UNIT - V : ELECTROMAGNETIC WAVES

Chapter - 1 : Electromagnetic Waves

Revision Notes

Electromagnetic Waves

Electromagnetic waves and their characteristics

- Waves that can travel through vacuum of outer space and do not need the presence of material medium for transporting energy from one location to another.
- EM waves are produced by accelerated charged particles.
- The electric and magnetic fields produced by accelerated charge change with time, which radiate electromagnetic waves.

Example:

- Electron jumping from its outer to inner orbits radiates EM waves.
- Electrical oscillations in LC circuit produce EM waves.
- Electric sparking generates EM waves.

Characteristics of EM waves:

- EM waves are propagated as electric and magnetic fields oscillating in mutually perpendicular directions.
- EM waves travel in vacuum along a straight line with the velocity 2.997924591×10^8 m/s which is often assumed as 3×10^8 m/s.
- EM waves are not affected by electric and magnetic fields.
- Relation between electric and magnetic field components is:

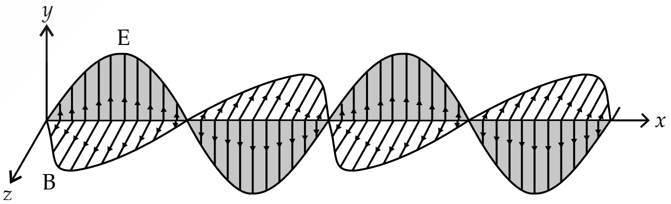
$$B_0 = E_0 / c$$

where, $c \cong 3 \times 10^8$ m/s. and $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$

The λ and f are related as $c = f\lambda$. where λ is the wavelength and f is the frequency.

Transverse nature of electromagnetic waves

- In electromagnetic wave, electric and magnetic field vectors are perpendicular to each other in the direction of propagation of wave which shows its transverse nature.



- A plane EM wave travelling in the x-direction is of the form:

$$E(x, t) = E_{max} \cos (kx - \omega t + \phi)$$
$$B(x, t) = B_{max} \cos (kx - \omega t + \phi)$$

where, E = electric field vector, B = magnetic field vector

- In this, wave propagates along z-axis, the electric and magnetic field propagation will be:

$$E = E_0 \sin (kz - \omega t)$$
$$B = B_0 \sin (kz - \omega t)$$

- **Gauss Law:** For electricity, electric flux through a closed surface equals to the charge enclosed divided by permittivity.

$$\oint \vec{E} . d\vec{A} = \frac{Q}{\varepsilon_0}$$

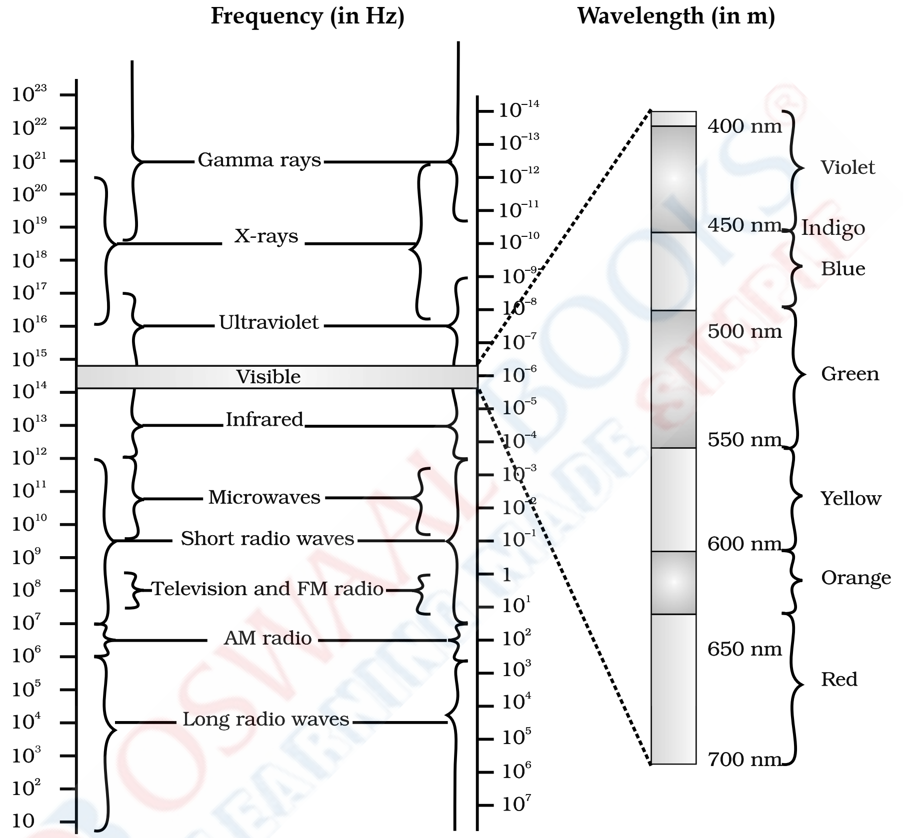
For magnetism, total magnetic flux through the closed surface is zero

$$\oint \vec{B}.\vec{dA} = 0$$

Electromagnetic Spectrum

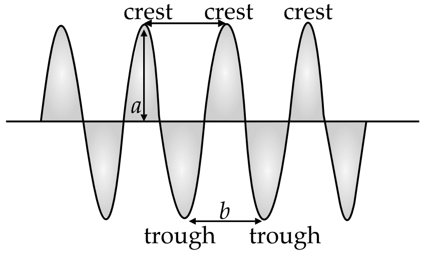
Electromagnetic spectrum

- Classification of EM-waves is based on their frequency or wavelength range.
- EM radiations are classified as per the frequency and wavelength of wave such as radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma rays.



General properties of electromagnetic waves (radio waves, microwaves, infrared, visible, ultraviolet, X-rays, gamma rays)

- Electromagnetic waves require no medium to travel or propagate.
- Varying electric and magnetic fields are the sources of electromagnetic waves.
- Electromagnetic waves are transverse waves which are characterized by their amplitude, wavelength, or distance between highest/lowest points.
- In electromagnetic waves, a crest is the highest point of the wave and through the lowest point of wave in a cycle.



a = Amplitude

b = wavelength

Electromagnetic spectrum is divided into following regions:

The electromagnetic spectrum is the distribution of electromagnetic radiation in terms of energy, frequency or wavelength. The electromagnetic radiation can be described as a stream of photons travelling in a wave like pattern, at the speed of light.

Type of radiation	Frequency range (H_z)	Wavelength range
Gamma rays	$> 3 \times 10^{20}$	<1 fm
X-rays	$3 \times 10^{17} – 3 \times 10^{20}$	1 fm – 1 nm
Ultraviolet	$7.5 \times 10^{14} – 3 \times 10^{17}$	1 nm – 400 nm
Visible	$4 \times 10^{14} – 7.5 \times 10^{14}$	0.4 μm – 0.75 μm
Near-infrared	$10^{14} – 7.5 \times 10^{14}$	0.75 μm – 3.0 μm
Midwave infrared	$5 \times 10^{13} – 10^{14}$	3.0 μm – 6 μm
Long wave infrared	$2 \times 10^{3} – 5 \times 10^{13}$	6.0 μm – 15 μm
Extreme infrared	$3 \times 10^{13} – 2 \times 10^{13}$	15 μm – 15 μm
Micro and radio waves	$< 3 \times 10^{11}$	> 1 mm

Applications of Electromagnetic waves:

Band designation	Applications
Audible	Acoustics
Extremely Low Frequency (ELF) Radio	Electronics, Submarine Communications
Infra Low Frequency (ILF)	Not applicable
Very Low Frequency (VLF) Radio	Navigation, Weather
Low Frequency (LF) Radio	Navigation, Maritime Communications, Information and Weather Systems, Time Systems
Medium Frequency (MF) Radio	Navigation, AM Radio, Mobile Radio
High Frequency (HF) Radio	Citizens Band Radio, Mobile Radio, Maritime Radio
Very High Frequency (VHF) Radio	Amateur (Ham) Radio, VHF TV, FM Radio, Mobile Satellite, Mobile Radio, Fixed Radio
Ultra High Frequency (UHF) Radio	Microwave, Satellite, UHF TV, Paging, Cordless Telephone, Cellular and PCS Telephony, Wireless LAN (Wi-Fi)
Super High Frequency (SHF) Radio	Microwave, Satellite, Wireless LAN (Wi-Fi)
Extremely High Frequency (EHF) Radio	Microwave, Satellite, Radio location
Infrared Light (IR)	Wireless LAN Bridges, Wireless LANs, Fiber Optics Remote control
Visible Light	Photographic plate, photocells.
Ultraviolet (UV)	Photocells, kill bacteria and germs.
X-Rays	In medical, Geiger tubes, ionization chamber.
Gamma and Cosmic Rays	In medical (cancer cell killing)

Types of Electromagnetic waves, wavelength range, Production and Detection:

Type of radiation	Wavelength range	Production	Detection
Radio	$> 1.0 \times 10^{-1}$ m	Rapid acceleration and decelerations of electrons in aerials	Receiver's aerials
Microwave	0.1 m $– 1.0 \times 10^{-3}$ m	Klystron valve or magnetron valve	Point contact diodes
Infra-red	1.0×10^{-3} m $– 700 \times 10^{-9}$ m	Vibration of atoms and molecules	Thermopiles Bolometer, Infrared photographic film

Light	700×10^{-9} m – 400×10^{-9} m	Electrons in atoms emit light when they move from one energy level to a lower energy level	The eyes, Photocells Photographic film
Ultraviolet	400×10^{-9} m – 1.0×10^{-9} m	Inner shell electrons in atoms moving from one energy level to a lower level	Photocells Photographic film
X-rays	1.0×10^{-9} m – 1.0×10^{-12} m	*X*-ray tubes or inner shell electrons	Photographic film, Geiger tubes, Ionization chamber
Gamma rays	$<1.0 \times 10^{-12}$ m	Radioactive decay of the nucleus	Photographic film, Geiger tubes, Ionization chamber

Mnemonics

Concept: Electromagnetic spectrum : Arrangement of em waves with increasing frequency (decreasing wavelength) :

Mnemonics: Russian magicians introduced and very unusual X-ray eye Game

Mnemonic: **R**ussian **m**agicians **i**ntroduced and **v**ery **u**nusual **X**-ray eye **g**ame.

Radio Wave | Micro Wave | Infra red | Visible Light | Ultra violet | X-Rays | Gamma Rays

Know the Terms

- **Electromagnetic waves:** The waves that are generated from changing of electric and magnetic fields.
- **Gamma rays:** Rays with smallest wavelengths and highest frequencies having high energy capable of traveling long distances through air and these are most penetrating.
- **X-rays:** These are the rays with small wavelengths having higher energy as compared to ultraviolet radiation.
- **Ultraviolet (UV) radiation:** It is a part of electromagnetic spectrum that lies between X-rays and visible light.
- **Visible light:** It is a visible spectrum which is part of electromagnetic spectrum which can be seen by human eyes.
- **Infrared (IR) radiation:** These are thermal radiations which is the part of electromagnetic spectrum that lie between visible light and microwaves.
- **Radio waves:** Waves with long wavelengths used in television, cell phone and radio communications.

Know the Formulae

- For the EM waves, the energy density is given by

$$U_E = \frac{1}{2}\varepsilon_0 E^2 \text{ (Due to electric field)}$$

$$U_B = \frac{1}{2}\frac{B^2}{\mu_0} \text{ (Due to magnetic field)}$$

- The energy transported by EM waves per unit area per second is called Poynting vector ($\vec{S}$).

