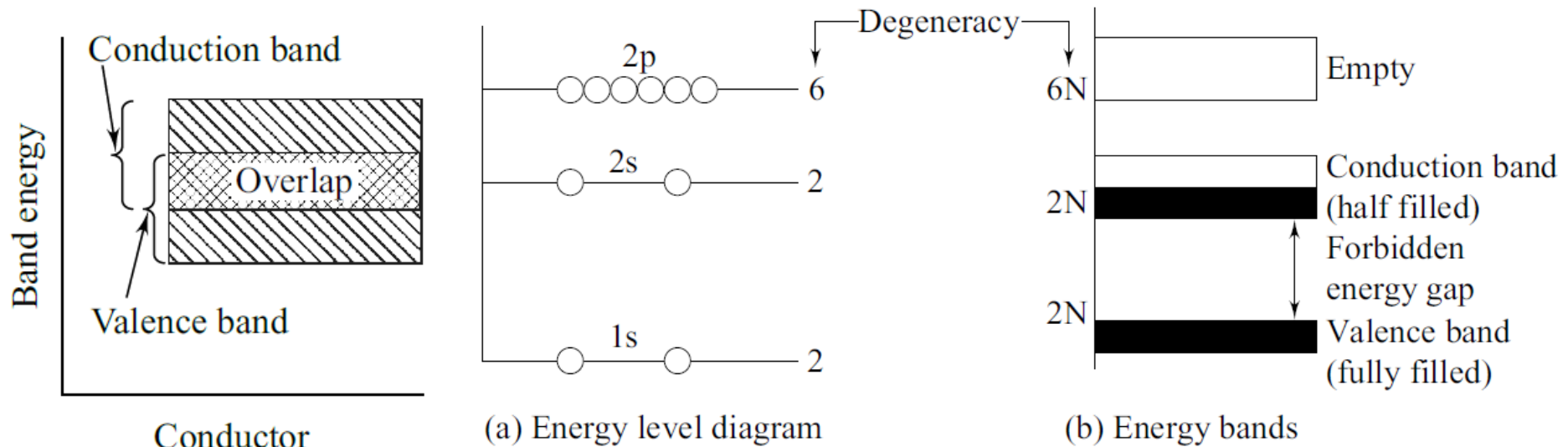
CLASSIFICATION OF SOLIDS ON THE BASIS OF BAND THEORY

- (1) Conductors
- (2) Insulators, and
- (3) Semiconductors



Conductors

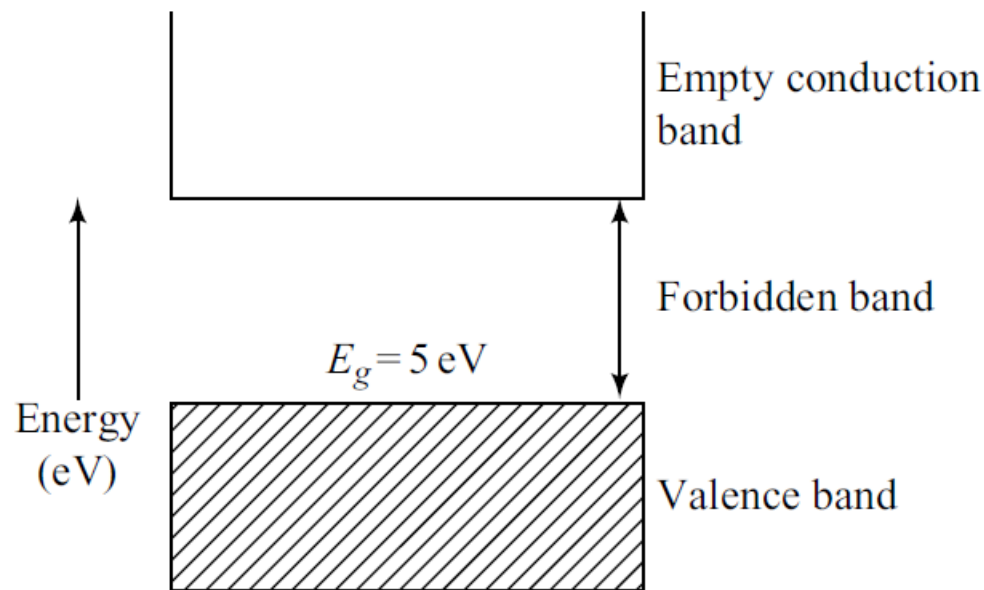
- Materials which conduct electric current when a potential difference is applied across them are known as conductors.
- In a conductor, the valence band is completely filled, while the conduction band is half filled,



Conductors—Lithium atom

Insulators

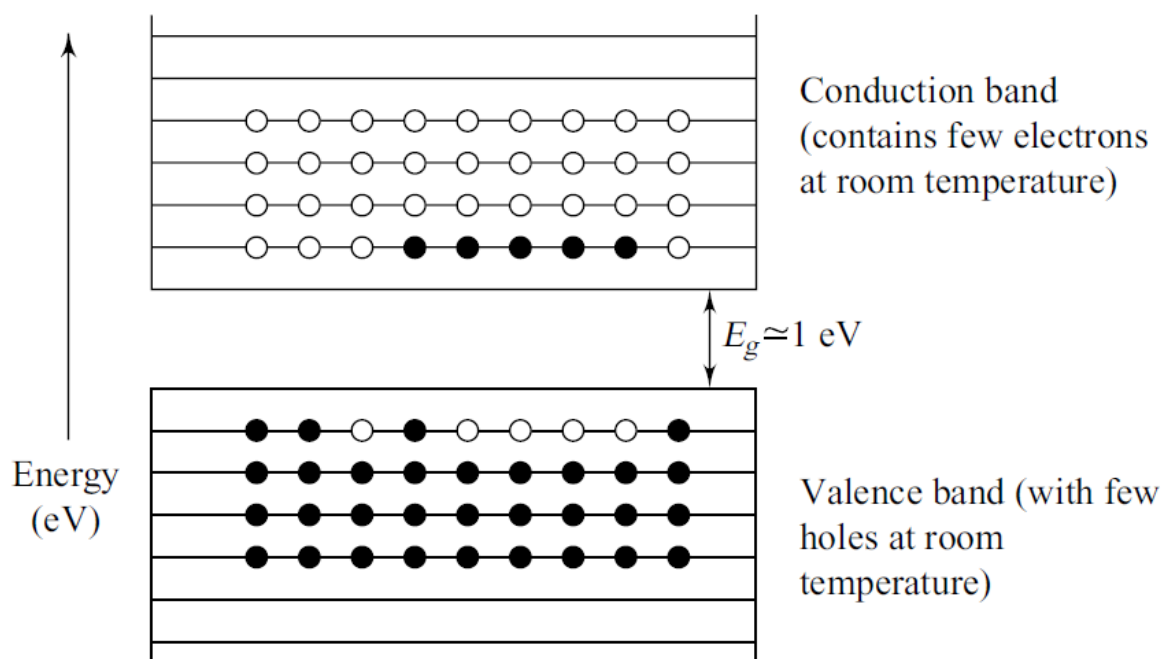
- Solid materials which do not conduct electric current under normal conditions are known as insulators.
- In insulators, the valence band is completely filled and it has no electron in the conduction band.
- The forbidden energy gap will be very high when compared with a conductor.



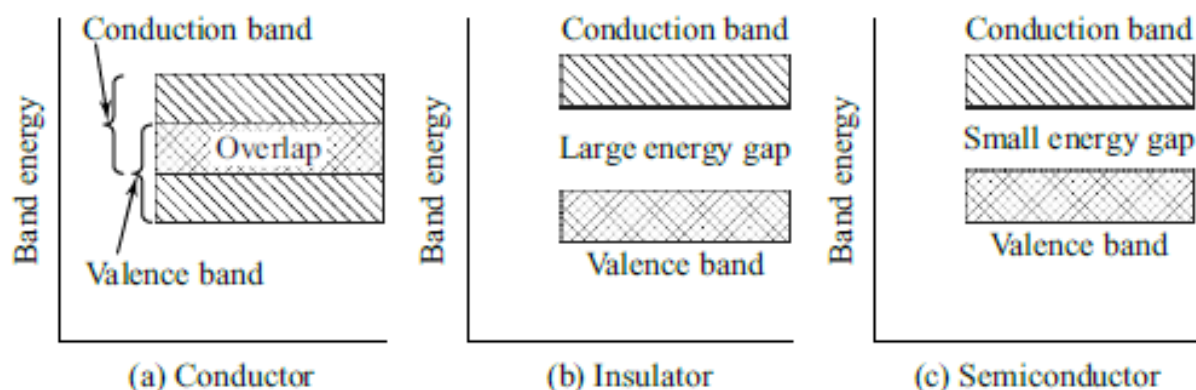
Energy bands in insulators

Semiconductors

- Semiconductors are materials whose electrical conductivity lies between that of conductors and insulators.
- The conductivity of semiconductors is in the order of 10^4 to 10^{-4} mho m^{-1} .
- The magnitude of the forbidden energy gap of a semiconductor lies in between the forbidden energy gap of insulators and conductors
- Eg. silicon and germanium (**elemental semiconductors**), gallium arsenide (GaAs), cadmium sulphide (CdS) (**compound semiconductors**) and Bi_2O_3 , Te_2O_3 , ZnO_3 , Cu_2O , etc (**oxide semiconductors**).



Energy bands in semiconductors



Comparison Between Metal, Semi-Conductor and Insulator

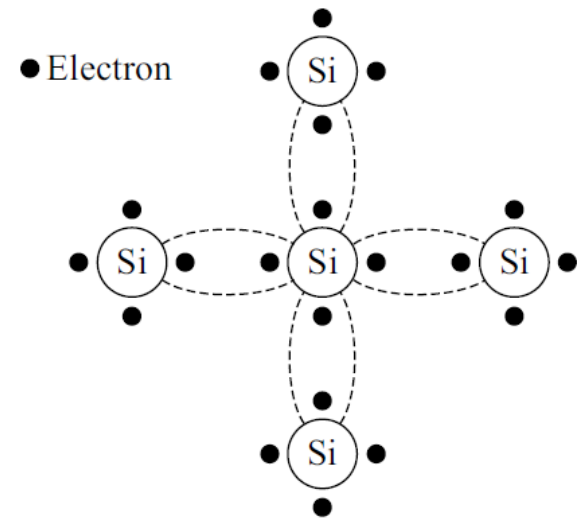
Sr. No	Conductors	Semiconductors	Insulators
1.	The valance band is completely filled.	At room temperature, few electrons are filled.	The valence band is completely filled.
2.	The forbidden energy gap is zero.	The forbidden energy gap is ~ 1 or 2 eV which is very small when compared to an insulator.	The forbidden energy gap in the order of few MeV which is higher than semiconductor.
3.	Electrons are loosely bound to the nucleus.	Electrons are not tightly bound to the nucleus.	Electrons are tightly bound to the nucleus.
4.	It will conduct electricity at normal condition.	It will conduct electricity partially at normal condition.	It will not conduct the electricity at normal condition.
5.	The resistivity of conductor is very small and it is in the order of few mill ohm m.	The resistivity of semiconductor is very less and it is in the order of 0.5 to 10^3 ohm m.	The resistivity of an insulator is very high and it is in the order of 10^7 to 10^{12} ohm m.
6.	Example for conductor are copper lithium, gold, silver, etc.	Example for semiconductor are silicon, germanium, gallium Arsenide, cadmium sulphate, etc.	Example for insulator are ebonite, glass, rubber, glass fibre, porcelain, etc.

CLASSIFICATION OF SEMICONDUCTORS

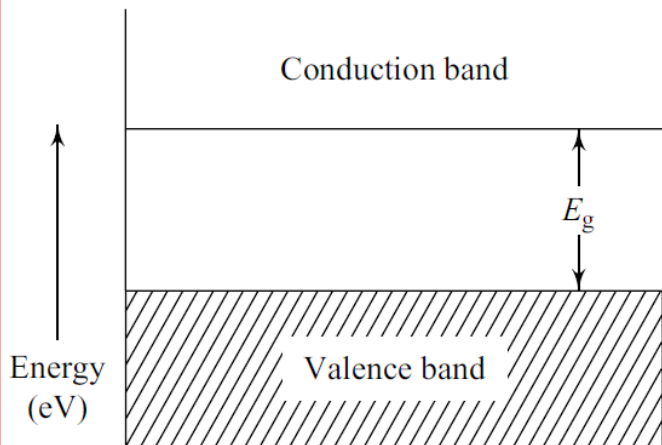
- (1) Pure or intrinsic semiconductors, and
- (2) Doped or extrinsic semiconductors

Pure or Intrinsic Semiconductors

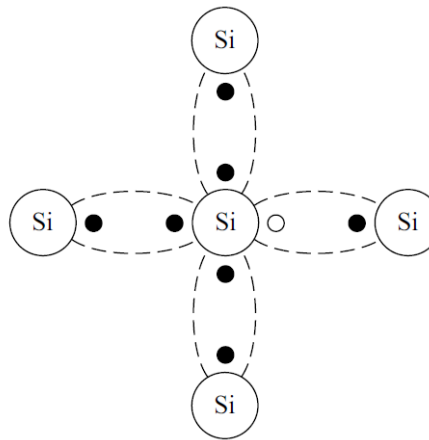
- Highly pure semiconductors are called intrinsic semiconductors
- The concentration of electrons must be equal to the concentration of holes
- Band gap E_g Ge=0.72 eV, Si=1.1 eV



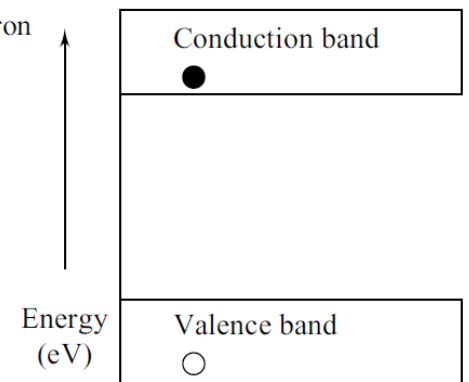
Two-dimensional arrangement of atoms in silicon at $T = 0$ K



Energy band diagram of silicon at $T = 0$ K



Two dimensional arrangement of atoms in silicon at $T > 0$ K



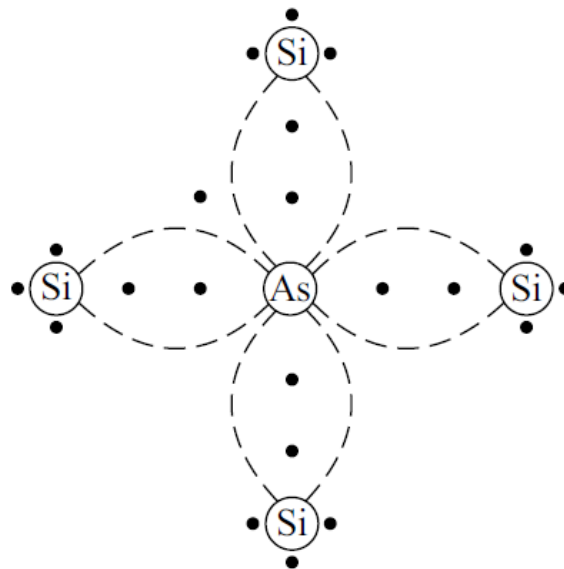
Energy band diagram of silicon at $T > 0$ K

Extrinsic Semiconductors

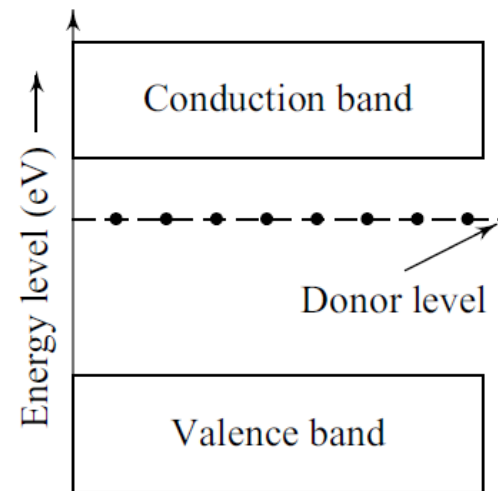
- Adding impurities (one atom in 10^7 host atoms) to the intrinsic semiconductors is known as extrinsic **semiconductor**.
- The process of adding impurity to the intrinsic semiconductors is known as **doping**.
- The concentration of electrons and holes are not equal in an extrinsic semiconductor.
- Extrinsic semiconductors are classified into **two categories** based on the concentration of the charge carriers
 - (1) n-type semiconductors
 - (2) p-type semiconductors

n-type semiconductors

- When a pentavalent atom such as arsenic (antimony, bismuth, phosphorus) is added as a dopant to the tetravalent silicon atom
- The arsenic atom will occupy one site of the silicon atom. Thus, out of five free electrons in arsenic, four electrons make covalent bonds with the four neighbouring silicon atoms and the fifth one is loosely bound to the silicon atom.
- the concentration of charge carriers (i.e., electrons) is more than that of holes. Therefore, these semiconductors are called n-type semiconductors.
- In an n-type semiconductor, electrons are the majority current carriers while holes are the minority current carriers.