It is given by $$\vec{S} = \vec{E} \times \frac{\vec{B}}{\mu_0}.$$

Since, $\vec{E} \perp \vec{B}$, hence $$S = \frac{EB}{\mu_0}.$$

- In EM waves, the total energy density of EM waves is

$$U = \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2}\frac{B^2}{\mu_0}$$

$$U = \varepsilon_0 E^2 = \frac{B^2}{\mu_0} \qquad \left[\text{As, } E = \frac{B}{\sqrt{\mu_0 \varepsilon_0}}\right]$$

- The variation in magnetic field causes electric field and vice versa.
- In the EM waves: $\vec{E} \perp \vec{B}$, both $\vec{E}$ and $\vec{B}$ are in the same phase.
- In the EM waves: $E = E_0 \sin(\omega t - kx)$, $B = B_0 \sin(\omega t - kx)$.
- The EM waves travel in the direction of $\vec{E} \times \vec{B}$ *i.e.*, EM waves propagate perpendicular to both $\vec{E}$ and $\vec{B}$.

UNIT – VI : OPTICS

Chapter - 2 : Ray Optics and Optical Instruments

Revision Notes

Refraction through Glass Slab, Prism, Lenses and Total Internal Reflection

- **Refraction of light:** Refraction is deviation of light when it obliquely travels from one medium to another medium. Snell experimentally found the following laws of refraction.

Laws of Refraction of Light

- The incident ray, the refracted ray and the normal to the interface of two transparent media, at the point of incidence, all lie in the same plane.
- The ratio of sine of angle of incidence to the sine of angle of refraction is a constant, for the light of a given colour and for the given pair of media. This constant value is called the refractive index of the second medium with respect to the first medium.

$$\frac{\sin i}{\sin r} = \text{constant } (n_{21})$$

This is known as Snell's law.

- From Snell's law

$$\sin i = \sin r \times n_{21}.$$

- It shows that if $\angle i = 0$, then $\angle r$ is also zero. This proves that the light rays do not deviate when they travel normally from one medium to another.
- If the first medium is air, then the refractive index is known as the absolute refractive index of the second medium. The absolute refractive index of a medium is expressed by

$$n_2 = \frac{\text{Velocity of light in free space}}{\text{Velocity of light in mediun}} = \frac{c}{v} \quad \text{since, } c > v \Rightarrow n_2 > 1$$

- If a ray of enters from one medium to another medium in such a way that bending of light happens away from normal, then second medium is optically rarer with respect to the first medium. If bending of light is towards normal, then second medium is optically denser with respect to the first medium.

Principle of Reversibility

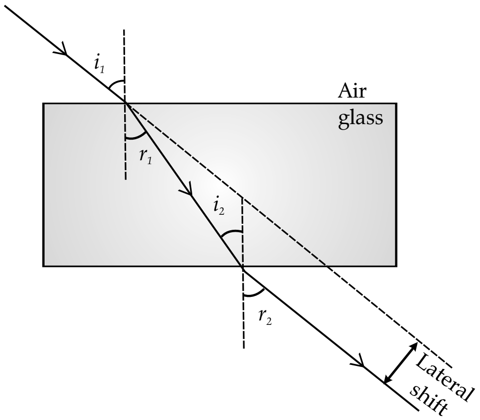
- According to the principle of reversibility, the path of light is reversible even if it is going through several media. It means light follows exactly the same path when its direction is reversed.
- Applying this rule, we may find that if light travels through several media say medium 1 to medium 2 and then to medium 3, then to medium 1.

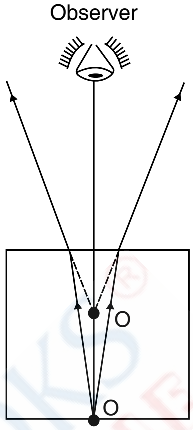
$$n_{21} \times n_{32} \times n_{13} = 1$$

- Though refraction rules are universal but direction of emergent ray depends upon the shape of the medium or in other words, on the shape and angle between incident and emergent interfaces (refracting surfaces).

Refraction through Glass Slab

- In a glass slab, refracting surfaces are plane and parallel to each other.
- Emergent ray is parallel to the incident ray but it suffers lateral displacement.





- The apparent depth of the object is always less than actual depth when looking through glass or water.

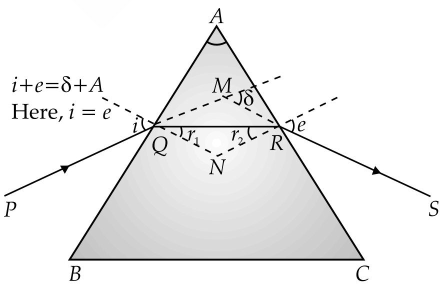
$$\text{Rise of image} = \text{Real depth}\left(1-\frac{1}{n_{21}}\right)$$

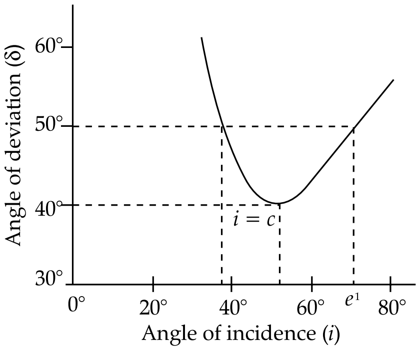
Here, $$n_{21} = \frac{\text{Real depth}}{\text{Apparent depth}}$$

- The following phenomena occur due to the refraction of light:-
  - Bottom surface of water pool seems to be raised.
  - The letter appears to be raised when we observe it through a glass slab.
  - Object looks bigger than its actual size and raised when we dip it into liquid.
  - Twinkling of stars.
  - Delayed sunset and early sunrise.

Refraction through Prism

- In prism, refracting surfaces are planes but inclined to each other.
- Refracted ray always bends towards the base.
- Angle of deviation, $\delta = (i - r_1) + (e - r_2)$
- **Angle of minimum deviation:** When incident angle is gradually increased, the angle of deviation initially decreases and after obtaining a minimum value, it starts increasing again. This angle obtained at the lowermost point is called angle of minimum deviation δ_m.





(i) $i + e = \delta + A$. Here, $i = e$ ...(i)

(ii) $r_1 + r_2 = A$ ...(ii)

- At minimum deviation stage, it is observed that angle of $i_1 = i_2\ (= i)$ and $r_1 = r_2\ (= r)$, then

$$r = \frac{A}{2}$$ ....using (ii)

$$i = \frac{\delta_m + A}{2} \qquad \text{.... using (i)}$$

$$n_{21} = \frac{n_2}{n_1} = \frac{\sin[(A+\delta_m)/2]}{\sin[A/2]}$$

As angle of prism and deviation can be found experimentally, this equation is used to determine the refractive index of the material of prism.

➢ For thin prism, $\delta_m = (n_{21} - 1)A$. This equation implies that thin prisms do not cause much deviation of light.

Total Internal Reflection:

➢ When light travels from an optically denser medium to a rarer medium at the interface, it is reflected into the same medium at a certain angle. This reflection is called the internal reflection.

- Critical angle is that value of incident angle for which angle of refraction is 90°. The refracted ray just brushes the surface. The critical angle for water-air, glass-air and diamond-air are 45°, 42° and 24° respectively.

$$n_{12} = \frac{1}{\sin C} \qquad \text{(where, } C \text{ is critical angle)}$$

- If the angle of incidence is more than the critical angle, refraction is not possible and incident ray reflects in denser medium. This process is known as total internal reflection.

➢ Hence, the conditions for total internal reflection are:

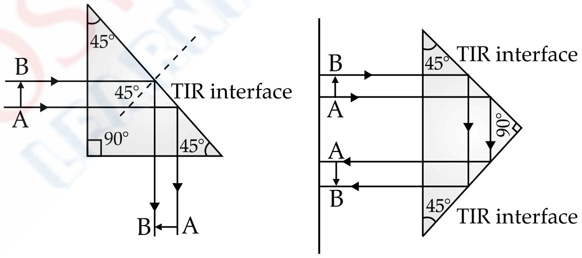
- The light should travel from denser medium to the rarer medium.
- Angle of incidence should be larger than the critical angle.

➢ Natural phenomenon based upon total internal reflection are as follows:

- **Mirage:** On hot summer days, light from tall objects successively bends away from the normal due to gradual decrease in air density towards the Earth. This results total internal reflection and formation of inverted images of distant tall objects. It causes an optical illusion to the observer. This phenomenon is called mirage.
- **Brilliance of diamond:** Refractive index of diamond is very high ($n \approx 2.42$). Their brilliance is mainly due to the total internal reflection of light inside it.

Applications of total internal reflection:

- For optical communication in optical fibres.
- **Prism:** Prisms designed to bend the light by 90° or by 180° make use of total internal reflection. Such types of are also used to invert images without changing their size.



TIR → Total internal reflection

Refraction at spherical surface

➢ If the rays are incident from a medium of refractive index n_1, to another medium of refractive index n_2, the formula comes out to be

$$\frac{n_2}{v} - \frac{n_1}{u} = \frac{n_2 - n_1}{R}$$

Where, R = Radius of curvature of spherical surface and object is placed at rarer medium.

u = Object distance from spherical surface

v = Image distance from spherical surface

➢ **Lens:** A lens is a piece of transparent glass which is bounded by two surfaces out of which at least one surface is spherical.

There are two types of lenses:

- **Convex lens:** A convex lens is one which is thinner at sides and thick at centre.
- **Concave lens:** A concave lens is one which is thicker at sides and thin at centre.

➤ **Relation between object distance, image distance with focal length of lens:**

The relation can be expressed as

$$\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$$

➤ **Magnification by lens:**

$$m = \frac{\text{Height of the image } (h')}{\text{Height of the object } (h)} = \frac{v}{u}$$

➤ **Power of a lens:**

The power of a lens is defined as the reciprocal of its focal length. It is represented by the letter P. The power P of a lens of focal length f is given by

$$P = \frac{1}{f}$$

The SI unit of power is dioptre when focal length is in metre. It is denoted by D. Hence, one dioptre is a power of lens whose focal length is 1 metre.

- When two or more lenses are combined, then the power of combined lens is sum of individual power of lenses.

$$P = P_1 + P_2 + ...$$

➤ **Lens maker's Formula:**

$$\frac{1}{f} = (n_{21} - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \qquad \left(n_{21} = \frac{n_2}{n_1}\right)$$

Power of a lens, $$P = \frac{1}{f(m)}.$$

So, the above formula is used to make lenses of required power. Hence, this formula is known as lens maker's formula.

- **Image formation in convex lens for different positions of object**

Position of the object	Position of the image	Relative size of the image	Nature of the image
At infinity	at focus F_2	Highly diminished, point sized	Real and inverted
Beyond $2F_1$	Between F_2 and $2F_2$	Diminished	Real and inverted
At $2F_1$	at $2F_2$	Same sized	Real and inverted
Between $2F_1$ and $2F_2$	Beyond $2F_2$	Enlarged	Real and inverted
At Focus F_1	At infinity	Infinitely enlarged	Real and inverted
Between focus F_1 and optical centre	On the same side of the lens as object	Enlarged	Virtual and erect

- **Image formation in concave lens for different positions of object**

Position of the object	Position of the image	Relative size of the image	Nature of the image
At infinity	At focus F_1	Highly diminished point sized	Virtual and erect
Between infinity and the optical centre O of the lens	Between focus F_1 and optical centre O	Diminished	Virtual and erect

Dispersion of white light through prism

➤ Splitting of white light into its constituent colours is known as dispersion of light. This is due to the various colours having different deviations.

- The seven constituent colours of white light are violet, indigo, blue, green, yellow, orange and red. The acronym of this colour band is **VIBGYOR**.