(a) With free electrons

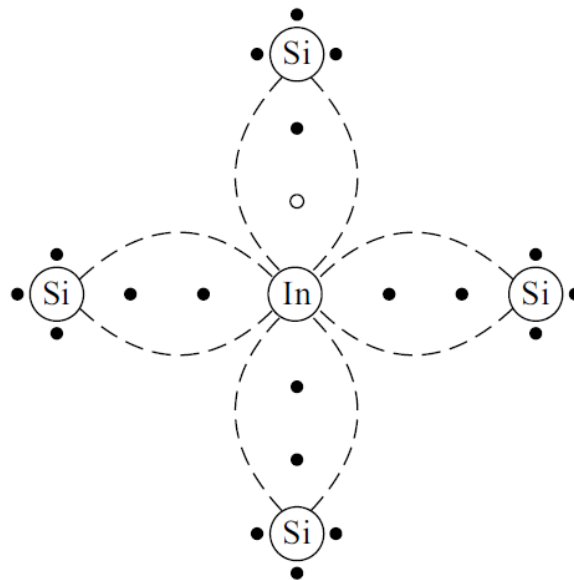


(b) Energy at donor level

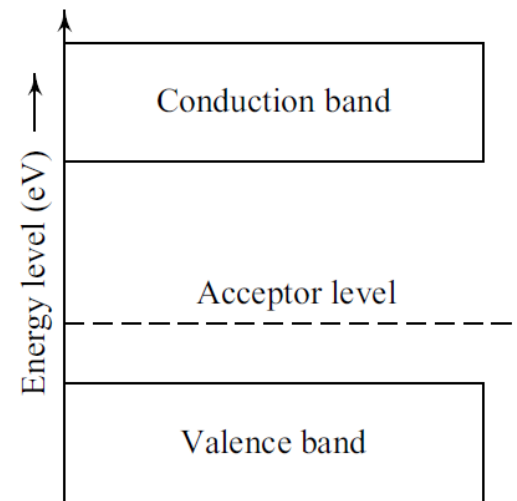
Doping in n-type semiconductors

p-type semiconductors

- The addition of a trivalent atom indium (In) to the tetravalent silicon atom, occupies the crystal site of the silicon atom.
- The three valence electrons in indium make covalent bonds with the three neighbouring silicon atoms, whereas the fourth bond has an empty space known as hole due to the deficiency of one electron.
- A trivalent atom is added to silicon, it creates a hole in the valence band.
- The dopant (indium) accepts an electron from the neighbouring silicon atom to form a covalent bond and hence, it is called an acceptor.
- The hole in the valence band moves freely and hence, the current flows through the material.
- In a p-type semiconductor, holes are the majority current carrier and electron are the minority current carriers.



(a) With vacancy



(b) Energy at acceptor level

Doping in p-type semiconductors

Semiconductor Materials

Silicon ($E_g = 1.1$ eV) is the most widely used semiconductor crystal.

- It is available in abundance in the earth's crust in the form of silica and silicates.
- It has a moderately high melting point (1410°C)

Germanium ($E_g = 0.7$ eV) is the other elemental semiconductor crystal with a lower melting point (937°C).

The advantages of Si over Ge

Property	Si	Ge
Energy gap	1.1 eV	0.66 eV
Upper temperature limit	150°C	100°C
Junction leakage current	less	more
Breakdown strength	higher	lower
Oxide quality	excellent	water soluble and unsuitable
Relative cost of electronic grade	1	10

- Si, Ge and GaAs are among the most important device materials
- In all VLSI (very large scale integration) circuits, silicon is *the* material played an important role
- GaAs used in optoelectronic devices
- A combination of Si and GaAs devices in integrated circuits is being developed
- At present, over 98% of all devices are based on silicon only

Properties of Some Semiconductor Compounds

<i>Semiconductor</i>	E_g (eV)
<i>Group IV</i>	
Diamond	5.3
Si	1.11
Ge	0.72
<i>Group II–VI</i>	
ZnS	3.5
ZnSe	2.8
ZnTe	0.85
<i>Group III–V</i>	
InP	1.27
InAs	0.33
InSb	0.18

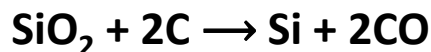
Compound	Energy gap, eV	Mobility, m ² V ^{−1} s ^{−1}		Melting point, °C
		<i>Electrons</i>	<i>Holes</i>	
GaP	2.26	–	0.002	1350
AlSb	1.52	0.02	0.02	1050
GaAs	1.43	0.85	0.04	1240
InP	1.29	0.46	0.015	1070
GaSb	0.78	0.4	0.07	705
InAs	0.35	2.3	0.024	940
InSb	0.18	6.5	0.1	525

Integrated Circuit (IC):

- An integrated circuit (IC), also called a chip or microchip, is composed up of semiconductor wafer on which millions of small resistors, capacitors, and transistors are fabricated by process of fabrication.
- IC is very small in size. In IC chips, the fabrication of circuit elements and their interconnections are done at same time.
- It has so many advantages such as extremely small size, low power consumption, low cost, high processing speed, easy replacement, and small weight.
- IC can work as amplifier, timer, oscillator, counter, computer memory etc.

Production of Metallurgical Grade Silicon

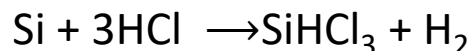
- The starting material is pure sand and carbon. Sand (SiO_2) is heated with carbon in an electric furnace to reduce it.



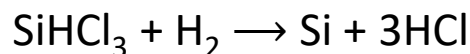
- The silicon thus obtained is of 99% purity and is called the metallurgical grade silicon.

Semiconductor Grade Silicon

The metallurgical grade silicon is dissolved in HCl:



The purified SiHCl_3 and H_2 is then evaporated and passed through a reactor, which contains “slim rods” of high purity silicon.



Fabrication of Integrated Circuits

The basic processes used to fabricate ICs are

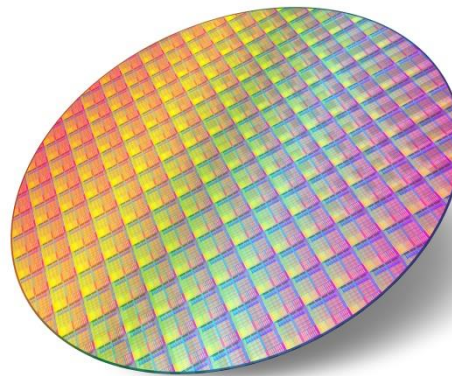
- I) Si-wafer preparation
- II) oxidation
- III) ion implantation
- IV) photolithography
- V) Isolation technique
- VI) Metallization
- VII) Assembly processing & packaging
- VIII) Diffusion.



Wafer production:

The first step is wafer production. The wafer is a round slice of semiconductor material such as silicon. It is the base or substrate for entire chip.

- Purification of polycrystalline silicon from the sand.
- Heating it to produce molten liquid.
- A small piece of solid silicon is dipped on the molten liquid and solid silicon is slowly pulled from the melt.
- The liquid is cooled down to form single crystal.
- A thin round wafer of silicon is cut using wafer slicer having thickness about 0.01-0.025”.
- Damaged surface is smoothened by polishing.
- The wafers are cleaned using high purity low particle chemicals.
- The silicon wafers are now exposed to ultra pure oxygen.



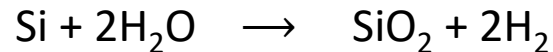
Oxidation

It consists of growing a thin film of SiO_2 on the surface of Si wafer. It serves two important purposes.

- SiO_2 is an extremely hard protective coating and is unaffected by almost all reagents except hydrofluoric acid.
- By selective etching of SiO_2 diffusion of impurities can be accomplished to fabricate various components.

Steps: 1) The silicon wafers are stacked up in a quartz boat and then inserted into quartz furnace tube.

2) The Si-wafers are raised to a Temperature in the range of $950 - 1150^\circ\text{C}$ and at the same time, exposed to a gas containing O_2 or H_2O or both. The chemical reaction is



Oxidation provides surface passivation and isolates one device from another. This oxidation process is known as thermal oxidation because high temperature is used to grow the oxide layer. The thickness is usually in the order of 0.02 to $2\ \mu\text{m}$

Photolithography

- It is a technique used to produce microscopically small circuit and **device patterns** on silicon wafers.
- Photolithographic process uses UV light exposure and device dimension or line width as small as 25 μm

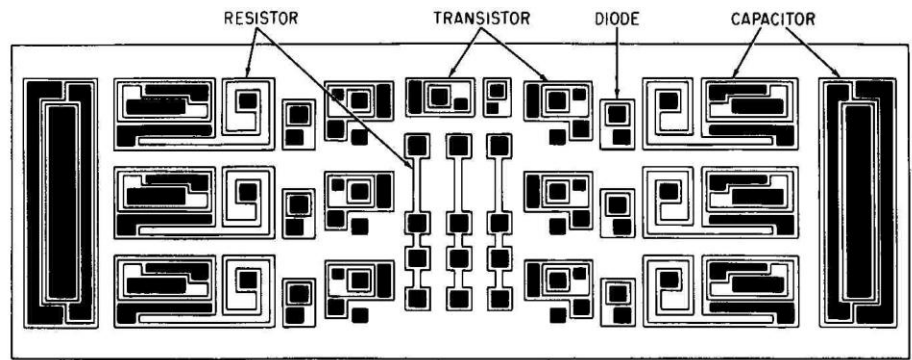
It involves two processes.

- Making of a photographic mask.
- Photo etching

i) Making of a photographic mask:

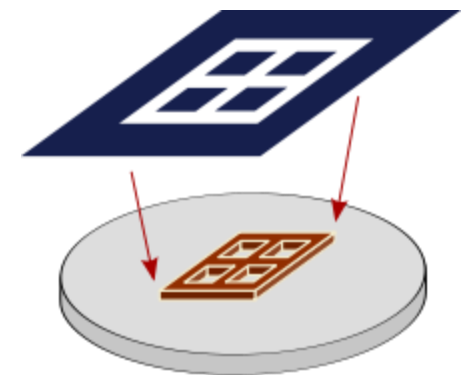
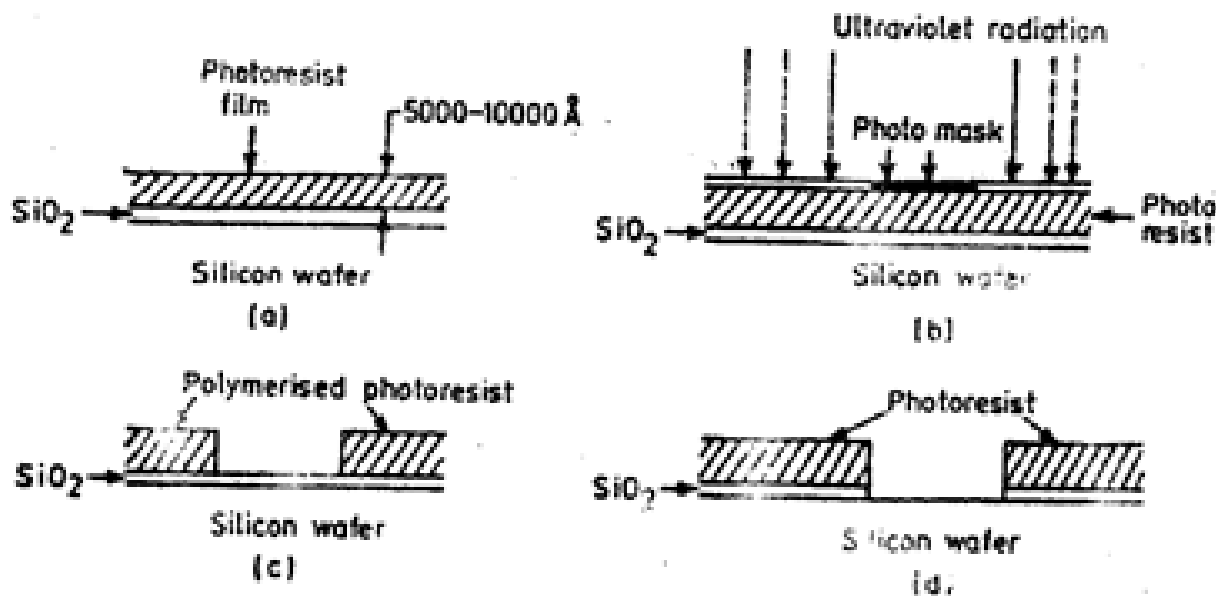
It involves following sequence of operations:

- Preparation of initial art work and
- Its reduction



ii) Photo etching:

Used for removal of SiO_2 from desired regions so that desired impurities can be diffused



A schematic illustration of a photomask (top) and an integrated circuit created using that mask (bottom)

Steps:

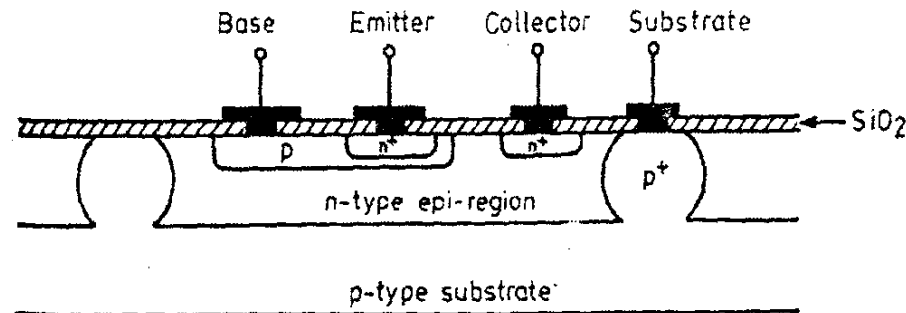
- Silicon wafer is coated with a film of photosensitive emulsion (Kodak photo resist KPR)
- The thickness of the film is in the range of 5000 – 10000 Å.
- The mask is placed over the photo resist coated wafer, and exposed to UV light so that KPR becomes polymerized beneath the transparent regions of the mask.
- The mask is then removed and wafer is developed using a chemical trichloroethylene, which dissolves unexposed regions on the photo resist and leaves the pattern as shown in Figure 'c'
- Next, the photo resist is fixed (or) cured, so that it becomes immune to certain chemicals called etchants used in subsequent processing steps.