- Different colours of light have different wavelengths and different frequency in medium. This is the cause of dispersion.
- In vacuum, the speed of light is independent of wavelength. Thus, vacuum (or air approximately) is a non-dispersive medium in which all colours travel with the same speed. This also follows from the fact that sunlight reaches us in the form of white light (combination of all colours) and not as its components in day (noon) time. On the other hand, glass is a dispersive medium.
- **Angular dispersion through thin prism** = $\delta_V - \delta_R = (n_V - n_R)A$. The relation shows that it depends upon the angle of prism A.
- **Power of dispersion,** $\omega = \frac{\delta_V - \delta_R}{\delta_Y} = \frac{n_V - n_R}{n_Y}$ is independent of A. It is property of dispersive material.
- **Recombination of white light:** If we place an inverted identical prism after the first prism, all components colours of light recombine again and became a beam of white light.

➢ **Phenomenon related to dispersion of light:**
- **Formation of Rainbow:** Rainbow is the natural phenomenon of dispersion of light. After a rain shower when sky becomes clear and sunny, we may observe a rainbow in a direction opposite to the direction of Sun when Sun is at our backside. It is caused due to the combined effect of refraction, total internal reflection and dispersion of sunlight by the raindrops suspended in the air.
- In **primary rainbow**, there is only single total internal reflection before different colours reach observer's eye. In this rainbow, observer watches red colour at top and violet at bottom.
- In **secondary rainbow**, there are two total internal reflections before different colours reach observer's eye. In this rainbow, observer watches violet colour at top and red at bottom.
- Secondary rainbow is higher (50° – 53°) on sky than the primary rainbow (40° – 42°).
- Intensity of secondary rainbow is lower than the primary rainbow.

➢ **Scattering of light:** When light deviates randomly from its path due to its interaction with small particles, it is known as scattering of light.

➢ **Tyndall Effect:** The Tyndall effect is the scattering of light as a beam of light passes through a colloid. The individual suspension particles scatter and reflect light, making the beam visible.

➢ The colour of the scattered light depends on the size of the scattering particles.

➢ For $a << \lambda$, where, a is the size of scattering particle, one has Rayleigh scattering which is proportional to $\frac{1}{\lambda^4}$. For $a >> \lambda$, *i.e.*, large scattering objects (for example, raindrops, large dust particles), all wavelengths are scattered nearly equally.

➢ **Phenomenon related to scattering of light:**
- Colour of the clear sky is blue.
- The red colour of the Sun at sunrise and sunset.
- White appearance of clouds.

Optical Instruments

➢ Based upon phenomenon of reflecting and refracting properties of mirrors, lenses and prisms, a number of optical devices and instruments have been designed.

Microscope:

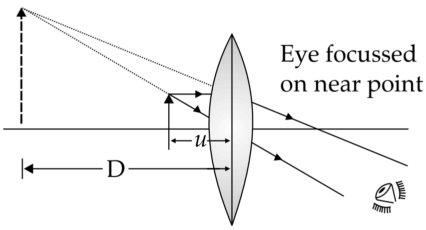
➢ **Microscope** is an optical instrument which helps us to see and study micro objects or organisms. It forms magnified image of the object.

➢ **Telescope** is an optical instrument which helps us to see and study far off objects magnified and resolved (with clarity).

➢ We generally set these instruments at two different image vision positions and they are as follows:
- **Image at least distance of distinct vision:** This is the least distance from eye where we are able to see objects distinctly. For normal human eye, the distance is 25 cm from our eye.
- **Image at relaxed vision:** This is the distance from eye where we are able to see objects distinctly in relaxed vision no strain to eye . For normal human eye, the distance is infinity from our eye.
- Magnification at distinct vision is always greater than magnification at relaxed vision.

Simple Microscope: Convex lens behaves as simple microscope.

The magnifying power of the simple microscope

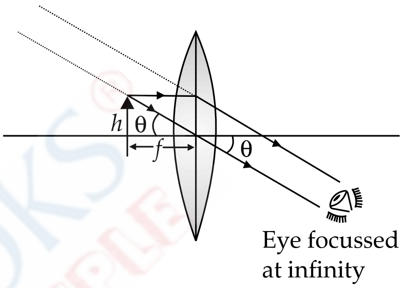


(i) For least distance of distinct vision, $m = 1 + \frac{D}{f}$

where, D is the least distance of distinct vision of the eye and f is focal length of the lens.

(ii) For relaxed eye,

$$m = \frac{D}{f}$$



From above formulae, it is clear that for larger magnifying power, the focal length of the convex lens should be small.

The angular magnification by optical instruments is the linear magnification by lenses only. It means magnification of an instrument means how many times it enlarges the image of an object. So it can be written as

$$m = \frac{h'}{h}$$

where, h is size of object (in one dimension) and h' is the size of image.

Compound Microscope: For much large magnification, compound microscope is used. It is a combination of two convex lenses when the magnification of each lens is compounded.

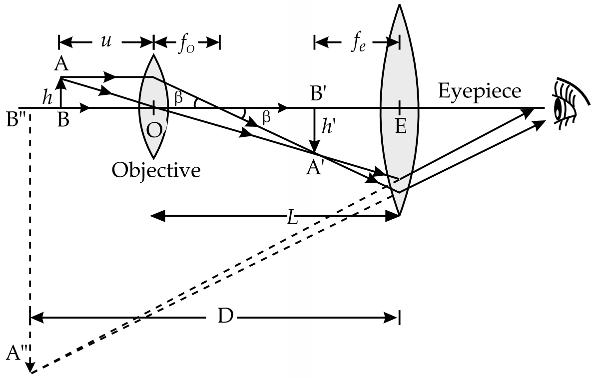
- The two lenses are placed co-axially and the distance between them is adjustable.
- The lens towards the object is called objective and that towards the eye is called eyepiece.
- The final image formed by the compound microscope is magnified and inverted.
- Total magnification by compound lens,

$$m = m_o \times m_e$$

where, m_o is magnification by objective lens and m_e is magnification by eyepiece.

- For least distance of distinct vision, magnification by objective lens is

$$m_o = \frac{v_o}{u_o} \approx \frac{L}{f_o}$$



where, L is the distance between the second focal point of the objective and the first focal point of the eyepiece (focal length f_e). It is called the tube length of the compound microscope.

Eyepiece lens will act as simple microscope.

Magnification by eyepiece lens is

$$m_e = 1 + \frac{D}{f_e}$$

Hence, Magnification by compound lens = $\frac{L}{f_o}\left(1 + \frac{D}{f_e}\right)$

➢ **For Relaxed Eye (normal adjustment)**

For relaxed eye, the magnification by objective lens remain same, the magnification by eyepiece will be $+\frac{D}{f_e}$

Hence, the total magnification of compound microscope in relaxed eye condition is

$$m = \frac{L}{f_o} \times \frac{D}{f_e}$$

- **Properties of Compound Microscope**
  - For large magnification of a compound microscope, both f_0 and f_e should be small.
  - If the length of the microscope tube increases, then its magnifying power increases.
  - Generally f_o is much smaller. So, the objective is placed very near to principal focus.
  - The aperture of the eyepiece is generally small so that whole of the light may enter the eye.
  - The aperture of the objective is also small, so the field of view may be restricted.

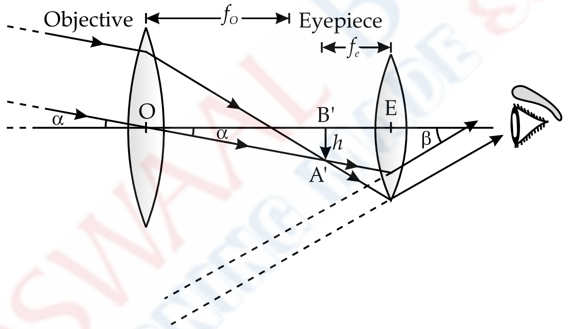
Telescope

- Telescope is an instrument to magnify and resolve far off objects.
- Far off objects make much smaller angle at our eye. Telescope makes that angle larger without much intensity loss.
- To maximise the intensity, aperture size of objective lens is quite large. It focuses a bright point size image at its focal plane.
- Now with eyepiece, we will observe the point size image to final inverted magnified image. This type of telescope is known as astronomical telescope.
- For least distance of distinct vision,

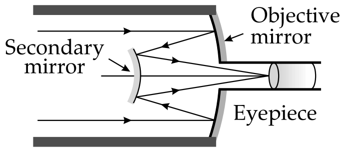
$$m = -\frac{f_o}{f_e}\left(1+\frac{f_e}{D}\right)$$

- **For Relaxed Eye (normal adjustment)**

$$m = \frac{\alpha}{\beta} = -\frac{f_o}{f_e}$$



- **Properties of astronomical telescope**
  - For larger magnifying power, f_o should be large and f_e should be small.
  - The length of the tube of an astronomical telescope is $L = f_o + f_e$ for relaxed vision adjustment.
  - When the length of the tube of the telescope increases, f_o increases and magnifying power also increases.
- **Limitations of refractive telescope**
  - Large objective lens makes the telescope very heavy. So, it is difficult to handle it by hand.
  - It has spherical and chromatic aberrations.
- **Modern Telescope (Reflective Telescope)**
  - Reflecting telescope consists of a concave mirror of large radius of curvature in place of objective lens
  - A secondary convex mirror is used to focus the incident light, which passes through a hole in the objective primary mirror .



  - The magnifying power of the reflecting telescope is $m = \frac{f_o}{f_e}$
- **Advantages of reflective telescope**
  - Very sharp point image by objective mirror removes spherical aberrations.
  - As it is very light, large aperture of parabolic mirror can be used for desired magnification.
  - This is based on the principle of reflection and there will be no chromatic aberrations.

Mnemonics

Lens formula:

Eat **f**ruit for **v**itamin and **u**ltimate strength.

↓ ↓ ↓

1/f = 1/v + 1/u

Know the Formulae

- Snell's law of refraction, $\frac{\sin i}{\sin r}$ = constant (n_{21})
- $n_{21} = \frac{c}{v}$
- $n_{21} \times n_{32} \times n_{13} = 1$
- Rise of image = Real depth $\left(1 - \frac{1}{n_{21}}\right)$
- Deviation through prism, $\delta = (i - r_1) + (e - r_2)$
- For thin prism, $\delta_m = (n_{21} - 1)A$
- Relation between refractive index, angle of prism and minimum deviation

$$n_{21} = \frac{\sin \frac{(\delta_m + A)}{2}}{\sin\left(\frac{A}{2}\right)}$$

- The conditions for total internal reflection are as follows:
  - The light must travel from the denser medium.
  - Angle of incident should be larger than critical angle.
- $n_{21} = \frac{1}{\sin C}$
- For lens $\frac{1}{f} = \frac{1}{v} - \frac{1}{u}$ and $m = \frac{h'}{h} = \frac{v}{u}$
- Power of lens, $P = \frac{1}{f}$
- When two or more lenses are combined, then the power of combined lens is sum of individual power of lenses.

$$P = P_1 + P_2 + ...$$

- Lens maker's Formula,

$$\frac{1}{f} = (n_{21} - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \qquad \left(n_{21} = \frac{n_2}{n_1}\right)$$

- Angular dispersion through thin prism = $\delta_v - \delta_r = (n_v - n_r)A$.
- Power of dispersion, $\omega = \frac{\delta_v - \delta_r}{\delta_y} = \frac{n_v - n_r}{n_y}$
- Magnification by simple microscope

$$m = 1 + \frac{D}{f} \text{ (for distinct vision)}$$

$$m = \frac{D}{f} \text{ (For relaxed eye)}$$

- Magnification by compound microscope

$$\frac{L}{f_o}\left(1+\frac{D}{f_e}\right) \text{ or } \frac{v_o}{u_o}\left(1+\frac{D}{f_e}\right) \text{ (for distinct vision)}$$

$$\frac{L}{f_o}\times\frac{D}{f_e} \text{ or } \frac{v_o}{u_o}\times\frac{D}{f_e} \text{ (for relaxed eye)}$$

- Magnification by telescope

$$m = -\frac{f_o}{f_e}\left(1+\frac{f_e}{D}\right) \text{ (for distinct vision)}$$

$$m = -\frac{f_o}{f_e} \text{ (for relaxed eye)}$$

Chapter - 3 : Wave Optics

Revision Notes

Wave Theory and Huygens' Principle

- Newton supported 'Descartes' corpuscular theory' of light and developed it further.
- According to the corpuscular theory, "sources of light emit large number of tiny massless particles known as corpuscles in a medium surrounding the source. They are perfectly elastic, rigid and have high speed.

  This theory could explain reflection and refraction of light but could not explain many other optical phenomenon like interference and diffraction of light. It was unable to explain the concept of partial reflection and refraction through a transparent surface.
- Huygens' proposed wave theory of light. According to the theory, light travels in the form of longitudinal waves with uniform speed in a homogenous medium. Different wavelengths of light represent different colours of light.
- As longitudinal and mechanical waves need medium to travel, he assumed a hypothetical medium known as 'ether'. He also proved that speed of light is slower in optically denser medium.
- Initially, Huygens' wave theory of light didn't get much success. Its main point of rejection was, that it was considered as longitudinal wave which need medium, but experimentally found that it could also travel in vacuum and there is no medium like ether.

  But later Maxwell's theory of electromagnetic waves and Young's famous double slit experiment firmly established this theory. Maxwell explained that light is an electromagnetic wave which does not need medium and its speed in vacuum is 3×10^8 m/s. Phenomenon of optical interference, diffraction and polarisation can be explained with wave nature of light.
- It had some points of failure. It could not explain photoelectric effect and Compton effect.
- With polarisation, it is established that light is not a longitudinal wave but a transverse wave.
- Huygens' principle brings concept of formation of new wave fronts and its propagation in forward direction.
- Wavefront is locus of all points in which light waves are in same phase. Propagation of wave energy is perpendicular to the wavefront.

Huygens' Principle:

- Every point of a wavefront becomes secondary source of light.
- These secondary sources give their own light waves. Within small time, they produce their own wave called secondary wavelets. These secondary waves have same speed and wavelengths as waves by primary sources.
- At any instant, a common tangential surface on all these wavelets give new wavefronts in forward direction.
- Shapes of wavefronts

Source	Wavefronts
Point source	Spherical wavefront
Line source	Cylindrical wavefront
Plane source	Plane wavefront
Point source very far away	Plane wavefront

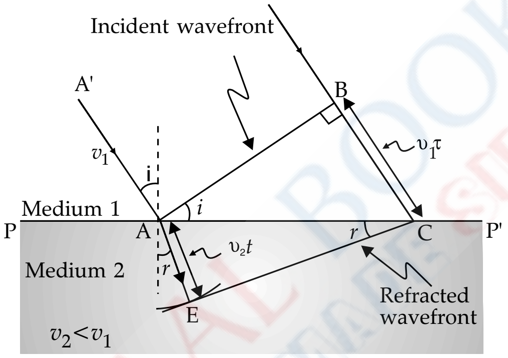
- Concave lens converts plane wavefront to convex wavefront and convex lens convert plane wavefront to concave wavefront.

Refraction of light by Huygens' Principle

Snell's law can be proved by Huygens' principle.

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \text{constant}$$

It has also been proved that the velocity of light in denser medium is less than velocity of light in rarer medium.



AB = Incident wavefront

EC = Refracted wavefront

$\angle i$ = Angle between incident wavefront AB and interface PP'

$\angle r$ = Angle between refracted wavefront EC and interface PP'

If medium 2 is optically denser than medium 1 and τ is the time in which disturbance from B reaches C. This is the same time t in which disturbance from A reaches E where distance $AE < BC$.

$$\Delta AEC \cong \Delta ABC$$

$$\sin i = \frac{BC}{AC}$$

$$\sin r = \frac{AE}{AC}$$

$$\frac{\sin i}{\sin r} = \frac{BC}{AE}$$

BC = Distance travelled by wave at B in time τ in medium 1

AE = Distance travelled by wave at A in time τ in medium 2

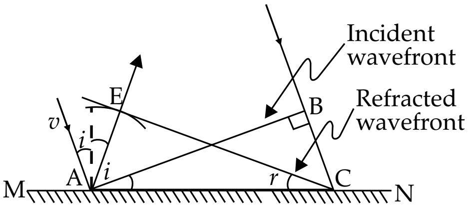
$$\frac{\sin i}{\sin r} = \frac{v_1\tau}{v_2\tau}$$

Hence,

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \text{constant}$$

This is law of refraction (Snell's law).

➢ **Reflection of light by Huygens' Principle**



AB = Incident wavefront

EC = Reflected wavefront

$\angle i$ = Angle between incident wavefront AB with the interface AC

$\angle r$= Angle between reflected wavefront EC with the interface AC

If disturbance at A is reflected from the interface AC, then disturbance at B and disturbance at A both travel in same medium. Thus, they will travel equal distance in time τ, where τ is the time in which disturbance from B reaches at C.

Now $AE = BC = v\tau$ (distance travelled in same medium in same time)

$$\Delta AEC \cong \Delta ABC$$

$$\angle i = \angle r$$

This is law of reflection.

Superposition of Light Waves (Interference and Diffraction)

➢ According to superposition principle, "At a particular point in the medium, the resultant displacement produced by a number of waves is the vector sum of the displacements produced by each wave".

It means that if individual displacement produced at a point by two coherent waves at any instant is given by

$$y_1 = a\cos \omega t \text{ and } y_2 = a\cos \omega t.$$

Then, resultant displacement at that point will be

$$y = y_1 + y_2 = 2a\cos \omega t.$$

Hence, the total intensity at that point will be:

$$I = 4I_0$$

where, $I_0 \propto a^2$; maximum intensity due to one wave.

Interference

➢ **Constructive Interference:** If two waves are propagating such that crest and trough of both waves would reach at a point in the same instant, then we say there is constructive interference of two waves at that point. The resultant amplitude of the wave is the sum of individual amplitudes. (We can generalize this to superposition of more than two waves) $a = a_1 + a_2$

➢ **Destructive Interference:** If two waves are propagating such that crest of one wave and trough of other wave reaching at a point in same instant, then we say that there is destructive interference of two waves at that point. The resultant amplitude of the wave is the difference of individual amplitudes. (We can generalize this to superposition of more than two waves) $a = a_1 - a_2$

➢ Two independent sources can never be coherent. We may create two coherent sources by deriving them from one source.

Condition for constructive Interference

➢ Waves would be coherent in nature. Coherent wave means that they should have equal frequency and constant phase difference (0, 2π, --- 2nπ) with each other at any time interval t.

Path difference between waves at this phase difference = 0 , λ, -----nλ, Here, n = 0, 1, 2, 3 ......

$$a_r = a_1 + a_2$$

if $$a_1 = a_2 = a$$

then $$a_r = 2a$$

$\because$ $$I \propto a^2$$

$$I_r = 4a^2$$

Condition for destructive interference

- Waves would be coherent in nature. The phase between the waves should be odd multiples of π, *i.e.*, $0, \pi, ... (2n-1)\pi$
- Path difference between waves at this phase difference = $\frac{\lambda}{2}, \frac{3\lambda}{2}, (2n-1)\frac{\lambda}{2}$, Here, $n = 1, 2, 3, 4....$

$$a_r = a_1 - a_2$$

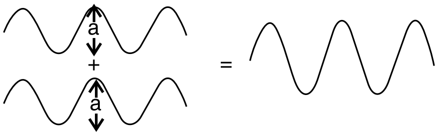
if $\quad a_1 = a_2$

then $\quad a_r = 0$

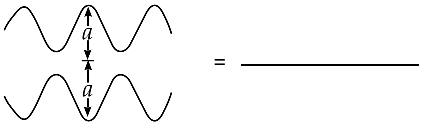
$\because \quad I \propto a^2$

$$I_r = 0$$

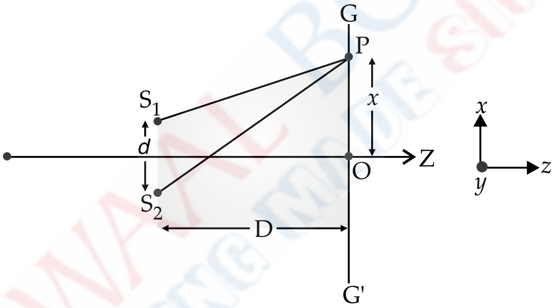
Constructive Interference



Destructive Interface



Young's double slit Experiment



- At "O" we get central maxima. Here, path difference $(S_2P - S_1P) = 0$
- At "P", which is at "x" height from "O" path difference $(S_2P - S_1P) = \frac{xd}{D}$
- **Condition for *P* to be a bright spot**

$$\frac{xd}{D} = 0, \lambda, 2\lambda........n\lambda$$

$$x_{n^{th}\text{ bright}} = \frac{nD}{d}\lambda$$

where, n is number of bright fringes after central fringe.

- **Condition for P to be a dark spot**

$$\frac{xd}{D} = 0, \frac{3\lambda}{2}...........(2n+1)\frac{\lambda}{2}$$

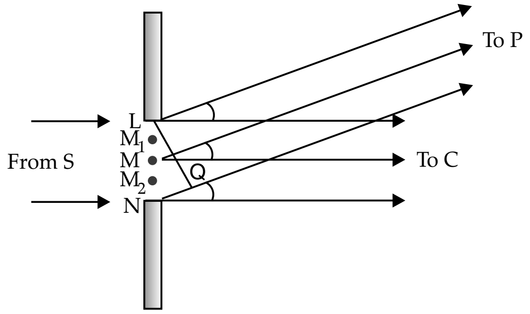
$$x_{n^{th}\text{ dark}} = \frac{(2n+1)D}{2d}\lambda$$

Here, n is the number of dark fringes after central fringe.

- Width of the bright fringe $(\omega_B) = x_{nB} - x_{(n-1)}B = \frac{D\lambda}{d}$
- Width of the dark fringe $(\omega_D) = x_{nD} - x_{(n-1)}D = \frac{D\lambda}{d}$
- Width of the central fringe $(\omega_C) = \frac{D\lambda}{d}$
- Hence $\omega_B = \omega_D = \omega_C$

Diffraction

It is defined as the bending of light around the corners of an obstacle or aperture into the region where we expect shadow of the obstacle.



If width of the opening = a

θ is the angle of elevation of point P from principal axis.