Diffusion:

Important process in fabrications of IC is diffusion of impurities in the silicon chip.

Steps:

- This uses a high temperature furnace having a flat temperature profile over a 20" length.
- A quartz boat containing about 20 cleaned wafers is pushed into the hot zone with temperature maintained at about 1000°C .
- Impurities diffused are B_2O_3 (boron oxide), BCl_3 (boron chloride) for Boron and P_2O_3 (Phosphorous pentoxide) and POCl_3 (Phosphorous oxy chloride) for phosphorous.
- Next a carrier gas such as N_2 or O_2 is used for carrying impurities to the high temperature zone.
- The depth of diffusion depends upon the time of diffusion (which normally extends to 2 hrs.)
- The diffusion of an impurity normally takes place both laterally as well as vertically.



The cross-section of an n-p-n transistor showing curved junction profiles as a result of lateral diffusion

Ion implantation:

Ion implantation is a technique used to introduce impurities into a silicon wafer.

➤ **Steps:**

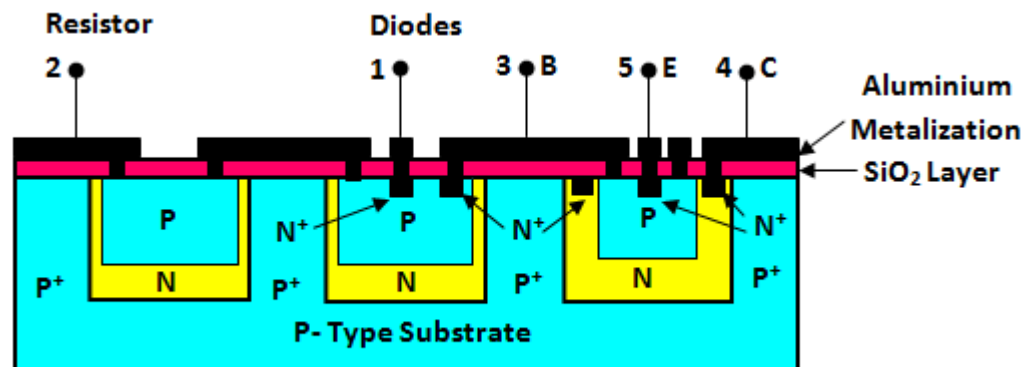
- Silicon wafers are placed in a vacuum chamber and are scanned by a beam of high energy dopant ions (borons for p-type and phosphorous for n-type).
- Those ions are accelerated by energies between 20KV to 250 KV.
- As the ions strike the silicon wafers, they penetrate into the wafer.
- Depth of penetration increases with increasing acceleration voltage.
- Then the chip is immersed in the etching solution of hydrofluoric acid which removes silica from the areas which are not protected by KPR.
- After diffusion of impurities, photo resist is removed by hot sulfuric acid and mechanical abrasion.
- The etching process described above is a wet etching process, since the chemical reagents are in the liquid form.
- A new process used these days is a dry etching process called plasma etching.

A major advantage of dry process is that it is possible to achieve smaller openings ($1\text{ }\mu\text{m}$) compared to wet process.

Metallization:

Process for creating contact silicon and its interconnections on chip.

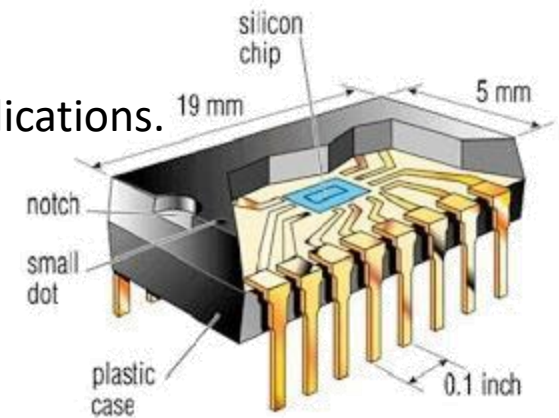
- Deposition of thin layer of aluminum over the whole wafer.
- Making successive layers.
- The process such as etching, masking and doping are repeated for each successive layers until all IC's are completed.
- Silicon dioxide is used as insulator between the components.
- Aluminum is deposited to make contact pads.
- The fabrication includes about three layers which are separated by dielectric layers. For electrical and physical isolation, solid layer of dielectric is surrounded in each component for purpose of isolation.
- Final dielectric layer is deposited to avoid damage and contamination of circuit.
- The individual IC is tested again for electrical function.
- Then by checking the functionality of each chip on wafer, those chips are not passed in the test will be rejected.



Assembly and packaging:

Each of the wafers contains lots of chips. These chips are separated and packaged by method known as cleaving and scribing.

- The wafer is similar to a piece of glass and diamond saw is used for cutting the wafer into single chips.
- For separation of the individual chips through the rectangular grid, diamond tipped tool is used.
- Those chips are discarded which are failed in electrical test.
- Observation under microscope before packaging.
- The good chip is then sent for packaging.
- For protection, thin wire is connected using ultrasonic bonding
- The chip is tested again before delivered to customer.
- There are three configurations available for packaging.
 - 1) Metal can package
 - 2) Dual in line package.
 - 3) Ceramic flat package
- The chip is assembled in ceramic packages for military applications.
- This complete IC's are sealed in anti static plastic bags.



Semiconductor devices

Two-terminal devices:

- [Diode](#) (rectifier diode)
- [Gunn diode](#)
- [Laser diode](#)
- [Light-emitting diode](#) (LED)
- [Photocell](#)
- [Phototransistor](#)
- [PIN diode](#)
- [Schottky diode](#)
- [Solar cell](#)
- [Tunnel diode](#)
- [Zener diode](#)
- [Zen diode](#)

Three-terminal devices:

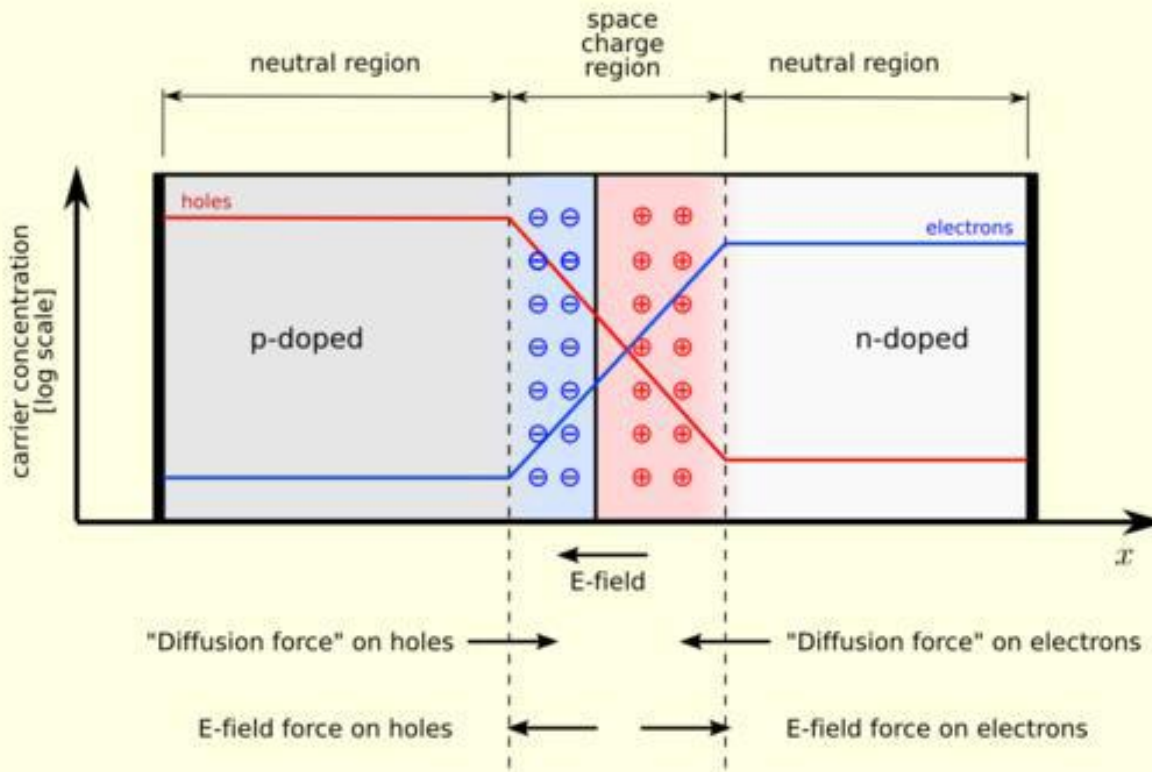
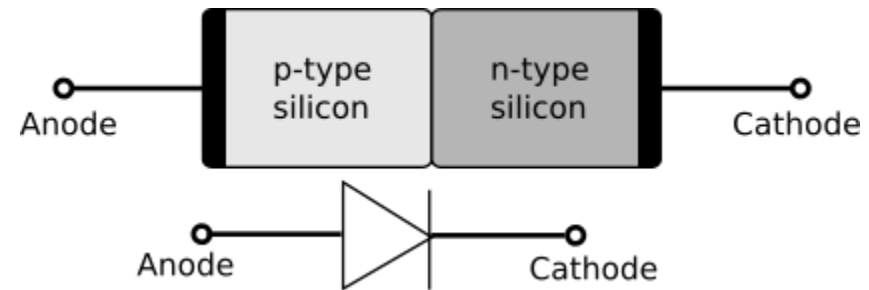
- [Bipolar transistor](#)
- [Darlington transistor](#)
- [Field-effect transistor](#)
- [Insulated-gate bipolar transistor](#) (IGBT)
- [Silicon-controlled rectifier](#)
- [Thyristor](#)
- [Unijunction transistor](#)

Four-terminal devices:

- [Hall effect sensor](#) (magnetic field sensor)
- [Photocoupler](#) (Optocoupler)

p-n JUNCTION DIODE

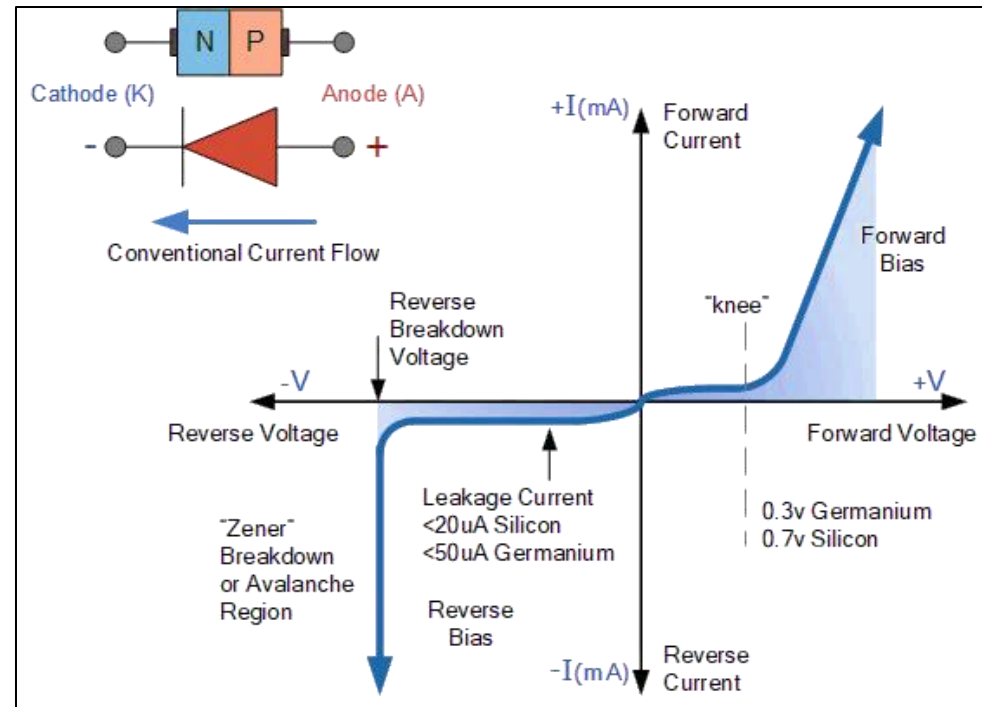
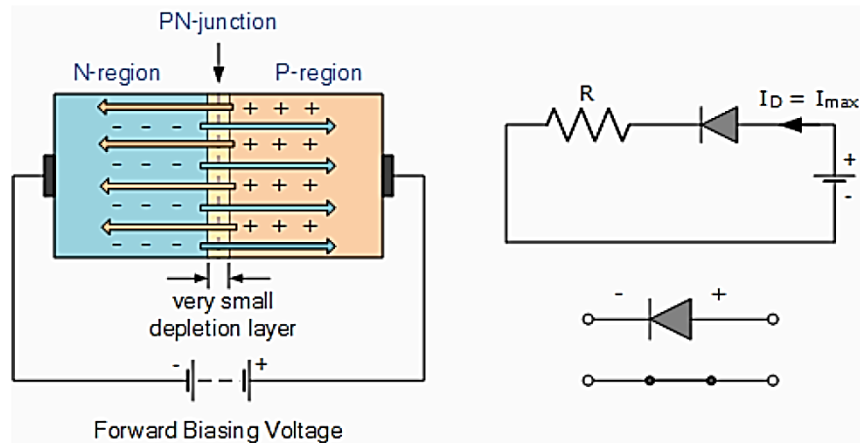
- One half is doped by p type impurity and the other half is doped by n type impurity
- Diffusion: at the junction there is a tendency of free electrons to diffuse over to the P side and the holes to the N side



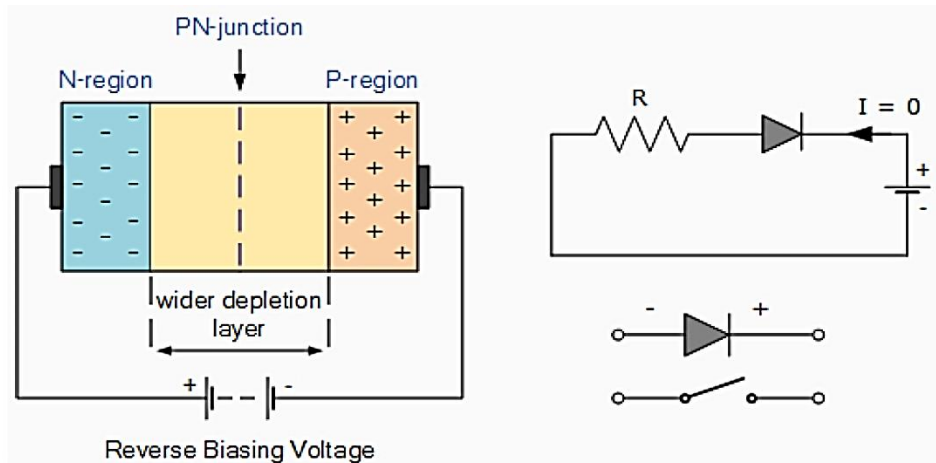
An electrostatic potential difference is established between P and N regions, which are called the **potential barrier, junction barrier, diffusion potential or contact potential**, V_o . The magnitude of the contact potential V_o varies with doping levels and temperature. V_o is 0.3V for Ge and 0.72 V for Si.

FORWARD BIASED JUNCTION DIODE

- Forward Biased Junction Diode showing a Reduction in the Depletion Layer



REVERSE BIASED JUNCTION DIODE



Diode terminal characteristics equation for diode junction current:

$$I_D = I_0 (e^{\frac{V}{nV_T}} - 1)$$

Where $V_T = KT/q$;

V_D _ diode terminal voltage, Volts

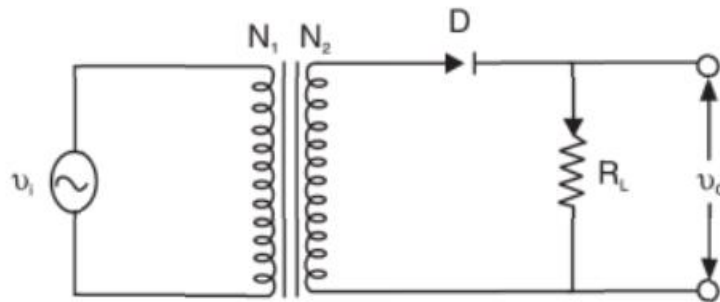
I_0 _ temperature-dependent saturation current, μA

T _ absolute temperature of p-n junction, K

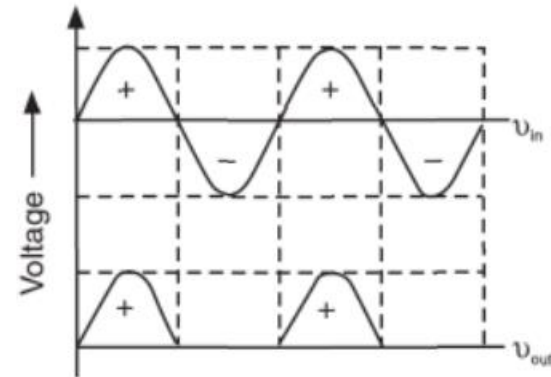
K _ Boltzmann's constant $1.38 \times 10^{-23} J/K$

q _ electron charge $1.6 \times 10^{-19} C$

Half-Wave Rectifier



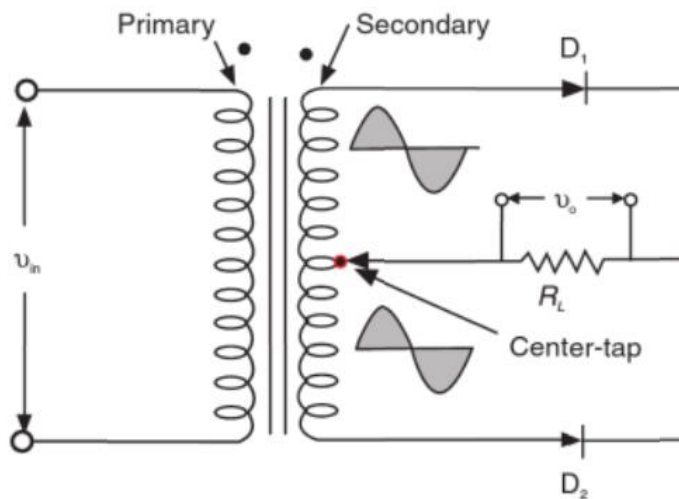
(a)



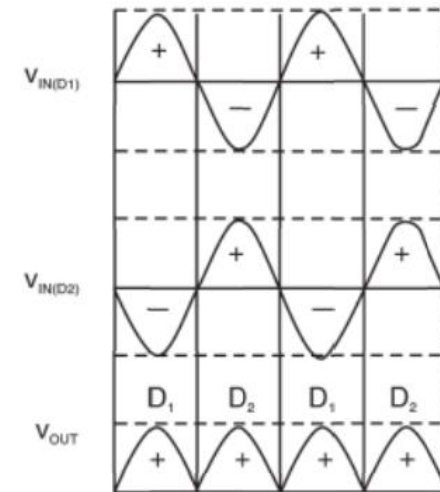
(b)

Half-wave rectifier (a) Circuit diagram (b) input and output voltage wave forms

Full-Wave Rectifier



(a)



(b)

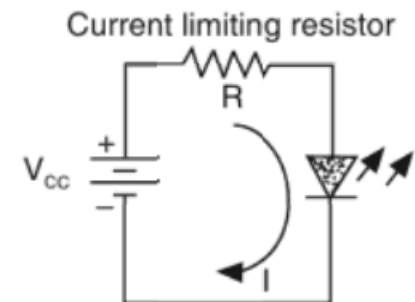
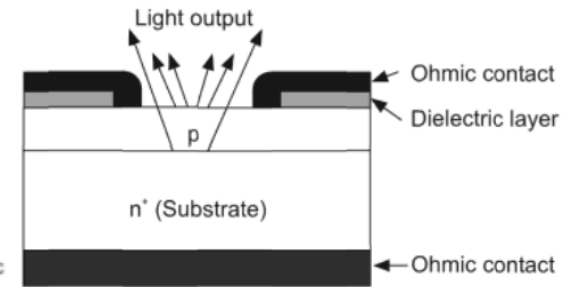
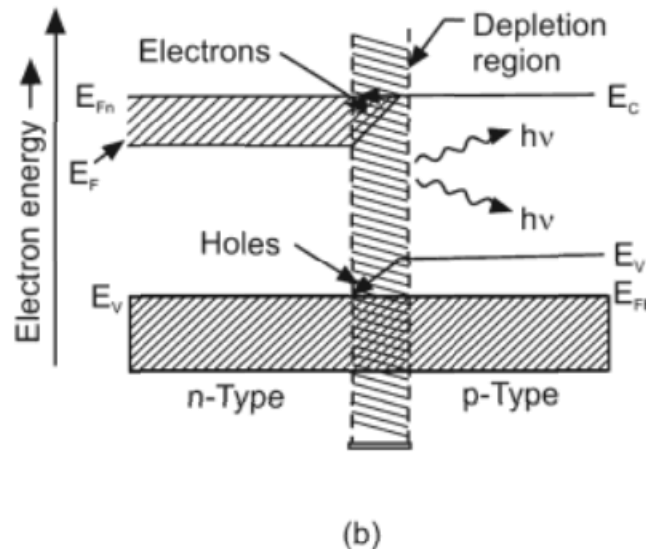
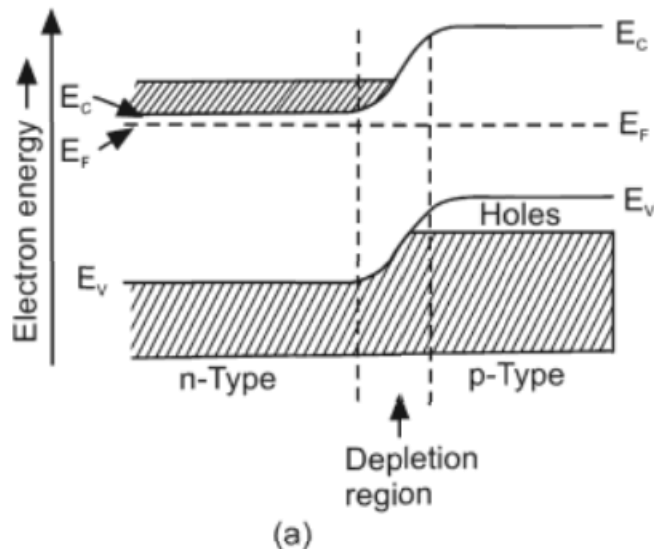
Full-wave rectifier (a) Circuit diagram (b) input and output voltage wave forms

LIGHT EMITTING DIODE (LED)

- A light emitting diode (LED) is a semiconductor diode (heavily doped p-n junction) that gives off light when it is forward biased.
- LEDs are generally fabricated using III-IV compound semiconductors, such as GaAs, which have a direct band gap.

Principle: When a p-n junction is forward biased, minority carriers flow in large numbers into regions where they can recombine with majority carriers producing light in the visible or infra red region. The wavelength of light is given by

$$\lambda = \frac{hc}{E_g} = \frac{1.24}{E_g (eV)} \mu m$$

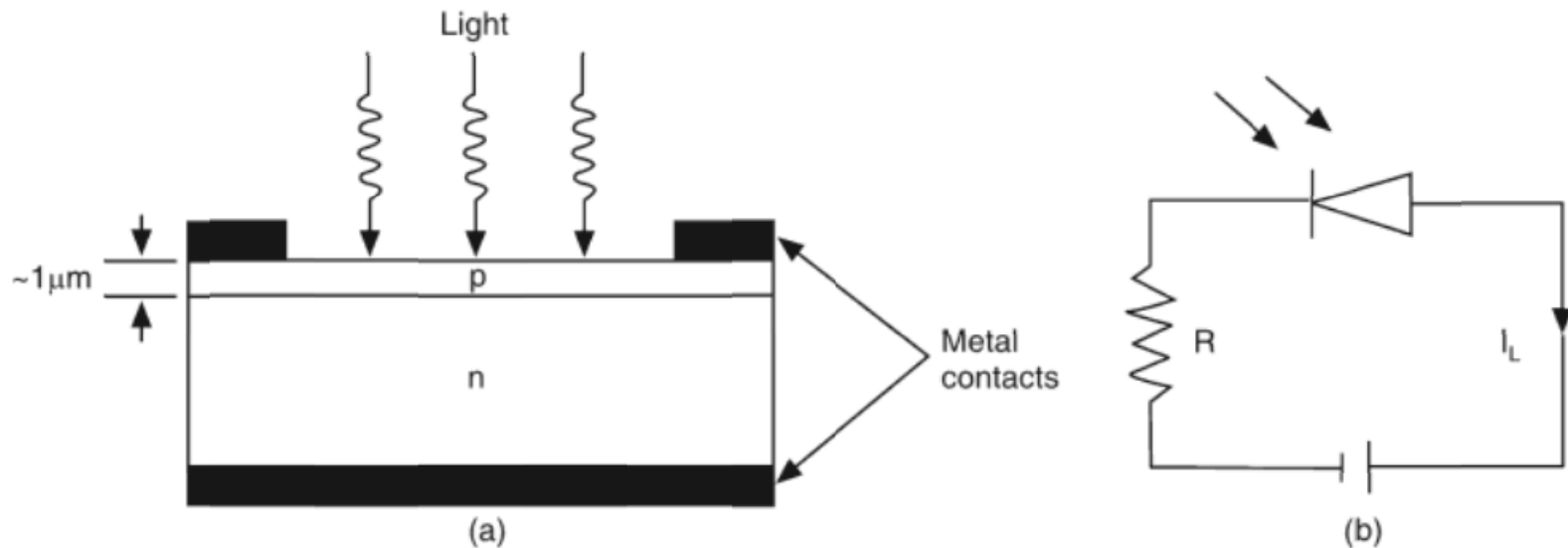


Energy band diagram of an LED- (a) without bias (b) under forward bias

Photodetectors

Photoconductive Effect: When light is absorbed by a material such as a [semiconductor](#), the number of free electrons and [electron holes](#) increases and raises its electrical conductivity.

- **Photodetectors** are devices that absorb optical energy and convert it to electrical energy.
- The operation of photoelectric detectors is based on the **internal photoelectric effect**. There are three main types of photodetectors, namely, photodiodes, pin diodes and avalanche photodiodes, which are widely used in optical communication systems.
- **A semiconductor photodiode is a reverse biased p-n junction.**

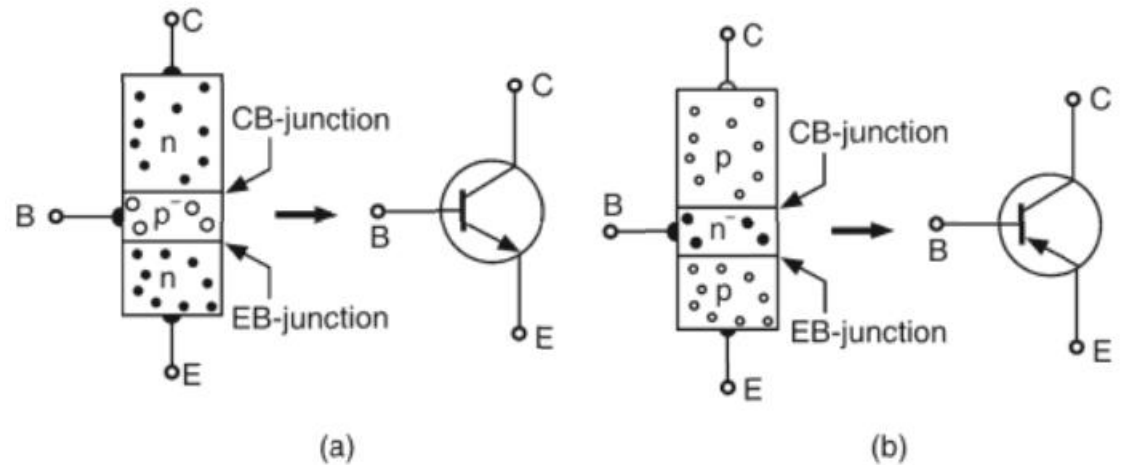
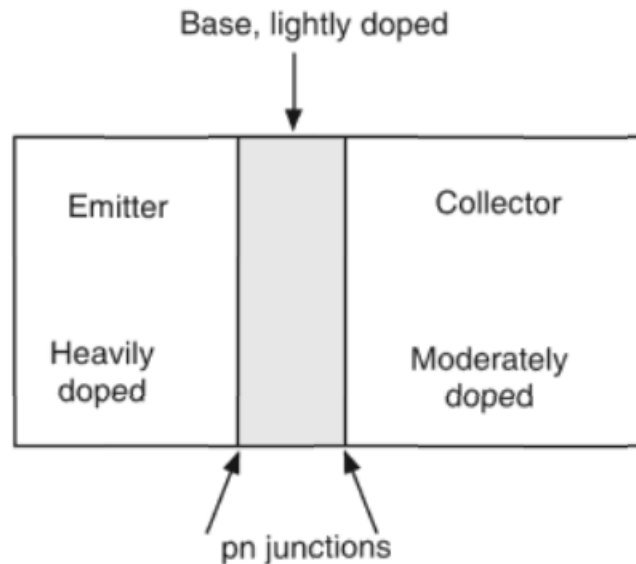


A photo diode (a) Side view (b) A reverse biased *pn*-junction

BIPOLAR JUNCTION TRANSISTOR

- A bipolar junction transistor (BJT) is a three terminal device in which operation depends on the interaction of both majority and minority carriers and hence the name bipolar.
- It is used as amplifier and oscillator circuits, and as a switch in digital circuits. It has wide applications in computers, satellites and other modern communication systems.