Path difference between ray from L and ray from N = LQ = $a\sin\theta$

$$a\sin\theta = \lambda$$

$\because$ for first maxima $\theta = \dfrac{\lambda}{a}$ $(\therefore \sin\theta \cong \theta)\ \sin\theta <<< 1$

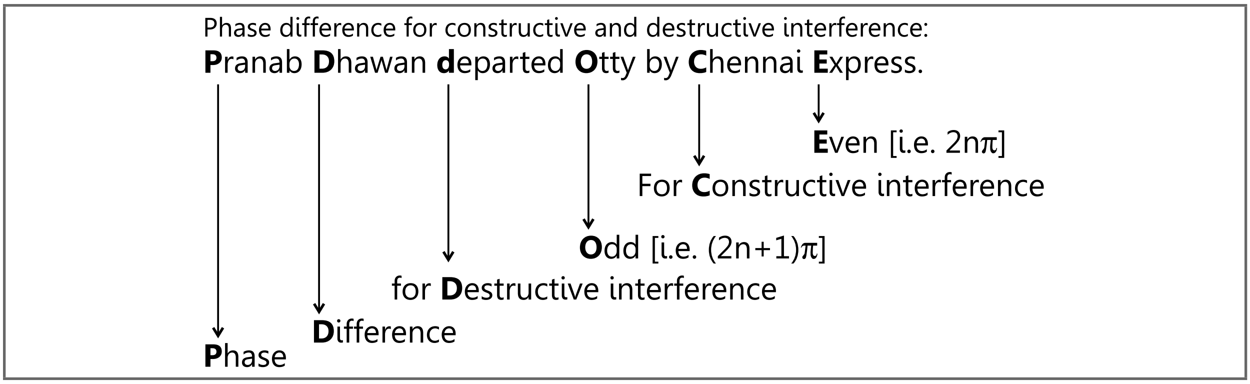
It is observed that when path difference = $\lambda, 2\lambda$ ...... $(2n-1)\lambda$, P is a dark point.

When $a\sin\theta = \dfrac{3\lambda}{2}$, ...$(2n+1)\dfrac{\lambda}{2}$, P is a bright point.

Elevation angle for first bright fringe, $\theta_{1D} = \dfrac{3\lambda}{2a}$

- Height of first dark fringe, $x_{1D} = \dfrac{3\lambda D}{2a}$
- Elevation angle for first dark fringe, $\theta_{1D} = \dfrac{\lambda}{a}$
- Width of the bright fringe = $\dfrac{D\lambda}{a}$
- Width of the dark fringe = $\dfrac{D\lambda}{a}$
- Width of the central fringe = $\dfrac{2D\lambda}{a}$
- There is no gain or loss of energy in interference or diffraction, which is consistent with the principle of conservation of energy. Energy only redistributes in these phenomena.

Mnemonics



Know the Formulae

- **Condition for constructive interference for coherent waves**
  - Constant phase difference(0, 2π, ... 2nπ)
  - Path difference = 0, λ ...... nλ
- **Condition for destructive interference for coherent waves**
  - Phase difference(0, π, ... (2n – 1)π) with each other at any time interval t.
  - Path difference = $\frac{\lambda}{2}$, ... $(2n-1)\frac{\lambda}{2}$
- **In Interference Pattern**
  - Width of the bright fringe = $\frac{D\lambda}{d}$
  - Width of the dark fringe = $\frac{D\lambda}{d}$
  - Width of the central fringe = $\frac{D\lambda}{d}$
  - All fringes have equal fringe width
- **In Diffraction Pattern**
  - Angle of elevation of any point P on screen = $\frac{\lambda}{a}$
  - Condition that P would be dark point when path difference = λ, 2λ .... (2n – 1)λ
  - Condition that P would be bright point when path difference = $\frac{3\lambda}{2}$, ...$(2n+1)\frac{\lambda}{2}$
  - Width of the bright fringe = $\frac{D\lambda}{a}$

    Width of the dark fringe = $\frac{D\lambda}{a}$

    Width of the central fringe = $\frac{2D\lambda}{a}$
  - Height of first bright fringe $x_{1B} = \frac{3\lambda D}{2a}$

UNIT VII – DUAL NATURE OF RADIATION AND MATTER

Chapter - 4 : Dual Nature of Radiation and Matter

Revision Notes

Photoelectric Effect

- In an attempt towards unification of study of Physics, Photoelectric effect was established in 19th century which stated that everything in nature can be classified into either matter or radiation.
- Several important experiments were carried out independently on matter and radiations during that time. In 1897, Maxwell established electromagnetic theory which unified all radiations like light and heat. Maxwell established the wave theory of light. X-ray radiation was also discovered during that time in 1895.
- Simultaneously, in study of matter, a milestone discovery of electron was done by J.J. Thomson in 1897. It established that atoms of different matters constitute same particles and one of them is electron.

- **Electron Emission:** Electron has two types of motion, *i.e.* orbital or zig-zag motion in free state depending upon its energy. *i.e.*, Free electrons have higher energy than orbital electrons.
  - Free electrons in metals cannot come out from the surface due to force by positive ions present in metals. Electron can come out of the metal surface only if it has got sufficient energy to overcome the attractive pull.
  - **Work Function of a metal:** Work function of a metal is the minimum amount of work done (energy given) to its electron so that it can escape the metal surface. Work function is different for different metals. It is measured in electron volt (eV).
  - One electron volt is the energy gained by an electron when it has been accelerated by a potential difference of 1 volt.

$$V = \frac{W}{e}$$

When $V = 1$ V; W = 1 eV; putting these values in equation

Hence, $1 \text{ eV} = 1.6\times 10^{-19}$ J

Three types of electron emissions are as follows:-

- **Thermionic emission:** When electron emission occurs by heating the metal, it is known as thermionic emission. Emitted electrons are called thermionic electrons.
- **Field emission:** When electron emission occurs by applying strong electric field, it is known as field emission and emitted electrons are called field electrons.
- **Photoelectric effect:** When electron emission is occurred by illumination of metal by light of suitable frequency, it is known as photoelectric emission. Here, emitted electrons are called photo electrons.
  - When light falls on the metal surface, free electrons absorb energy from light and if this energy is more than the work function of metal, the electron escapes from the surface. This phenomenon is known as photoelectric emission. This was first observed by Hertz.
- **Hallwachs' and Lenard's detailed study of Photoelectric effect:**
  - In 1888, Lenard observed that when ultraviolet light falls on zinc metal, metal becomes positively charged. With the discovery of electrons, it was established that this is due to emission of electrons. The current produced by these photoelectrons is called photoelectric current.
  - The frequency of light should have a certain minimum value. This is called the Threshold frequency. Below this frequency, no emission of electrons take place.
- **Hertz and Lenard's experiment:** This experiment led the formation of quantum theory of light as wave theory could not explain photoelectric effect.

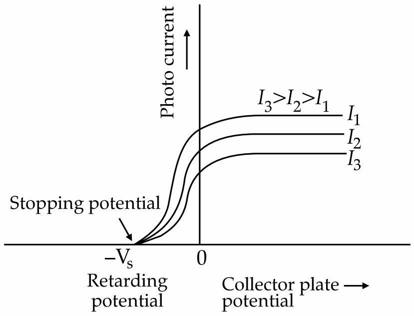
  Experiment was carried to study the following two properties of light:-
  - **Intensity of light:** Power of light is directly proportional to the intensity of light. A higher power bulb (say 100 watt) has more intensity than the lower power bulb (say 50 watt).
  - **Frequency of light:** Colour of light is due to its characteristic property of frequency.

$$\nu = \frac{c}{\lambda}$$

where, ν is frequency of light.

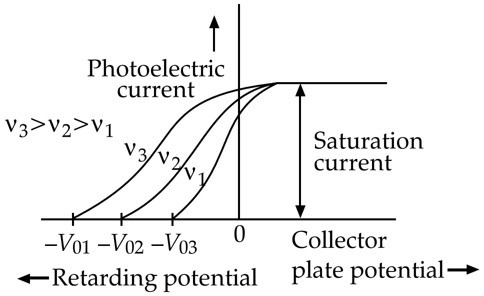
- **Experimental outcome:** It showed that intensity of light has linear relationship with photoelectric current at a potential higher than the stopping potential.
- **Effect of Potential on photoelectric current:**

For a given frequency of the incident radiation, the stopping potential is independent of its intensity.



➢ **Effect of frequency of incident radiation on stopping potential:**

- It was observed that photoemission current starts only at certain minimum frequency of light known as **threshold frequency** of that metal. Below this frequency, photoemission does not take place inspite of intensity of light of that frequency, falling on photosensitive plate.



➢ Wave theory was inadequate or failed to explain the photoelectric effect due to the following reasons:

- According to wave theory, higher amplitude means higher energy but experiments show that even larger amplitude (higher intensity) of light below threshold frequency can not give photoelectric effect.
- According to wave theory, same intensity of different colour should have same energy but experiment shows that energy depends upon frequency, not on amplitude.
- According to wave theory, wavefront should take some time to give energy to electron but experimentally, it was found that ejection of electron is instantaneous.

➢ In 1900, Max Planck stated that electromagnetic energy can be emitted only in quantized form.

$$E = h\nu$$

where, h is Planck's constant.

➢ Based upon this postulate, Einstein established quantum theory of radiation and was able to explain photoelectric phenomenon by this theory. It states that light energy packets are known as photons (Particle nature of light).

➢ In photoelectric effect, an electron absorbs a quantum of energy ($E = h\nu$) of radiation. If this absorbed quantum of energy exceeds, the minimum energy needed for the electron to escape from the metal surface (work function ϕ_0), the electron is emitted with maximum kinetic energy.

$$K.E. = h\nu - \phi_0$$

where, ϕ_0 is the work function of the metal.

- At stopping potential, kinetic energy of the ejected electron is zero. Below this potential, the electrons can not be ejected. Hence, maximum kinetic energy of an electron is calculated by

$$K.E._{max} = eV_0$$

where, V_0 is stopping potential.

Work function of metal, $\phi_0 = \nu_0 h$

where, ν_0 is the cutoff frequency or threshold frequency.

- Maximum speed of emitted photoelectrons can be calculated as

$$\nu_{max} = \sqrt{\frac{2K.E._{max}}{m}}$$

- According to quantum theory, all photons of specific light frequency have equal energy. Intensity of light only increases the number of photons per unit area and not the energy of photons.
- Photons are electrically neutral and are not deflected by electric and magnetic field.
- Photon has energy to propagate, hence it has momentum.

Momentum of photon $p = \frac{h\nu}{c}$

- In photon- electron collision, number of electrons or photons are not conserved but energy and momentum are conserved.

➢ As interference, diffraction and polarization cannot be explained by quantum theory of light, hence it was said that light has dual nature. When it travels in a medium, it travels as wave and while interacting with other medium, it acts like particles (photons).

Dual Nature of Matter

- De-Broglie's postulate is based upon the symmetry of nature. If radiation has dual nature, then matter should also have dual nature.
- According to his hypothesis, moving particles of matter should display wave nature under suitable conditions. He named the wave as matter wave. It is a third type of wave. It is different from mechanical wave and electromagnetic wave.
- **Properties of matter wave:** Whenever a particle moves, the matter wave envelops it and controls its motion.
  - De-Broglie proposed that the wave length λ known as de-Broglie wavelength; associated with momentum of particle p is given as

$$\lambda = \frac{h}{p}$$

Hence, de-Broglie's wavelength of particle,

$$\lambda = \frac{h}{mv}$$

  - **Calculation of electron-wave:**

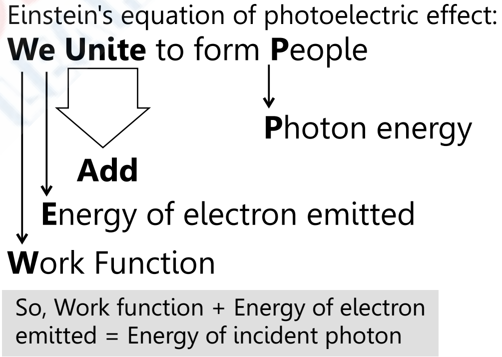
In photoelectric equation, kinetic energy of electron at potential V is $K = eV$. Putting this value of kinetic energy in de-Broglie wavelength equation,

$$\lambda_e = \frac{h}{\sqrt{2meV}}$$

By putting the value of mass of electron, its charge and Planck's constant, it becomes $\lambda_e = \frac{1.227}{\sqrt{V}}$ nm. This is theoretical calculation of de-Broglie wavelength of electron, where, V is the magnitude of accelerating potential in volts.