TRANSISTOR STRUCTURE



Circuit symbol of transistor (a) *n-p-n* transistor (b) *p-n-p* transistor

Two types of transistors are available. They are called npn and pnp transistors. The npn transistor is constructed using n type material as the emitter and collector while the base is made of p type material. The pnp transistor is constructed using p type material as the emitter and collector while the base is made of n type.

BIASING THE TRANSISTOR

The two junctions of a transistor can be biased in four different ways.

(i) Both the junctions may be forward biased. It causes large currents to flow across the junctions. The currents join together in the base and flow down the common lead. Then the transistor is said to be operating in **saturation region**.

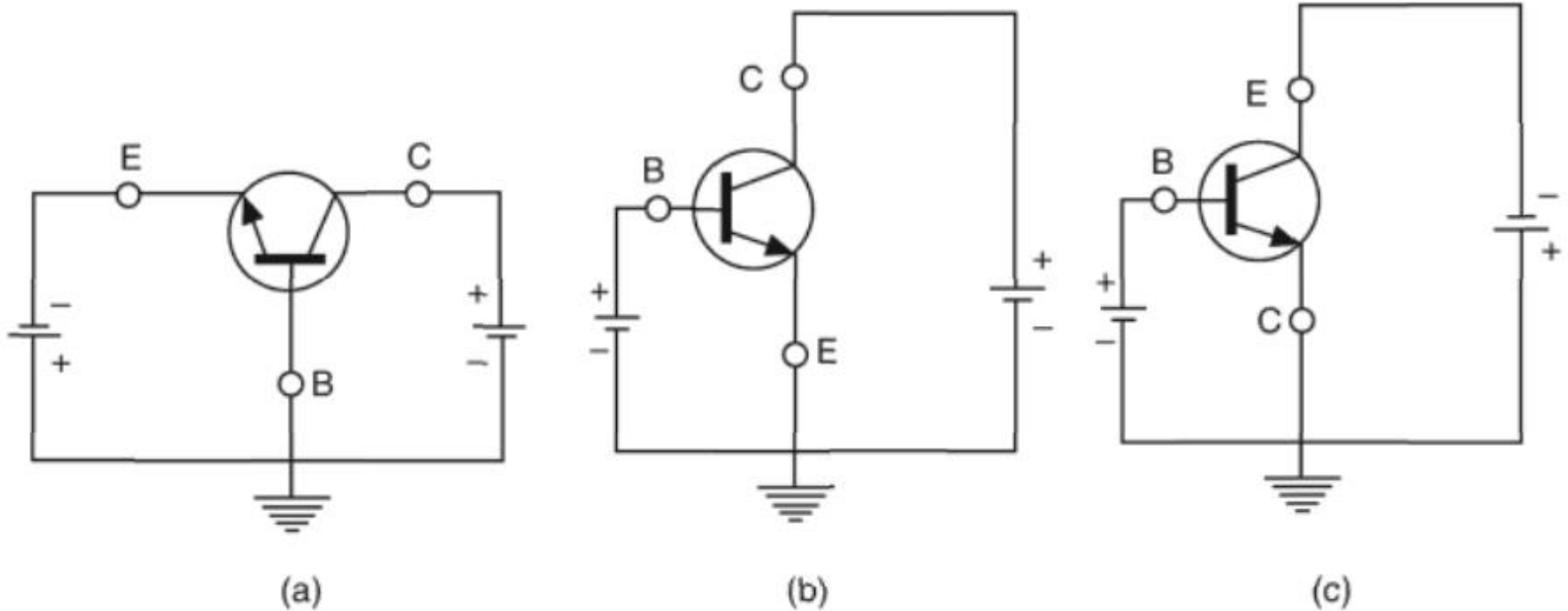
(ii) Both the junctions may be reverse biased. Very small currents flow through the junctions. The transistor is said to be in **cut-off region**.

(iii) EB-junction may be reverse biased and CB-junction forward biased. The transistor is said to operate in **an inverted mode**.

(iv) EB junction may be forward biased and the CB junction reverse biased. Such biasing arrangement causes a large current to flow across the EB-junction as well as CB-junction. Further, the collector current is controlled by the emitter current or base current. With such biasing, the transistor is said to **operate in active region** or in normal mode.

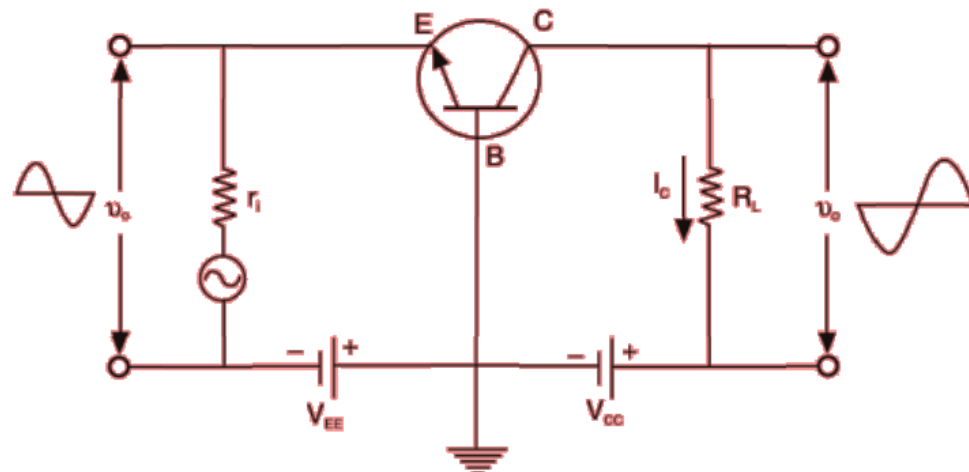
We are interested in the particular biasing where the transistor operates in normal mode.

CIRCUIT CONFIGURATIONS



The three different ways of connecting a transistor (a) Common-base configuration. (b) Common-emitter configuration. (c) Common-collector configuration.

TRANSISTOR AS AN AMPLIFIER



$$\Delta I_E = v_i / r_i$$

The collector current I_C changes by ΔI_C due to the variation ΔI_E caused in I_E .

$$\Delta I_C = \alpha_{dc} \Delta I_E$$

This current ΔI_C flows through R_L causing a voltage drop $(\Delta I_C) R_L$. Therefore,

$$\begin{aligned} v_o &= (\Delta I_C) R_L \\ &= \alpha (\Delta I_E) R_L \\ &= \alpha (v_i / r_i) R_L \end{aligned}$$

The voltage gain of an amplifier is defined as the ratio of output signal voltage v_o to the input signal voltage v_i . Thus,

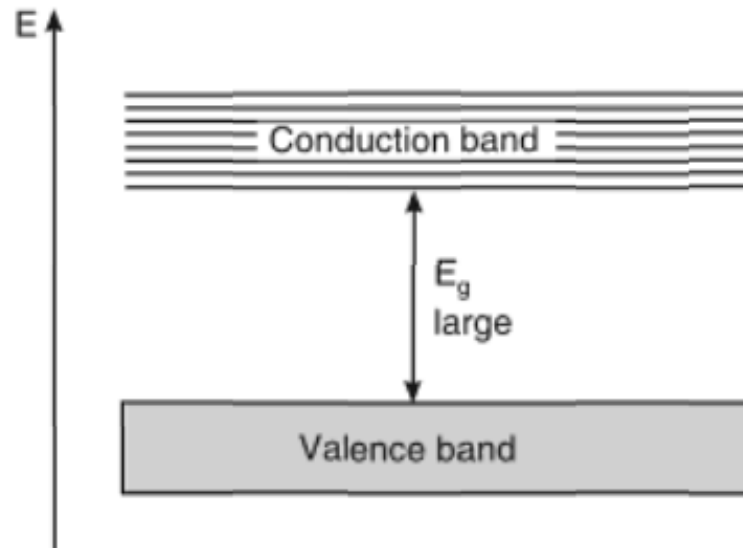
$$\begin{aligned} \text{Gain} &= \frac{\text{Output Voltage, } v_o}{\text{Input Voltage, } v_i} \\ &= \frac{\alpha R_L}{r_i} \\ &\cong \frac{R_L}{r_i} \quad (\because \alpha \approx 1) \end{aligned}$$

R_L is of the order of kilo ohms and is far larger than r_i . Consequently, v_o is larger than v_i and the gain of the circuit is larger than unity. It means that the transistor amplifies a small input voltage to give a larger output voltage.

Transistor amplifier

Dielectrics

- Dielectric materials are insulators.
- Insulating materials are used to resist the flow of current through it when a difference of potential is applied across its ends.
- **Dielectric materials** are used to store electrical energy.
- Dielectric materials are characterized **by dielectric constant, dielectric loss, dielectric strength and high resistivity**.
- Eg. Ferroelectric materials exhibit very high dielectric constant and low dielectric loss.
- Dielectric materials have resistivity range from 10^{10} to 10^{20} ohm-m



DIELECTRIC CONSTANT

$$\epsilon_r = \frac{C}{C_0}$$

where C_0 is the capacitance with air as the medium between the plates and C is the capacitance with dielectric as medium.

ϵ_r is called dielectric constant or relative permittivity. It is a dimensionless quantity, which is always greater than unity in case of dielectrics, and it is independent of the size or shape of the dielectric.

➤ ϵ_r describes the ability of the dielectric material to store electric charges.

$$\epsilon_r = \frac{\epsilon}{\epsilon_0}$$

Where permittivity of the medium (ϵ) to the permittivity of free space (ϵ_0)

Electric Field Intensity or Electric Field Strength

Consider a point charge dq in the region of an electric field. Let F be the force acting on the point charge dq . The force per unit test charge dq is known as electric field strength (E), given by

$$E = \frac{F}{dq} = \frac{Q}{4\pi\epsilon r^2}$$

From Coulomb's law, when two point charges Q_1 and Q_2 are separated by a distance r , the force of attraction or repulsion between the two charges is

$$F = \frac{Q_1 Q_2}{4\pi\epsilon r^2} \hat{n}$$

where ϵ is the permittivity or dielectric constant of the medium in which the charge is placed. For vacuum, $\epsilon = \epsilon_0 = 8.854 \times 10^{-12} \text{ F m}^{-1}$

Electric Flux Density or Electric Displacement Vector

The electric flux density or electric displacement vector D is the number of flux lines crossing a surface normal to the lines, divided by the surface area.

The electric flux density at a distance r from the point charge Q can be written as,

$$D = \frac{Q}{4\pi r^2}$$

where, $4\pi r^2$ is the surface area of a sphere of radius r .

We know that

$$E = Q/4\pi \epsilon r^2$$

So,

$$\mathbf{D} = \epsilon \mathbf{E} = \epsilon_0 \mathbf{E} + \mathbf{P}$$

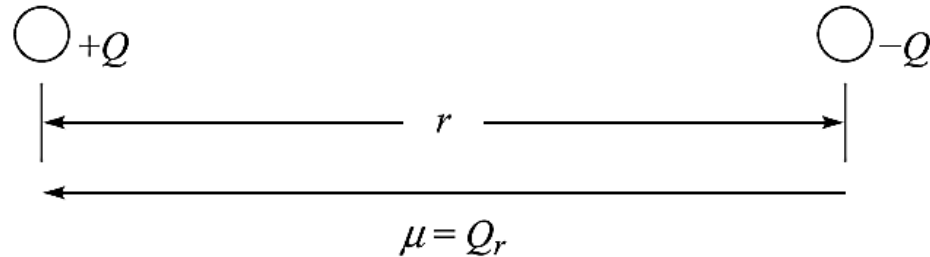
where P is the polarisation and it has the same unit as D , i.e., coulomb per square metre (Cm^{-2}).

Here D , E and P are three filed vectors

Dielectric Parameters

- a. Dielectric constant (ϵ_r)
- b. Electric dipole moment (μ)
- c. Polarisation (P)
- d. Polarisability (α).

Electric Dipole Moment



The arrangement of two equal and opposite charges $+Q$ and $-Q$, separated by a distance r is known as **electric dipole**.

The product of magnitude of the charge and the distance of separation is known as **electric dipole moment (μ)**.

$$\mu = \text{charge} \times \text{distance} = Qr$$

The total dipole moment of a system constituting of point charges $Q_1, Q_2, Q_3, \dots, Q_n$ and the distances of separation r_1, r_2, \dots, r_n is

$$\mu_{\text{total}} = \sum_{i=1}^n Q_i r_i$$

Polarisation

polarisation: the induced dipole moment per unit volume.

$$P = \mu / \text{volume}$$

Polarisability

$$P \propto E$$

$$P = \alpha E$$

where α is a proportionality constant known as **polarisability**. The unit of α is F m^2 .

➤ If the solid material contains N number of particles per unit volume, then the polarisation can be

$$P = N \alpha E$$

where $\alpha = \alpha_e + \alpha_i + \alpha_0$. Here α_e , α_i and α_0 are the **electronic, ionic and orientation polarisability**

DIFFERENT TYPES OF POLARISATIONS

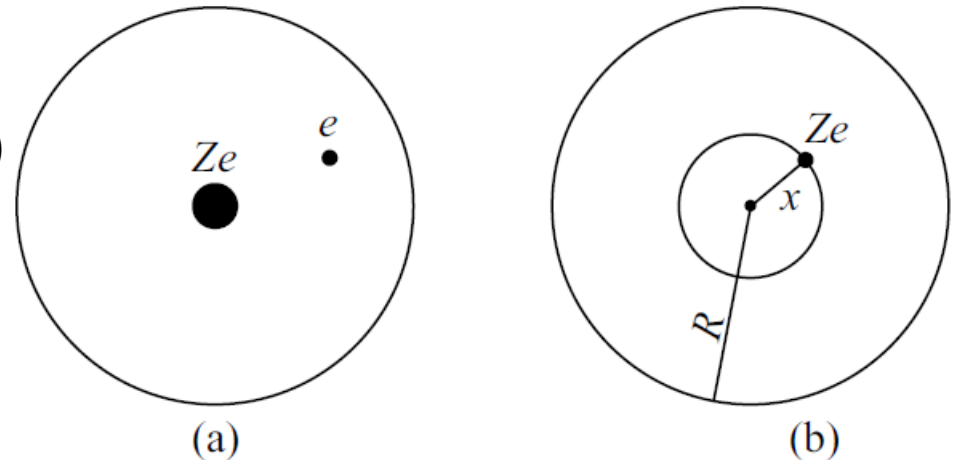
The application of an electric field to a dielectric material creates or realigns the dipoles resulting in polarisation. There are four different types of polarisations

- (1) Electronic or induced polarisation (P_e)
- (2) Atomic or ionic polarisation (P_i)
- (3) Orientation polarisation (P_o), and
- (4) Interfacial or space charge polarisation

Electronic or Induced Polarisation

The polarisation produced due to the displacement of electrons is known as **electronic polarisation**.

- The force acquired by the nucleus is \mathbf{ZeE} due to the applied electric field intensity (\mathbf{E})



$$\text{The charge inside the sphere} = \frac{\frac{4}{3}\pi x^3}{\frac{4}{3}\pi R^3} Ze$$

$$\Rightarrow = \frac{x^3}{R^3} Ze$$

The Coulomb force acting between the nucleus and the electron clouds inside the sphere of radius x is given by,

$$F = \frac{Ze \left(\frac{-x^3}{R^3} Ze \right)}{4\pi\epsilon_0 x^2}$$

At equilibrium, the nucleus is balanced and hence, the total force on the nucleus is zero. Therefore,

$$ZeE = \frac{Ze \left(\frac{x^3}{R^3} Ze \right)}{4\pi\epsilon_0 x^2}$$

Simplifying the above equation, we get $x = \frac{4\pi\epsilon_0 R^3 E}{Ze}$

The induced dipole moment is given by

$$\mu_{\text{ind}} = Ze \ x$$

$$x = \frac{4\pi\epsilon_0 R^3 E}{Ze}$$

Substituting the value of x

$$\mu_{\text{ind}} = 4\pi \epsilon_0 R^3 E$$

$$\mu_{\text{ind}} = \alpha_e E$$

where, α_e is the electronic polarisability and is equal to

$$\alpha_e = 4\pi \epsilon_0 R^3$$

the electronic polarisation

$$P_e = N \alpha_e E$$

Substituting the value of α_e

$$P_e = N 4\pi \epsilon_0 R^3 E$$

$$\epsilon_0(\epsilon_r - 1) E = 4 N \pi \epsilon_0 R^3 E$$

$$\epsilon_r - 1 = 4 N \pi R^3$$

Atomic or Ionic Polarisation

When an electric field is applied to an ionic crystal, the polarisation that arises due to the displacement of the positive ions away from the field and the displacement of the negative ions towards the field is known as **atomic or ionic polarisation**.

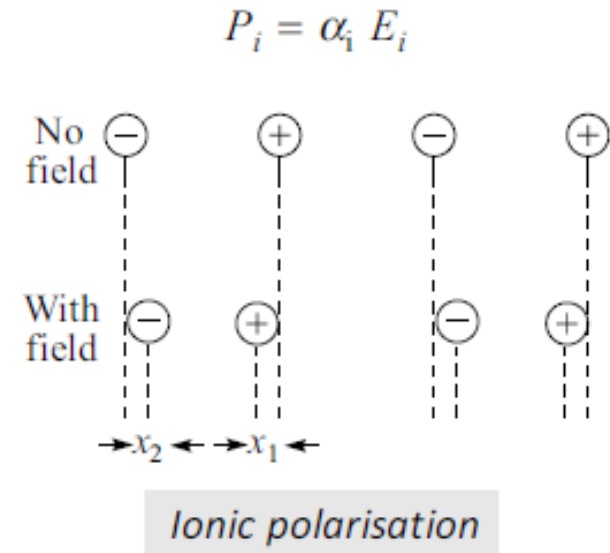
Eg. NaCl, KBr, KCl and LiBr.

The polarisation produced for a crystal having N number of dipoles per unit volume is given by

$$P_i = N \alpha_i E_i$$

Let x_1 and x_2 be the displacements of the positive and negative ions, produced due to the application of an electric field. The dipole moment induced is given by,

$$\mu_i = e (x_1 + x_2)$$



Let F be the force experienced by the ions due to the application of the electric field. The restoring force acting on the ions is directly proportional to their displacements.

$$\begin{aligned} F &\propto x_1 \\ &\propto x_2 \\ &= \beta_1 x_1 = \beta_2 x_2 \end{aligned}$$

where, β_1 and β_2 are the proportionality constants and they are directly proportional to the mass and angular frequency of the respective ions.

$$\begin{aligned} \beta_1 &\propto m \text{ and } \beta_2 \propto M \\ &\propto \omega_0^2 \end{aligned}$$

the force experienced by the positive and negative ions is given by,

$$\mathbf{F} = e\mathbf{E} = m\omega_0^2 \mathbf{x}_1 = M\omega_0^2 \mathbf{x}_2$$

Therefore,

$$x_1 = \frac{eE}{m\omega_0^2} \quad \text{and} \quad x_2 = \frac{eE}{M\omega_0^2}$$

Substituting the values of x_1 and x_2 , the induced dipole moment can be written as,

$$\mu_i = \frac{e^2}{\omega_0^2} \left[\frac{1}{m} + \frac{1}{M} \right] E$$

The ionic polarisability

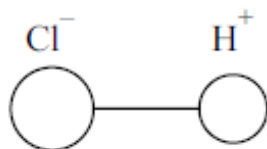
$$\alpha_i = \frac{e^2}{\omega_0^2} \left(\frac{1}{M} + \frac{1}{m} \right)$$

Using Clausius–Mosotti equation, the dielectric constant for an ionic crystal can be written as

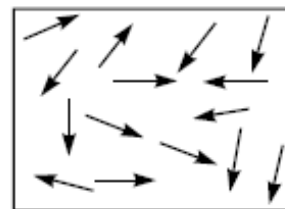
$$\frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{N\alpha_i}{3\epsilon_0}$$

Dipolar or Orientation Polarisation

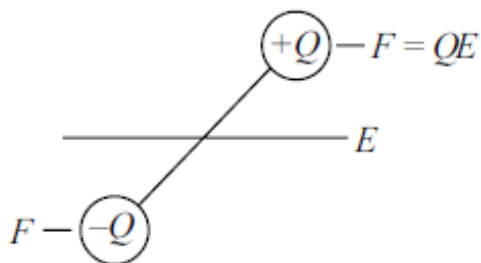
The dipolar or orientation polarisation is produced only in case of polar molecules such as H_2O , HCl and nitrobenzene. When an electric field is applied to a polar molecule, the dipoles experience a torque and try to align parallel to the applied field, which results in a rotation of the dipoles.



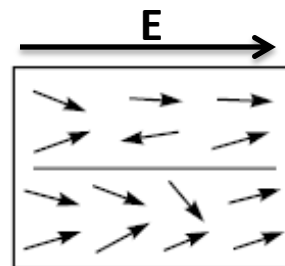
(a) the dipole in a HCl molecule



(b) the random orientation of dipoles in the absence of electric field



(c) the rotation of a dipole due to the applied electric field



(d) the dipoles try to align parallel to the applied field

Dipolar polarisation

Consider a polar molecule is subjected to an electric field of strength E . Let θ be the angle of rotation of the dipoles.

Then the torque produced by the field on the dipole is

$$\tau = \mu_p E \sin \theta$$

$$(\because \tau = r.F \sin \theta \\ = r. Q. E \sin \theta)$$

where μ_p is the permanent dipole moment.

The maximum work is done when the dipole is rotated through an angle of $\theta = 180^\circ$. When the dipole is already parallel to the applied field, i.e., when $\theta = 0^\circ$, the work done is minimum. Therefore, the maximum energy is given by

$$E_{\max} = \int_0^\pi \mu_p E \sin \theta d\theta \\ = 2\mu_p E$$

The average dipole energy E_{dip} $E_{\text{dip}} = \mu_p E$

The ratio of the average dipole energy to average thermal energy is, given by

$$\frac{\text{Average dipole energy}}{\text{Average thermal energy}} = \frac{\mu_p E}{\frac{5}{2} kT}$$

If this ratio is greater than unity, then the orientation polarisation is said to be effective.

The average orientation polarisation is

$$P_o \propto \frac{\text{Permanent dipole moment} \times \text{Average dipole energy}}{\text{Average thermal energy}}$$

$$P_o \propto \mu_p \frac{\mu_p E}{\frac{5}{2}kT}$$

If the calculation for average dipole energy is properly done using Boltzmann's statistics, then the average orientation polarisation is

$$P_o = \frac{1}{3} \frac{\mu_p^2 E}{kT}$$

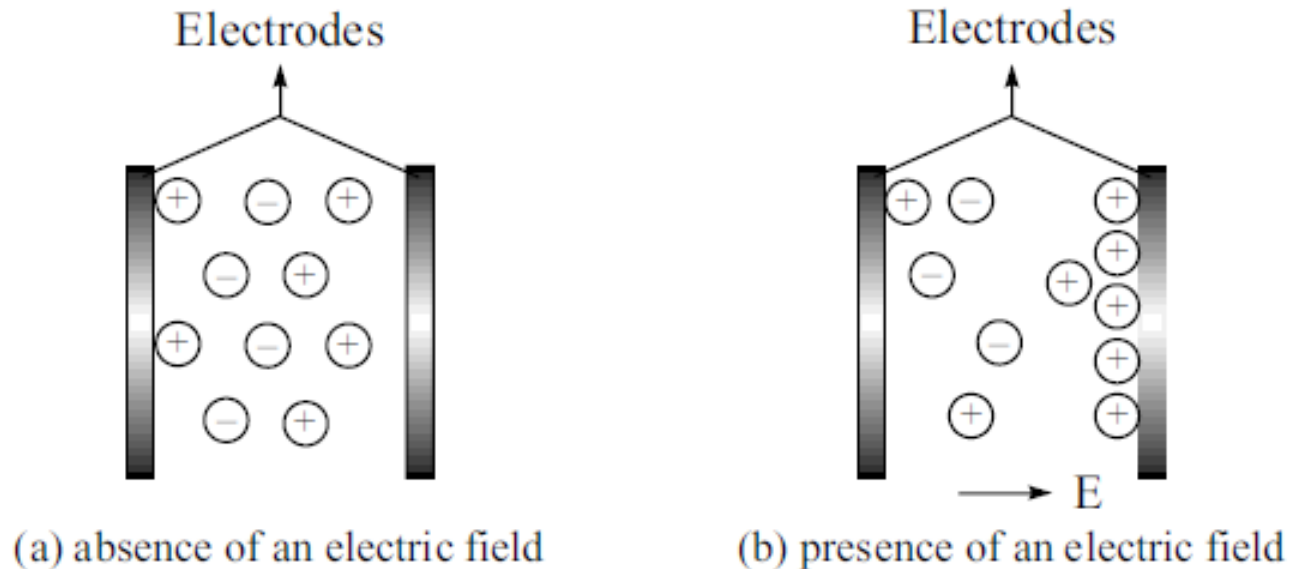
Therefore, the orientation polarisability can be written as

$$\alpha_e = \frac{\mu_p^2}{3kT}$$

It is clear from above Eq. that the orientation polarisation is temperature dependent.

Interfacial or Space Charge Polarisation

Consider a dielectric medium is placed between any two electrodes, When no field is applied to the electrode, the positive and negative charges are not separated and there are fixed number of charges. On the other hand, when an electric field is applied, the charges are separated. The positive charges are accumulated near the negative electrode. Therefore, a dipole moment is induced due to displacement of the ions. Then, the induced dipole moment per unit volume gives the induced polarisation. This polarisation is known as interfacial polarisation.



Space-charge polarisation

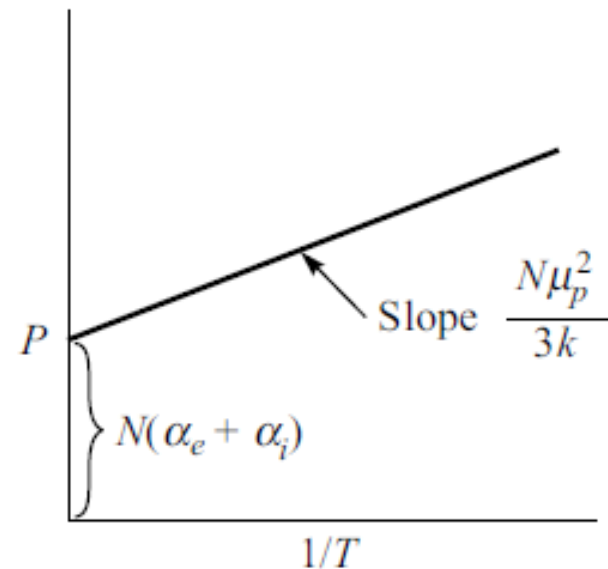
Total Polarisation

the total polarisation is the sum of the electronic, ionic and orientation polarisation.
Therefore, total polarisation is given by

$$\mathbf{P} = \mathbf{P}_e + \mathbf{P}_i + \mathbf{P}_o$$

$$P = N \alpha_e E_i + N \alpha_i E_i + N \alpha_o E_i$$

$$P = N E_i \left(4\pi\epsilon_0 R^3 + \frac{e^2}{\omega_0^2} \left(\frac{1}{M} + \frac{1}{m} \right) + \frac{\mu_p^2}{3kT} \right)$$



Plot of P versus $1/T$

CLAUSSIUS-MOSOTTI EQUATION

Elemental solid dielectrics like germanium, silicon, diamond, sulphur, etc., have no permanent dipoles or ions and will have only cubic structure, thereby exhibiting only electronic polarisation. The total polarisation is written as,

$$\mathbf{P} = \mathbf{N} \alpha \mathbf{E}_i$$

where $\alpha = \alpha_e + \alpha_i + \alpha_0$

Elemental solid dielectrics have only electronic polarisation and the remaining polarisation namely, ionic and orientation, are equal to zero, since there is no ionic character or permanent dipoles.

the total polarisation

$$\mathbf{P} = \mathbf{N} \alpha_e \mathbf{E}_i$$

where $\alpha_i = \alpha_0 = 0$, and N is the number of atoms per unit volume

Internal field $E_i = E + \frac{P}{3\epsilon_0}$

$$P = N \alpha_e \left[E + \frac{P}{3\epsilon_0} \right] \dots\dots\dots (1)$$

We know that,

$$D = \epsilon_0 E + P$$

$$\frac{P}{E} = \frac{D}{E} - \epsilon_0$$

From the definition of electric displacement vector,

$$\mathbf{D} = \epsilon \mathbf{E}$$

Therefore, $\frac{P}{E} = \epsilon - \epsilon_0 = \epsilon_r \epsilon_0 - \epsilon_0$

where

$$\epsilon = \epsilon_r \epsilon_0$$

$$\frac{P}{E} = \epsilon_0 (\epsilon_r - 1)$$

$$P = E \epsilon_0 (\epsilon_r - 1)$$

Substituting P value in Eq. (1), we get

$$E \epsilon_0 (\epsilon_r - 1) = N a_e \left[E + \frac{E \epsilon_0 (\epsilon_r - 1)}{3 \epsilon_0} \right]$$

$$\epsilon_0 (\epsilon_r - 1) = N a_e \left[1 + \frac{\epsilon_0 (\epsilon_r - 1)}{3 \epsilon_0} \right]$$

$$N a_e = \frac{\epsilon_0 (\epsilon_r - 1)}{\left[1 + \frac{\epsilon_0 (\epsilon_r - 1)}{3\epsilon_0} \right]}$$

$$\frac{N \alpha_e}{3\epsilon_0} = \frac{\epsilon_0 (\epsilon_r - 1)}{3\epsilon_0 + \epsilon_0 \epsilon_r - \epsilon_0}$$

Simplifying the above equation, we get

$$\frac{N \alpha_e}{3\epsilon_0} = \frac{\epsilon_r - 1}{\epsilon_r + 2} \dots\dots\dots(2)$$

where, N is the number of dipoles per unit volume. Equation (2) is known as Claussius–Mosotti equation.