  - From this formula, wavelength of particle is inversely proportional to the mass of particle and its velocity. Hence, heavier particles have shorter wavelengths.

Mnemonics



Know the Formulae

- Einstein equation of photoelectric effect

$$K.E. = h\nu - \phi_0$$

- Work function $\phi_0 = h\nu_0$

  where, ν_0 is the cut-off frequency.
- Maximum speed of emitted photoelectrons can be calculated as

$$v_{\max} = \sqrt{\frac{2KE_{\max}}{m}}$$

➢ Momentum of photon, $p = \frac{h\nu}{c} = \frac{h}{\lambda}$ as $c = \upsilon\nu$

➢ 1eV (one electron volt) = 1.6×10^{-19} J

➢ Energy of light $E = \frac{hc}{\lambda} = \frac{12375}{\lambda(\beta)}$(eV)

➢ If applied potential is V, the emitted energy $E = eV$

➢ De Broglie wavelength associated with momentum of particle p as

$$\lambda = \frac{h}{p} \text{ or } \lambda = \frac{h}{m\nu}$$

➢ $\lambda_e = \frac{h}{\sqrt{2meV}}$ or $\lambda_e = \frac{1.227}{\sqrt{V}}$, where V is the magnitude of accelerating potential in Volts.

UNIT VIII – ATOMS & NUCLEI

Chapter - 5 : Atoms

Revision Notes

➢ There are roughly hundred types of atoms. (An atom is the identity of an element. 118 types of elements are known to us till date.)

➢ All atoms radiate different light spectra which shows these atoms are different and may be the smallest particles.

➢ With the discovery of electron by J. J. Thomson, it was evident that atoms have identical sub atomic particles and different light spectra of different atoms exists due to the motion of these particles.

➢ **Atomic models**

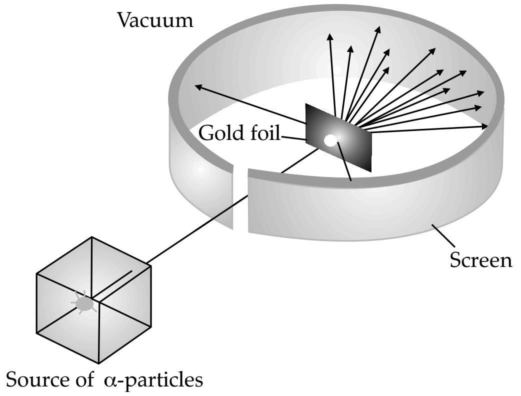
- As atom is electrically neutral, the discovery of electron led by J. J. Thomson established that it should also have positive charge. Hence, he proposed first model of atom- Plum-Pudding model.
- **Plum-Pudding model:** According to plum pudding model "the positive charge of the atom is uniformly distributed throughout the volume of the atom and the negatively charged electrons are embedded in it like seeds in a watermelon."
- But subsequent studies on atom showed that the distribution of charges are very different from the results stated by this atomic model.

Rutherford's atomic model:

- With the discovery of Avogadro number, the atomic size was understood to be quite big as compared to the sizes of atomic sub-particles.
- This led Rutherford to establish the second theoretical atomic model known as "nuclear model of the atom". It was inspired by planetary position around the Sun.
- According to this model "The entire positive charge and most of the mass of the atom is concentrated in a small volume called the nucleus, with electrons revolving around the nucleus just as planets revolve around the Sun."
- Though, it was initially a theoretical model but it was a major step towards the modern atomic model.
- **Geiger** and **Marsden** experimentally proved Rutherford's atomic model.

- **Geiger and Marsden scattering experiment:**

  Experimental setup:



- Radioactive element $^{214}_{83}Bi$ was taken as α-particles generating source.
- Gold was taken as target metal. The selection of gold was based upon its two important characteristics:
  - Gold has the highest malleability. Gold foil that was used in experiment was almost transparent.
  - Gold is a heavy metal, hence it helped in discovery of nucleus.
- Lead bricks absorbed the α-particles which were not towards the direction of gold foil. They worked as collimator.
- Detector consisted of ZnS screen and a microscope. It's rotatable in nature.

Experimental observations:

- When α-particles hit ZnS screen, it absorbs and glows. Hence, the number of α-particles can be counted by intensity variation.
- Most of the α-particles passed roughly in straight line (within 1°) without deviation. This showed that no force was acting upon most of α-particles.
- A very small number of α-particles were reflected. (1 out of 8000)

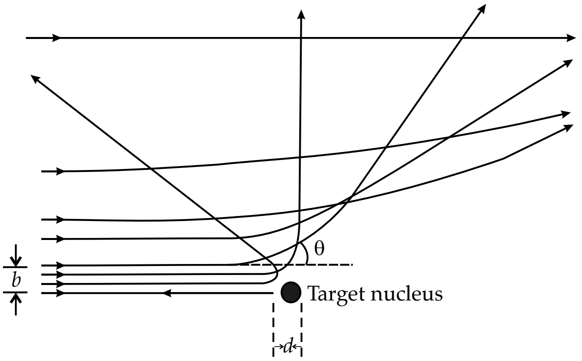
Conclusions:

- Most of the space in the atom is empty (only 0.14% scatters more than 1°).
- Experiment suggests that all positively charged particles are together at centre. It was called nucleus. So, nucleus has all the positive charges and the mass. Therefore, it has capability to reflect heavy positive α-particles.
- Size of nucleus calculated to be about 10^{-15} m to 10^{-14} m. According to kinetic theory, size of one atom is of the order of 10^{-10} m.
- Magnitude of force between α-particles and gold nucleus

$$F = \frac{1}{4\pi\varepsilon_0}\cdot\frac{2eZe}{r^2}$$

Alpha-particle trajectory:

- **Impact parameter:** It is the perpendicular distance between direction of given α-particle and centre of nucleus. It is represented by '*b*'.
- **Distance of closest approach:** It is the distance between centre of nucleus and the α-particle where it stops and reflects back. It is represented by '*d*'. This distance gives approximation of nucleus size.



Electron Orbits

- We can calculate the energy of an electron and radius of its orbit based upon Rutherford model.
- The electrostatic force of attraction, F_e between the revolving electrons and the nucleus provides the requisite centripetal force (F_c) to keep them in their orbits.

$$F_e = F_c$$

For hydrogen atom,
$$\frac{1}{4\pi\varepsilon_0}\frac{e^2}{r^2} = \frac{mv^2}{r}$$

or,
$$r = \frac{e^2}{4\pi\varepsilon_0 mv^2}$$

Electron has kinetic energy, $K = \frac{1}{2}mv^2$. Putting the value of mv^2 in the above equation

$$K = \frac{e^2}{8\pi\varepsilon_0 r}$$

And
$$v = \frac{e}{\sqrt{4\pi\varepsilon_0 mr}}$$

P.E. of an electron, $U = -\frac{1}{4\pi\varepsilon_0}.\frac{e^2}{r}$ (negative sign shows that it is due to attractive force)

Total energy,
$$E = K + U$$
$$E = \frac{e^2}{\pi 8\varepsilon_0 r} + \left(-\frac{1}{4\pi\varepsilon_0}\cdot\frac{e^2}{r}\right)$$
$$= -\frac{e^2}{8\pi\varepsilon_0 r}$$

- Due to this negative energy, electron is bound to nucleus and revolves around it. This energy is known as binding energy of electron.
- From the equation, it is clear that if energy is zero, then radius is infinity. Practically, if we provide this amount of energy to this electron, it gets free.

Atomic Spectra:

- Each element has a characteristic spectrum of radiation, which it emits. There are two types of atomic spectra: Emission atomic spectra and absorption atomic spectra.
- **Emission atomic spectra:** Due to excitation of atom usually by electricity, light of particular wavelength emitted. Atomic spectra is known as emission spectra.
- **Absorption atomic Spectra:** If atoms are excited in presence of white light, it absorbs its emission spectral colour and black line will appear in the same place of that atoms' emission spectra. This type of spectra are known as absorption spectra.

Spectral series:

- The atom shows range of spectral lines. Hydrogen is the simplest atom and has simplest spectrum.
- The spacing between lines within certain sets of the hydrogen spectrum decreases in a regular way. Each of these sets is called a spectral series.
- **Balmer Series:** Balmer observed the first hydrogen spectral series in visible range of hydrogen spectrum. It is known as Balmer Series.

$$\frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{n^2}\right)$$

Longest wavelength = 6566.4 Å

Shortest wavelength = 3648 Å

where, R is Rydberg's constant. The value of R is 1.097×10^7 m^{-1}; $n = 3, 4, 5...$

$$\frac{1}{\lambda} = \frac{\nu}{c}$$

Hence, $$\nu = Rc\left(\frac{1}{2^2} - \frac{1}{n^2}\right)$$

Other series of spectra for hydrogen were as follows:

➢ **yman Series:** $\frac{1}{\lambda} = R\left(\frac{1}{1^2} - \frac{1}{n^2}\right)$; n = 2, 3, 4, 5, ... This is in UV range.

Longest wavelength = 1216 Å
Shortest wavelength = 912 Å

➢ **Paschen Series:** $\frac{1}{\lambda} = R\left(\frac{1}{3^2} - \frac{1}{n^2}\right)$; n = 4, 5, 6, ...

Longest wavelength = 18761.14 Å
Shortest wavelength = 8208 Å

➢ **Brackett Series:** $\frac{1}{\lambda} = R\left(\frac{1}{4^2} - \frac{1}{n^2}\right)$; n = 5, 6, ...

Longest wavelength = 40533.33 Å
Shortest wavelength = 14592 Å

➢ **Pfund Series:** $\frac{1}{\lambda} = R\left(\frac{1}{5^2} - \frac{1}{n^2}\right)$; n = 6, 7, 8 ....

Longest wavelength = 74618.1 Å
Shortest wavelength = 22800 Å

➢ The Lyman series is in the ultraviolet while the Paschen, Brackett and Pfund series are in the infrared region.

Limitation of Rutherford model:

➢ **It could not explain the stability of the atom:** The electron orbiting around the nucleus radiates energy. As a result, the radius of the electron orbit should continuously decrease and ultimately the electron should fall into the nucleus.

➢ **It could not explain nature of energy spectrum:** According to the Rutherford's model, the electrons can revolve around the nucleus in all possible orbits. Hence, the atom should emit radiations of all possible wavelengths or in other words, it should have continuous spectrum. However, in practice, the atoms are found to have line spectrum or discrete spectrum.

It didn't mention anything about the arrangement of an electrons in orbit.

Bohr's Model and Postulates:

➢ An electron can revolve in certain stable orbits without emission of radiant energy. These orbits are called stationary states of atom.

➢ Electron revolves around nucleus only in those orbits for which the angular momentum is the integral multiple of $\frac{h}{2\pi}$, where, h is Planck's constant.

➢ Hence angular momentum, $$L = \frac{nh}{2\pi}$$

➢ An electron may make a transition from one of its specified non-radiating orbit to another of lower energy. When it does so, a photon is radiated having energy equal to energy difference between initial and final state.

$$h\nu = E_i - E_f$$ (where, ν is frequency)

Angular momentum, $$L = mv_n r_n$$

According to Bohr's postulate, $$L = \frac{nh}{2\pi}$$

Hence, $$mv_n r_n = \frac{nh}{2\pi}$$

$$mr_n = \frac{nh}{2\pi v_n}$$

For hydrogen atom, $$v = \frac{e}{\sqrt{4\pi\varepsilon_0 mr}}$$

Combining these two equations, we get

$$v_n = \frac{1}{n} \cdot \frac{e^2}{4\pi\varepsilon_0} \frac{1}{(h/2\pi)}$$

This equation depicts that electron speed in n[th] orbit falls by a n factor.

$$r_n = \left(\frac{n^2}{m}\right)\left(\frac{h}{2\pi}\right)^2 \frac{4\pi\varepsilon_0}{e^2}$$

For innermost orbit $n = 1$; the value of r_1 is known as Bohr's radius a_0.

$$a_0 = \frac{h^2\varepsilon_0}{\pi me^2}$$

If we put values of all constants, we get $a_0 = 5.29 \times 10^{-11}\ m \approx 0.53$ Å

It can also be observed that radii of n^{th} orbit increases by n^2 times.