In this equation, by substituting the values of ϵ_r , ϵ_0 and N, one can determine the electronic polarisability α_e .

For a dielectric material consisting of N number of dipoles

$$\frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{1}{3\epsilon_0} \sum_i N_i \alpha_{ei}$$

where N_i and α_{ei} are the appropriate quantities for the types of atoms or molecules.

DIELECTRIC LOSS

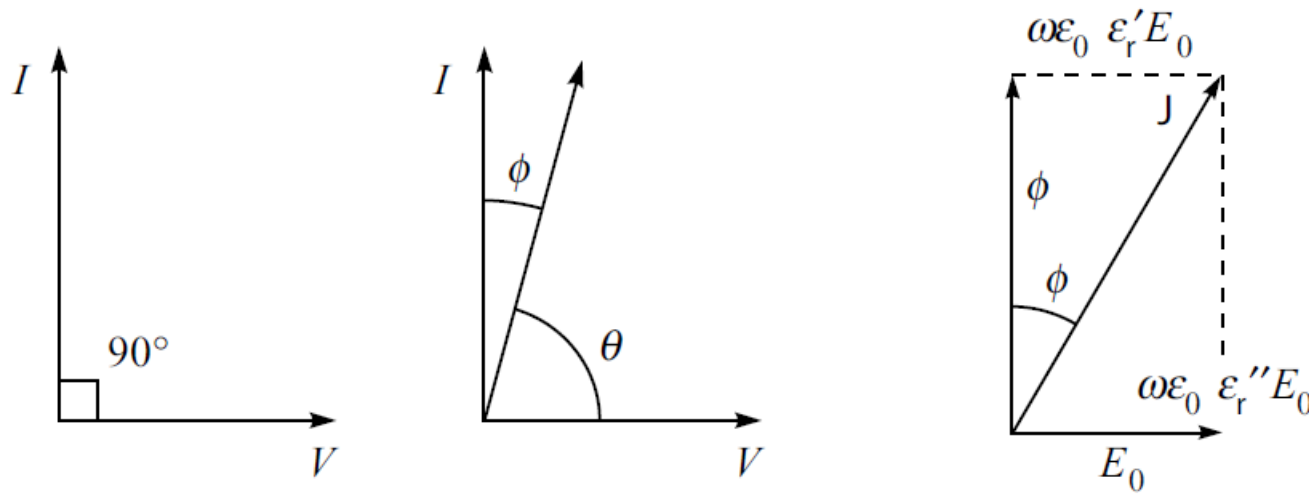
When an AC field is applied to a dielectric material, some amount of electrical energy is absorbed by the dielectric material and is wasted in the form of heat. This loss of energy is known as **dielectric loss**.

The dielectric loss is a major engineering problem. In an ideal dielectric, the current leads the voltage by an angle of 90° . But in case of a commercial dielectric, the current does not exactly lead the voltage by 90° .

It leads by some other angle ϕ that is less than 90° . The angle $\phi = 90 - \theta$ is known as the **dielectric loss angle**.

For a dielectric having capacitance C and voltage V applied to it at a frequency f Hz, the dielectric power loss is given by

$$P = VI \cos \theta$$



Relation between current and voltage in dielectrics

$$P = VI \cos \theta$$

Since $I = V/X_c$ where, X_c is the capacitive reactance and is equal to $1/j\omega C$.

$$P = \frac{V^2}{X_c} \cos (90 - \Phi) = V^2 j\omega C \sin \Phi$$

Since θ is very small,

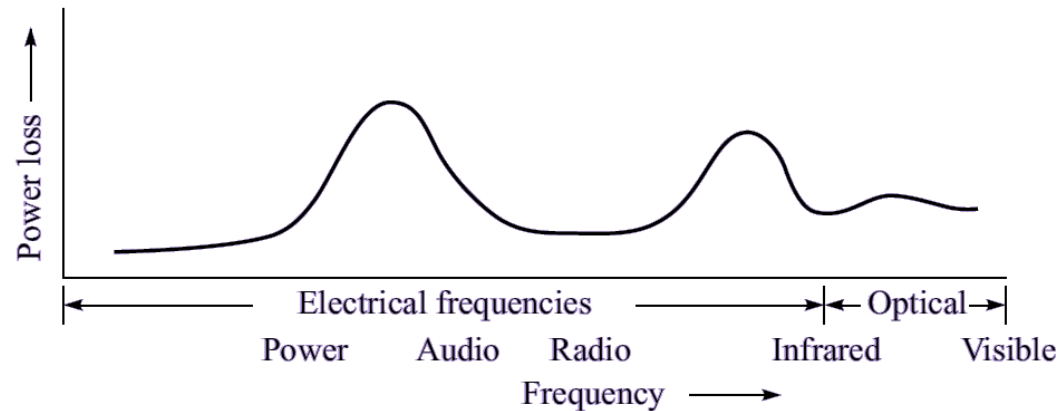
$$\sin \Phi = \tan \Phi$$

$$\text{and } P = j V^2 \omega C \tan \Phi$$

where $\tan \Phi$ is said to be the power factor of the dielectric.

The dielectric loss is increased by the following factors:

- (1) High frequency of the applied voltage
- (2) High value of the applied voltage
- (3) High temperature, and
- (4) Humidity



Frequency versus dielectric loss

- The dielectric losses in the radio frequency region are usually due to dipole rotation.
- The dielectric losses at lower frequencies are mainly due to dc resistivity.
- The dielectric losses in the optical region are associated with electrons and they are known as **optical absorption**.

PIEZOELECTRICITY

Dielectric materials may be divided into the two following categories:

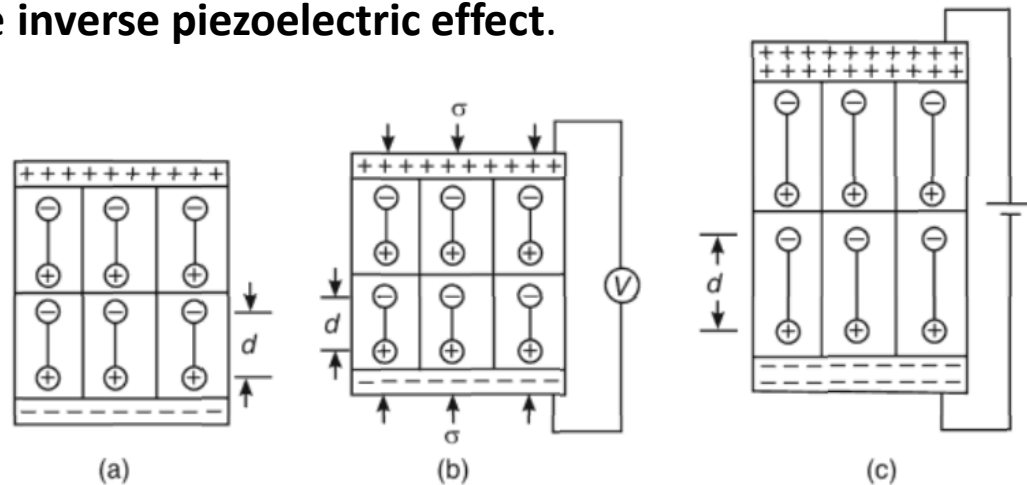
- (i) **Linear dielectrics** are those materials in which the polarization \mathbf{P} and displacement \mathbf{D} are directly proportional to the intensity of the electric field \mathbf{E} ; and relative permittivity ϵ_r and susceptibility χ do not depend on the intensity of electric field. They are also known as **passive dielectrics**.
- (ii) **Nonlinear dielectrics** are those materials in which relative permittivity ϵ_r and susceptibility χ depend on the intensity of electric field. These materials are known as **active dielectrics**.

eg. Piezoelectrics, pyroelectrics, ferroelectrics and some of the optical media.

- Piezoelectric crystals provide a relation between electrical and mechanical forces and hence serve as **transducers** which produce or detect electrical or mechanical signals.
- Hence they are used to detect very small mechanical displacements and small amounts of electric charge.
- All commercial piezoelectric materials used today are **ferroelectrics**.

Piezoelectric Effect

- The French physicists Pierre Curie and Paul-Jean Curie discovered the piezoelectric effect in 1880.
- When one pair of opposite faces of certain asymmetric crystals such as quartz is compressed, opposite electric charges appear on the other pair of opposite faces of the crystal.
- If the crystals are subjected to tension, the polarities of the charges are reversed. The development of charges as a result of the mechanical deformation is known as the **direct piezoelectric effect**. Crystals that exhibit piezoelectric effect are called **piezoelectric crystals**.
- If an electric field is applied across one pair of faces of a piezoelectric crystal, it gets deformed along the direction of the other opposite pair of faces. If an alternating voltage is applied between the two opposite faces of the crystal, it vibrates with the frequency of the field. The mechanical deformation of piezoelectric materials caused by an external electric field is known as the **inverse piezoelectric effect**.



(a) Electric dipoles in a piezoelectric crystal. (b) Mechanical forces cause appearance of polarization charges (c) An external voltage applied across ends of the crystal causes dimensional changes.

- In ordinary solids, a stress causes a proportional strain 's' related by an elastic modulus. Piezoelectricity is the additional creation of the **electric charge** by an **applied stress**.
- The induced polarization P, in direct piezoelectric effect, is directly proportional to the applied mechanical stress, σ .

$$P = d\sigma$$

where d is the proportionality constant and is known as **piezoelectric coefficient** and is expressed in Coulombs/Newton. It may be defined as the charge developed per unit force. A change in sign of σ , reverses the sign of polarization. The value of d should be high for practical applications.

- In the inverse piezoelectric effect, an electric field E produces a proportional strain,

$$s = dE$$

Thermodynamics proves that the piezoelectric coefficient d of direct and inverse piezoelectric effects are equal for the same dielectric.

Electrostriction

Electrostriction is a property of all electrical non-conductors, or dielectrics, that causes them to change their shape under the application of an electric field

electromechanical coupling factor, k is used to describe the piezoelectric effect in actual piezoelectric elements. Energy can be given to a piezoelectric element either mechanically by stressing it or electrically by charging it. All the energy given to it is not converted in producing the effect. Therefore, the piezoelectrics are characterized by strength of piezoelectric effect. This strength is measured by the electromechanical coupling factor, k.

- In case of **direct piezoelectric effect**, the external force is expended not only on the deformation of the element but also on its polarization. The square of the piezoelectric coupling factor is defined as the ratio of the electrical energy generated by the piezoelectric element to the total energy expended on the deformation.

$$K^2 = \frac{\text{Mechanical energy converted to electrical energy}}{\text{Total input mechanical energy}}$$

- In case of **inverse piezoelectric effect**, the external voltage is expended not only on charging the element but also on its deformation. The square of the piezoelectric coupling factor is defined as the ratio of the electrical energy generated by the piezoelectric element to the total energy expended on the deformation.

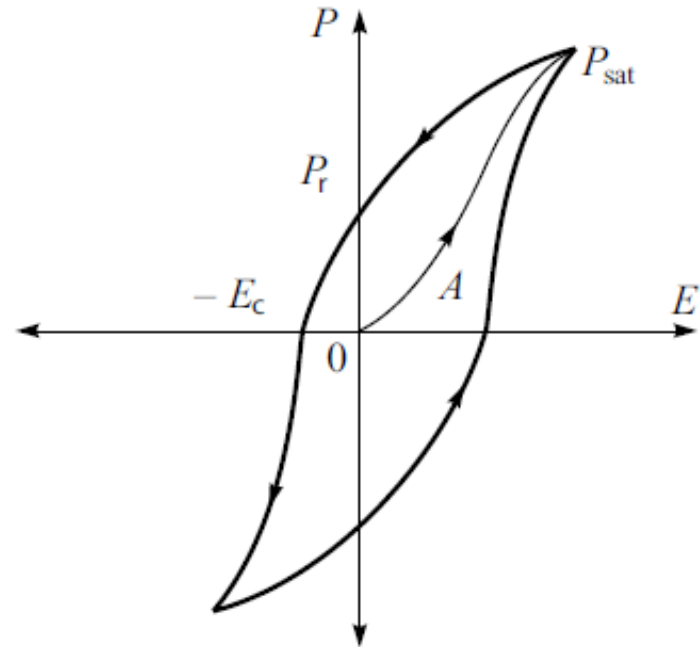
$$K^2 = \frac{\text{Electrical energy converted to mechanical energy}}{\text{Total input electrical energy}}$$

FERROELECTRIC MATERIALS

In certain dielectric materials, polarisation is not a linear function of applied electric field. Such materials exhibit hysteresis curve similar to that of ferromagnetic materials and are known as **ferroelectric materials**.

Hysteresis Properties

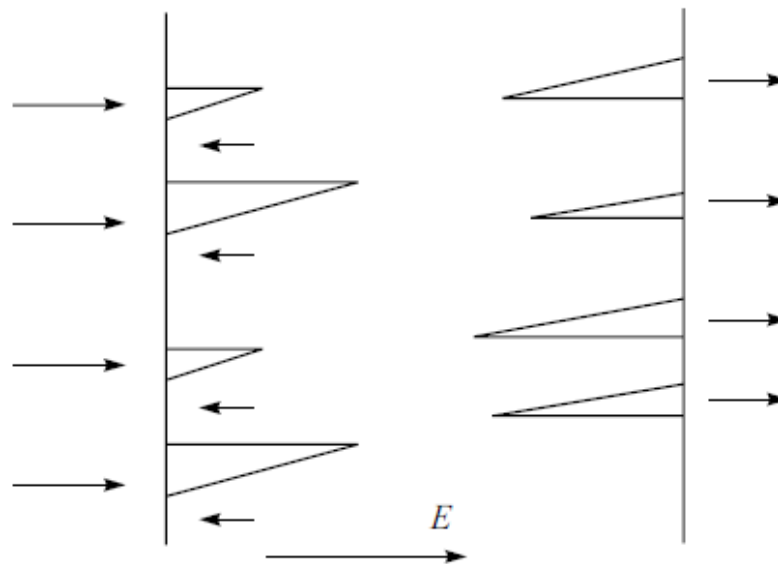
- When an increasing electric field is applied to a ferroelectric material, it results in an increase in polarisation and it reaches a maximum value for a particular field strength.
- On the other hand, if we decrease the electric field, the polarisation decreases. When the field strength is zero, i.e., $E = 0$, a small amount of polarisation exists in the material. This polarisation is known as **remanent polarisation (P_r)**. Now the ferroelectric material is said to be spontaneously polarised.
- In order to reduce the value of polarisation to zero, an electric field strength ($-E_c$) should be applied. This field is known as **coercive field**



Hysteresis curve for ferroelectric material

- The hysteresis loop of a ferroelectric material is explained on the basis of the domain concept. Domain is experimentally observed by applying polarised light, which makes the domain visible.
- Domains which are opposite in direction to the applied field decrease in size and domains which are parallel to the field direction increase in size in the form of needles of approximately 10^{-6} m width.

Eg. Rochelle salt (sodium-potassium salt of tartaric acid; $\text{NaKC}_4\text{H}_4\text{O}_{21} \cdot 4\text{H}_2\text{O}$), potassium dihydrogen phosphate (KH_2PO_4), barium titanate (BaTiO_3), etc., are typical examples.

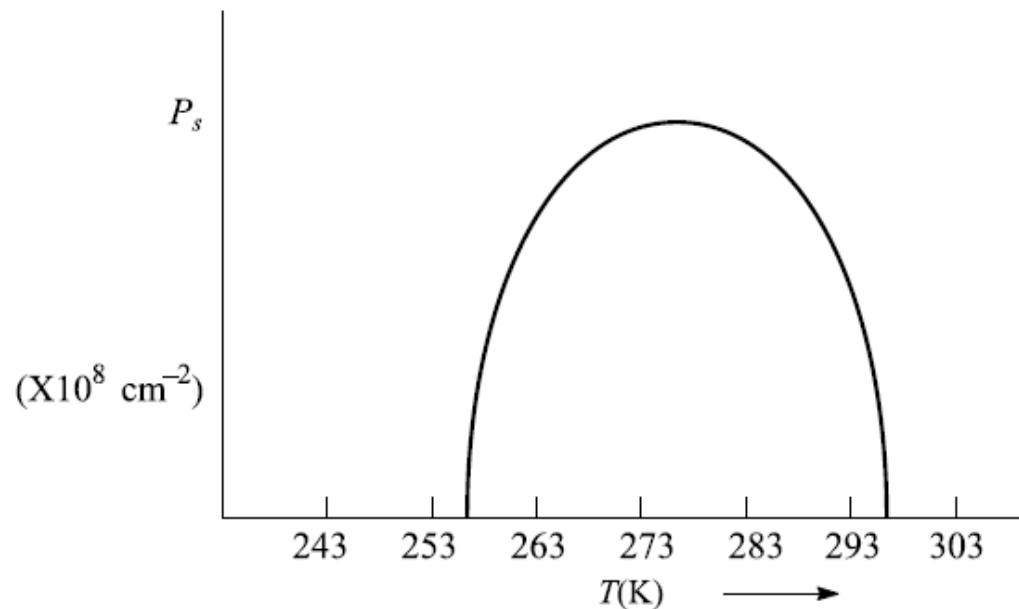


Domain structure of barium titanate

Classification of Ferroelectric Crystals Ferroelectric crystals are classified into three groups

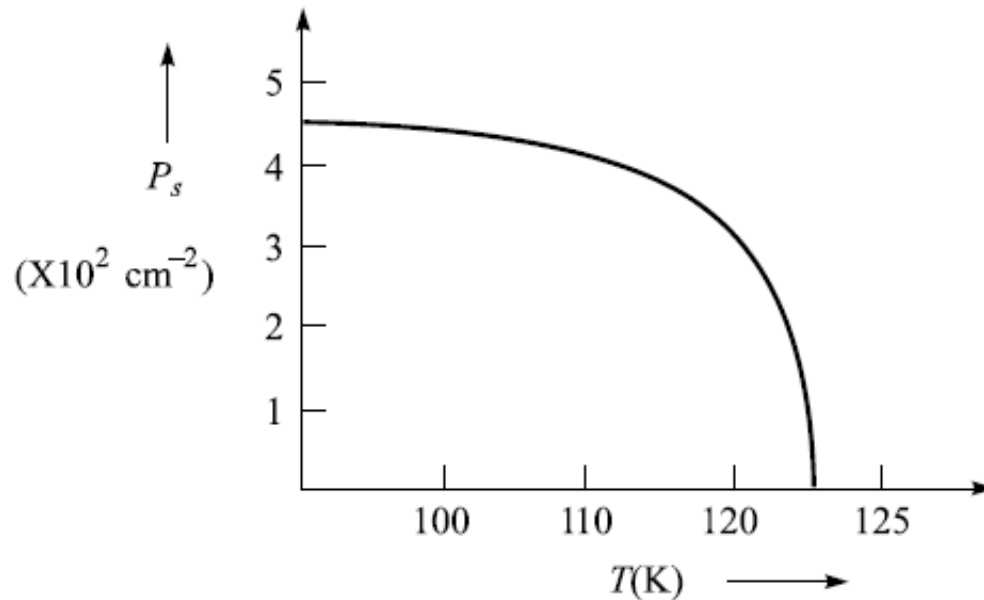
- (1) Rochelle salt
- (2) Potassium dihydrogen phosphate, and
- (3) Barium titanate

(1) Rochelle Salt It behaves as a ferroelectric material in the temperature range from 255 to 296 K, i.e., it possesses two transition temperatures (Curie temperature). The crystal structure is orthorhombic above upper curie temperature. Below this transition temperature, the crystal structure is monoclinic in nature.



Temperature versus polarisation of Rochelle salt

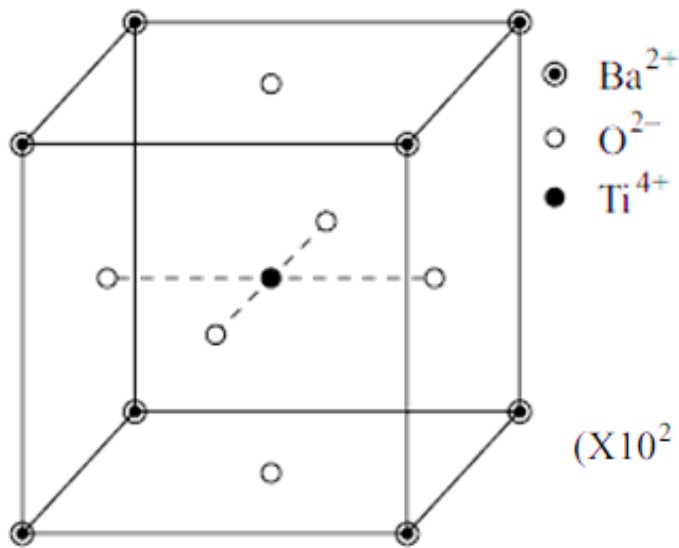
(2) Potassium Dihydrogen Phosphate It has only one Curie temperature and its value is 123 K. It possesses ferroelectric property below this temperature. Above Curie temperature, its crystal structure is tetragonal. Below Curie temperature, the crystal structure is orthorhombic. Other ferroelectric crystals belonging to this family include KD_2PO_4 , RbH_2PO_4 , CsH_2AsO_4 , CsD_2AsO_4 .



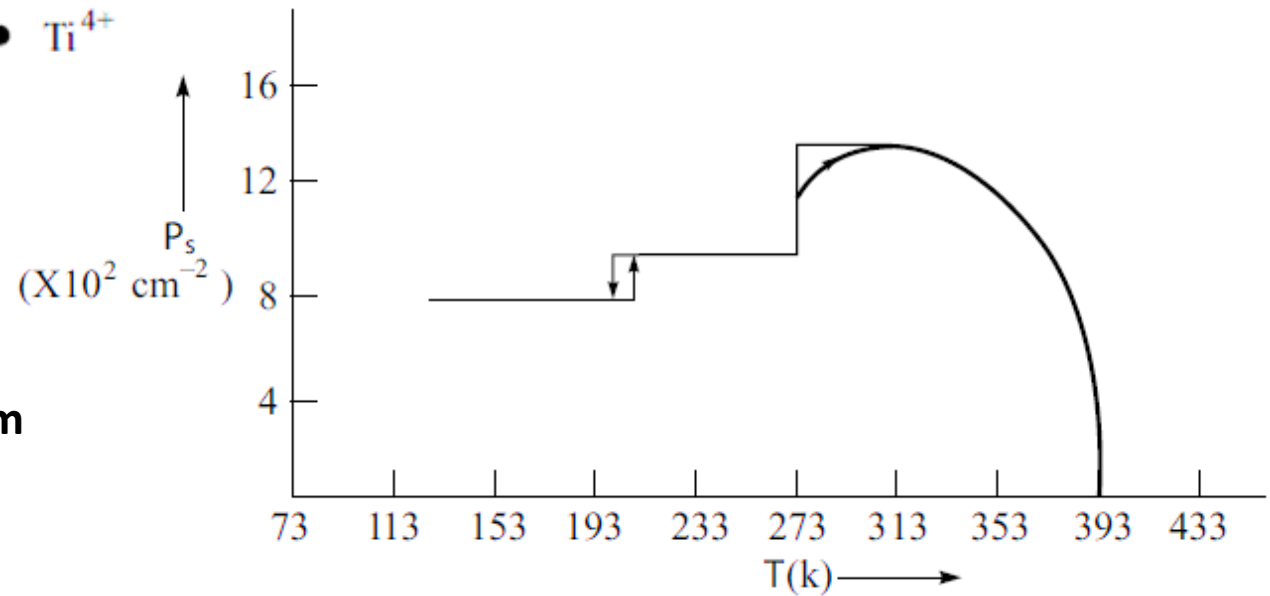
Polarisation versus temperature in potassium dihydrogen phosphate

(3) Barium Titanate

This crystal exhibits three different ferroelectric phases. The transition temperatures of barium titanate are 278 K, 193 K and 393 K. The structure of barium titanate is cubic above 393 K. It has orthorhombic structure when the temperature lies between 278 K and 193 K. Below 193 K, it has rhombohedron structure.



Crystal structure of barium titanate (above 393 K)



Polarisation versus temperature in barium titanate

TYPES OF DIELECTRIC MATERIALS

The dielectric materials are classified into three types as given below.

- (1) Solid dielectric
- (2) Liquid dielectric, and
- (3) Gaseous dielectric

Solid Dielectric

There are three types of solid dielectric materials.

- (1) Elemental Solid Dielectrics** Solid materials consisting of single type of atoms, such as diamond, sulphur, germanium, etc., are said to be elemental solid dielectric materials. These materials exhibit electronic polarisability only.
- (2) Ionic Nonpolar Solid Dielectrics** In ionic crystals such as alkali halides, the total polarisation is ionic and electronic in nature. These solids contain more than one type of atoms, but no permanent dipoles. These types of dielectric materials are said to be ionic nonpolar dielectric materials.
- (3) Polar Solid Dielectrics** In solids, whose molecules possess permanent dipole moments, the total polarisation has all the three components, i.e., it is the sum of electronic, ionic and orientation polarisations. These types of materials are known as polar solid dielectric, e.g., solid $\text{C}_6\text{H}_5\text{NO}_2$.

Liquid Dielectric Materials

Liquid dielectric materials are also classified into three types as given below.

(1) Mineral Insulating Oils Transformer oil, capacitor oil and cable oil are said to be mineral insulating oils. They are directly obtained from crude petroleum by distillation. They are used as coolant in transformers and capacitors.

(2) Synthetic Insulating Oils Synthetic insulating oils are also used for the purpose of cooling in high-tension transformers. Compared to mineral insulating oils, synthetic oils are low-grade. Also, they are very cheap, e.g., karels, sovol, etc.

(3) Miscellaneous Insulating Oils Silicone liquid and vegetable oil are said to be miscellaneous insulating oils. The silicone liquid is costly compared to synthetic insulating oils. It is used in high tension transformers.

Gaseous Dielectrics

Air, nitrogen, hydrogen, sulphur hexafluoride are some of the gaseous dielectric materials used.

- (1) Air** Air is one of the most important and naturally available gas used for electrical insulation. Its resistivity is infinity under normal conditions, when there is no ionisation. The relative permittivity of air is 1. It is used as a dielectric in long-distance electrical transmissions, and in air-capacitors. Compressed air is used as an arc-extinguishing medium which provides dielectric insulation in air-blast circuit breakers.
- (2) Nitrogen** Nitrogen is chemically inert and is used as a dielectric medium to prevent oxidation. It is used in gas-filled high-voltage cables as an inert medium to replace air in the space above the oil. It is also used in transformers and in low-loss capacitors for high-voltage testing, and so on.
- (3) Sulphur Hexafluoride** It is an electronegative gas and is used as a dielectric in X-ray equipment, waveguides, coaxial cables, transformers and as an arc-quenching medium in circuit breakers. Its dielectric strength is nearly 2.3 times higher than that of air or nitrogen. It sublimates at about 209 K and may be used up to a temperature of 423 K. It is nontoxic, non-inflammable and chemically inert.
- (4) Hydrogen** The dielectric strength of hydrogen is about 65% higher than that of air. It is used as a cooling medium in large turbo-generators and synchronous motors. The injurious effects of hydrogen gas are considered to be negligibly small, since during the discharge it does not produce ozone or oxides of nitrogen. Further, the high voltage discharge of hydrogen is not so severe.

APPLICATIONS

Some of the applications of dielectric materials are given below.

1. Quartz crystal is used for the preparation of ultrasonic transducers, crystal oscillators, delay lines, filters, etc.
2. Barium titanate is used for the preparation of accelerometers.
3. Lead zirconate titanate ($\text{PbZr}_x\text{Ti}_{1-x}\text{O}_3$) is used for the preparation of earphones, microphones, spark generators (gas lighter, car ignition, etc.), displacement transducer, accelerometers, etc.
4. The insulating dielectric liquids are used in transformers, switchgears and generators.
5. Dielectric materials are used as insulating material in power cables, signal cables, electric motors, electric iron, etc.
6. Dielectric materials are used in radiation detectors, thermoionic valves, strain gauges, capacitors, resistors and many other electric devices
7. The electro-optic devices are prepared using dielectric material.