By putting this value in total energy of an electron and convert the unit in eV, we get

$$E_n = \frac{-13.6}{n^2}\text{eV}$$

Negative value shows that electron is bound to nucleus.

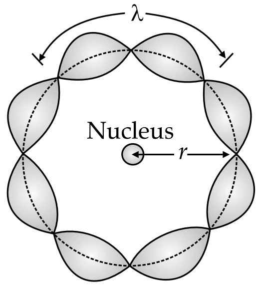
- The explanation of the hydrogen atom spectrum provided by Bohr's model was a brilliant achievement.

De-Broglie's explanation of Bohr's second postulate by quantization theory:

- According to Bohr's postulate, electron in hydrogen atom can revolve in certain orbit only in which its angular momentum, $L = n\frac{h}{2\pi}$. In these stationary orbits, electron does not radiate energy.
- De-Broglie proved it with the help of wave nature of electron.
- Travelling wave propagates energy but stationary wave does not propagates energy. In analogy to waves travelling on a string, particle waves can lead to standing waves under resonant conditions. Resonant condition is

$$l = n\lambda$$

where, l = perimeter of orbit.



Standing wave when $l = n\lambda$

For hydrogen atom, length of the innermost orbit is its perimeter. hence

$$2\pi a_0 = n\lambda \quad ...(i)$$

According to de-Broglie's wavelength of electron,

$$\lambda = \frac{h}{p}\cdot$$

Now equation (i) can be written as (taking $a_0 = r$)

$$2\pi r = n\frac{h}{p} \qquad \text{...(ii)}$$

But

$$p = mv$$

Hence, equation (ii) can be reduced as,

$$2\pi r = n\frac{h}{mv}$$

$$mvr = \frac{nh}{2\pi}$$

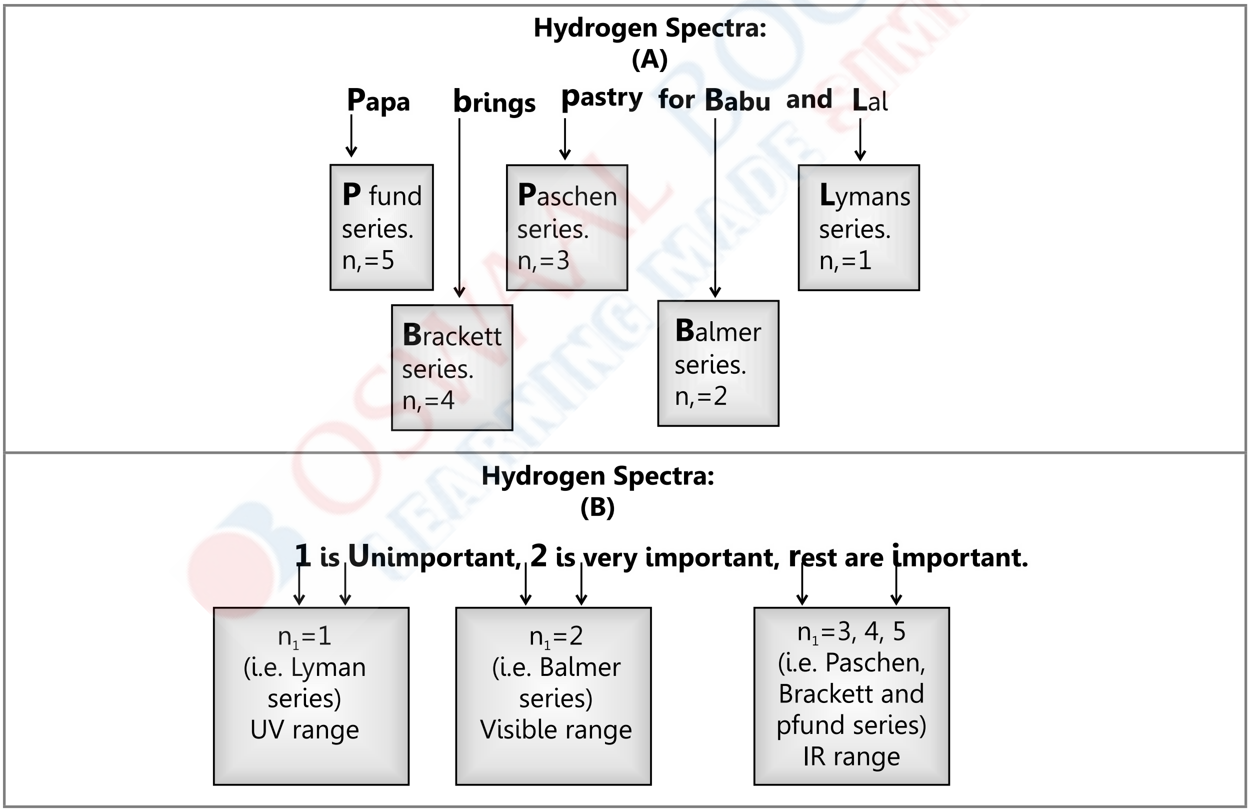
$$L = \frac{nh}{2\pi}$$

This is Bohr's second postulate.

Limitation of Bohr's atomic model:

- Bohr's model is for hydrogenic atoms. It does not hold true for multi-electron model.

Mnemonics



Know the Formulae

- **Radius of orbit,** $r = \dfrac{e^2}{4\pi\varepsilon_0 mv^2}$
- **inetic energy of electron in its orbit,** $K = \dfrac{e^2}{4\pi\varepsilon_0 r}$
- **PE of an electron;** $U = -\dfrac{1}{4\pi\varepsilon_0}\cdot\dfrac{e^2}{r}$

- **Velocity of electron in its orbit;** $v = \frac{e}{\sqrt{4\pi\varepsilon_0 mr}}$
- Total energy of an electron in an orbit; $E = -\frac{e^2}{8\pi\varepsilon_0 r}$
- **Spectral series**
- **Balmer Series:** $\frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{n^2}\right)$, n = 3, 4, 5..... This is in Visible range.
- **Lyman Series:** $\frac{1}{\lambda} = R\left(\frac{1}{1^2} - \frac{1}{n^2}\right)$; n = 2, 3, 4, 5, ...This is in UV range.
- **Paschen Series:** $\frac{1}{\lambda} = R\left(\frac{1}{3^2} - \frac{1}{n^2}\right)$; n = 4, 5, 6
- **Brackett Series:** $\frac{1}{\lambda} = R\left(\frac{1}{4^2} - \frac{1}{n^2}\right)$; n = 5, 6, 7...
- **Pfund Series:** $\frac{1}{\lambda} = R\left(\frac{1}{5^2} - \frac{1}{n^2}\right)$; n = 6, 7, 8....

} These series are in infrared region.

- **Relation between speed, total energy of an electron and its radius with respect to orbital number *n*:**

$$v_n = \frac{1}{n}\frac{e^2}{4\pi\varepsilon_0}\frac{1}{(h/2\pi)}$$

$$r_n = \left(\frac{n^2}{m}\right)\left(\frac{h}{2\pi}\right)\frac{4\pi\varepsilon_0}{e^2}$$

Bohr radius, $a_0 = \frac{h^2\varepsilon_0}{\pi me^2} = 0.53\ \text{Å}$

Energy for n^{th} orbiting electron, $E_n = \frac{-13.6}{n^2}\text{eV}$

□□

Chapter - 6 : Nuclei

Revision Notes

Nucleus and Mass-Energy Relation

- As per Rutherford scattering experiment, it is established that radius of atom is 10^4 times of its nucleus. Hence, volume of nucleus is 10^{-12} times smaller than atom. This leads to the conclusion that the total mass comes from the nucleus and that the atom is almost empty.
- For measuring atomic mass and its sub-particles, new unit of mass is introduced as atomic mass unit 'u'.

$$1\text{ u} = \frac{\text{Mass of one } {}^{12}_{6}C \text{ atom}}{12}$$

$$1\text{ u} = 1.660539 \times 10^{-27}\text{ kg}$$

- Atomic mass unit is not an integral multiple of u due to presence of isotopes (atoms of same element with different atomic masses).
- All mass and positive charge of an atom is concentrated in its centre known as nucleus.
- Chadwick discovered a new sub-particle in nucleus known as neutron. It is electrically neutral in nature.

$$\text{Mass of neutron, } m_n = 1.00866\text{ u} = 1.6749\times10^{-27}\text{ kg}$$

- The composition of a nucleus can now be described using the following terms and symbols :
  - Z = Atomic number = Number of protons (equal to the number of electrons)
  - N = Neutron number = Number of neutrons
  - A = Atomic mass number = $(Z + N)$ = Total number of protons and neutrons
- An atom is represented by ${}^{A}_{Z}X$ where

  X = Symbol of element
  A = Atomic mass number
  Z = Atomic number
- **Isotopes :** Two atoms of an element having same atomic number (Z is same) but different atomic mass number (due to the different number of neutrons) are said to be isotopes.
- **Isobars :** Two atoms of different elements having same mass number but different atomic numbers are said to be isobars.
- **Isotones :** Two atoms of different elements having different mass numbers and atomic numbers such that their difference is same are said to be isotones. It means they have same number of neutrons.

Size of the nucleus : A nucleus of mass number A has a radius

$$R = R_0 A^{1/3} \qquad \text{where, } R_0 = 1.2 \times 10^{-15} \text{ m}$$

- Nuclear matter density = 2.3×10^{17} kgm^{-3}
- Earlier, it was believed that anything in the universe can be classified into matter or radiation. Einstein proposed that there are two forms of energy which are inter-convertible.

$$E = mc^2; \qquad \text{where, } c \text{ is speed of light.}$$

- With this relation, we may calculate 1 amu = 931.5 MeV
- **Mass defect :** The difference in mass of a nucleus and its constituents, ΔM, is called the mass defect, and is given by,

$$\Delta M = [Zm_p + (A - Z)m_n] - M.$$

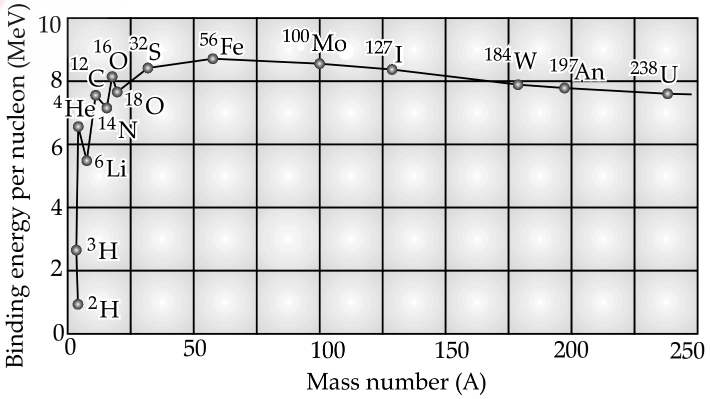
- **Binding energy :** Binding energy of a nucleus is that quantity of energy which when given to nucleus, its nucleons will become free and will leave the nucleus. It is having negative sign.

$$E_b = \Delta Mc^2 \qquad \text{where, } E_b \text{ is binding energy.}$$

- **Binding energy per nucleons (E_b/A) :** A measure of the binding between the constituents of the nucleus is the binding energy per nucleon, E_{bn} or E_b/A, which is the ratio of the binding energy E_b of a nucleus to the number of the nucleons, A, in that nucleus.

$$E_{bn} = \frac{E_b}{A}$$

Relation between E_b/A and Stability of elements



- Higher the Binding Energy per Nucleons, more stable is the element. Higher binding energy per nucleon means we have to supply more energy to free nucleons or it is difficult to break the nucleus.
- Most of the atoms where atomic mass number are in the range 30 < A < 200, the binding energy per nucleon is fairly constant and quite high. It is maximum for A = 56 about 8.75 MeV.
- For A < 30 and A > 170; Binding energy per nucleon is quite low.

- If a nucleus of lower binding energy is converted into higher binding energy, then energy is released.
- There are two methods of converting lower binding energy nucleons into higher binding energy nucleons.
  - **Fission :**A heavy nucleus (low binding energy per nucleon) is broken into two lighter nuclei (higher binding energy per nucleon) with the release of energy. This process is known as fission.

    Example : ${}_0^1n + {}_{92}^{235}\text{U} \rightarrow {}_{92}^{236}\text{U} \rightarrow {}_{56}^{144}\text{Ba} + {}_{36}^{89}\text{Kr} + 3{}_0^1n + 200 \text{ MeV}$
  - **Fusion :**Two light nucleus (low binding energy per nucleon) are joined to form one nucleus of higher binding energy per nucleon and energy is released. This process is known as fusion.

    Example : ${}_1^1\text{H} + {}_1^1\text{H} \rightarrow {}_1^2\text{H} + e^+ + \nu + 0.42 \text{ MeV}$
- **Nuclear force :**
  - The binding energy per nucleon is approximately 8 MeV, which is much larger than the binding energy in atoms.
  - This high binding energy per nucleon counters the repulsive force between protons and bind both protons and neutrons into the tiny nuclear volume.
  - The nuclear force is much stronger than the Coulomb force acting between charges or the gravitational forces between masses but it's a short range force $\left(\propto \frac{1}{r^7}\right)$
- **Nuclear energy by artificial fission and fusion processes**
  - **Fission :** When a heavy nucleus is broken into two smaller nuclei, the process is known as fission. In this process, huge amount of energy is released.
  - When a neutron was bombarded on a uranium target, the uranium nucleus broke into two nearly equal fragments releasing huge amount of energy.
  - **Some combination of products of above reaction are**

    ${}_0^1n + {}_{92}^{235}\text{U} \rightarrow {}_{92}^{236}\text{U} \rightarrow {}_{56}^{144}\text{Ba} + {}_{36}^{89}\text{Kr} + 3{}_0^1n$

    ${}_0^1n + {}_{92}^{235}\text{U} \rightarrow {}_{92}^{236}\text{U} \rightarrow {}_{51}^{133}\text{Ba} + {}_{41}^{99}\text{Nb} + 4{}_0^1n$

    ${}_0^1n + {}_{92}^{235}\text{U} \rightarrow {}_{54}^{140}\text{Xe} + {}_{38}^{94}\text{Sr} + 2{}_0^1n$
  - **The energy released (the *Q* value) in the fission reaction of nuclei like uranium is of the order of 200 MeV per fissioning nucleus.**
- **Nuclear fusion :** Two light nuclei (low binding energy per nucleon) join and form one nucleus of higher binding energy per nucleon, energy is released. This process is known as Fusion.

  Some Examples of nuclear fusion are

$$ {}_1^1\text{H} + {}_1^1\text{H} \rightarrow {}_1^2\text{H} + e^+ + \nu + 0.42\text{MeV} $$

$$ {}_1^2\text{H} + {}_1^2\text{H} \rightarrow {}_2^3\text{He} + n + 3.27\,\text{MeV} $$

$$ {}_1^2\text{H} + {}_1^2\text{H} \rightarrow {}_1^3\text{H} + {}_1^1\text{H} + 4.03\,\text{MeV} $$

- Nuclear fusion is the source of energy for the stars.
- Fusion process gives more energy than fission process. In the above examples of fusion and fission, energy from one unit mass by fusion is 6.7 MeV and from fission, it is 1 MeV
- **Advantages of Nuclear fusion reactor :**
  - It is a clean fuel. No radioactive wastage in this process.
  - Hydrogen is available in plenty.
- **Problems of nuclear fusion reactor :**
  - Cannot be stopped unless the whole stock is burnt.
  - Storage of hydrogen plasma.
- Hydrogen bomb is uncontrollable nuclear fusion reaction.
- **Thermal nuclear fusion reaction in Sun :** Fusion of hydrogen nuclei into helium nuclei is the source of energy of all stars including our Sun.

$$^1_1H + ^1_1H \rightarrow ^2_1H + e^+ + \nu + 0.42 \text{ MeV} \quad ...(i)$$

$$e^+ + e^- \rightarrow \gamma + \gamma + 1.02 \text{ MeV} \quad ...(ii)$$

$$^2_1H + ^1_1H \rightarrow ^3_2He + \gamma + 5.49 \text{ MeV} \quad ...(iii)$$

$$^3_2H + ^3_2H \rightarrow ^4_2He + ^1_1H + ^1_1H + 12.86 \text{ MeV} \quad ...(iv)$$

The combined effect of above reactions is

$$4\,^1_1H + 2e^- \rightarrow ^4_2He + 2\nu + 6\gamma + 26.7\text{ MeV}$$

Mnemonics

Isotopes, Isobars and Isotones:

ISO

TOPE — **BAR** — **TONE**

- TOPE: Note **P** in Tope, So, only PROTON NOS. are same.
- BAR: There is no P, no N in BAR, i.e. PROTON NOS. are different.
- TONE: Note **N** in TONE. So, only NEUTRON NUMBERS are same.

In ISOTOPES→ Number of protons are same. Number of neutrons are different.
In ISOTONES→ Number of neutrons are same. Number of protons are different.
In ISOBARS→ Number of neutrons are different. Number of protons are also different But the total number of nucleons remain same

Know the Formulae

- **Size of the nucleus:**
  $R = R_0 A^{1/3}$ where $R_0 = 1.2 \times 10^{-15}$ m
- **Mass defect :** $\Delta M = [Zm_p + (A - Z)m_n] - M$
- **Binding energy :** $E_b = \Delta M c^2$
- **Binding energy per nucleon (BE/A) :** $E_{bn} = \dfrac{E_b}{A}$

UNIT IX – ELECTRONIC DEVICES

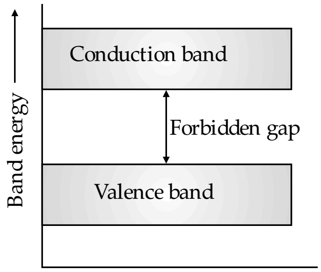
Chapter - 7 : Semiconductor Electronics: Materials, Devices and Simple Circuits

Revision Notes

Energy Bands

Energy bands:

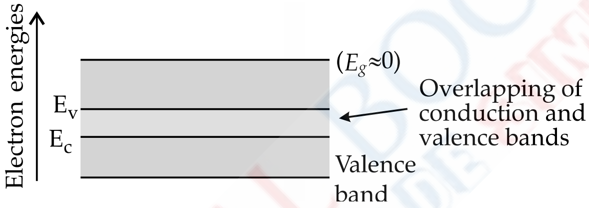
- In a crystal or the crystal, each electron has a different energy level with continuous energy variation.
- Energy bands consist of a large number of closely spaced energy levels that exist in crystalline materials.
- In solids, there are three important energy bands such as valence band, conduction band, forbidden band or forbidden gap.



- The collection of energy levels of free electrons which move freely around the material are called as conduction band.
- There is extra energy required for valence electrons to move to conduction band which is known as forbidden energy.
- The energy associated with forbidden band is known as energy gap which is measured in electron volt (eV) where, 1 eV = 1.6×10^{-19} J.
- The collection of energy levels that are partially or wholly filled is known as valence band.
- Materials may be classified as conductors, insulators or semiconductors on the basis of energy band theory.

Energy bands in Conductors:

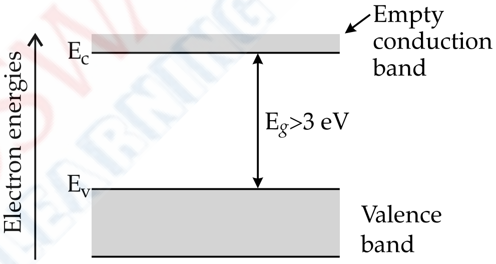
- In conductors, the overlapping of conduction and valence bands without energy gap forms a conduction band.



- In this, an electron that receives any acceptable low energy is able to move freely among the bands.

Energy bands in Insulators:

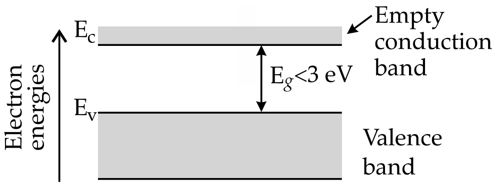
- In insulators, conduction band and valence band have large forbidden energy gap.



- The gap between conduction band and valence band exceeds by 3 eV as electrons that transfer from valence band to conduction band need more energy.
- Due to the requirement of more energy, insulators do not conduct any electric current.
- Example of an insulator is diamond, with energy gap of around 5.4 eV.

Energy bands in Semiconductors:

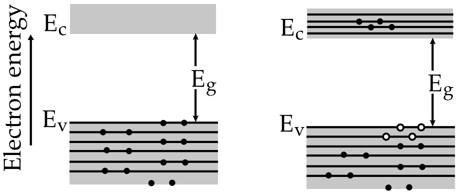
- In semiconductors, are materials in which, conduction band and valence band are neither overlapping nor have a wide gap.
- In such materials, the energy provided by the heat at room temperature is sufficient to lift the electrons from the valence band to the conduction band.



- Semiconductors behave like insulators at 0 K as no electron exists in the conduction band.
- Examples of semiconductors are Silicon (14) and Germanium (32) having energy gaps as 1.12 eV and 0.75 eV respectively.

- **Intrinsic semiconductors:** Pure semiconductors are called intrinsic semiconductors. They can not be used in electronic circuits as their conductivity is low.
- For intrinsic semiconductors, the number of free electrons is equal to the number of holes.

$$n_e = n_h = n_i$$



(a) (b)

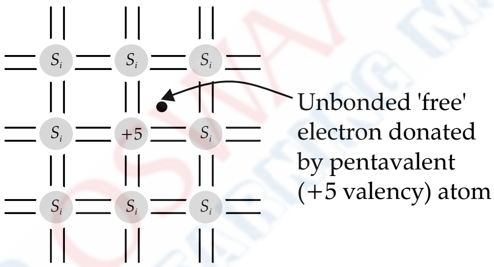
- An intrinsic semiconductor (a) at T = 0 K behaves like insulator. (b) At T > 0 K forms thermally generated electron-hole pairs. The filled circles (•) represent electrons and empty circles (o) represent holes.
- **Extrinsic semiconductors:** When a small fixed amount of charged impurity is mixed with intrinsic semiconductors, they become extrinsic.
- **In extrinsic semiconductors:**
  (i) Conductivity increases
  (ii) Conductivity is controlled by doping carriers
- In extrinsic semiconductors, the number of free electrons is not equal to the number of holes.

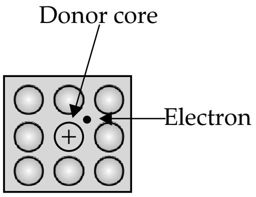
$$n_e \neq n_h$$

- Doping is adding impurities to intrinsic semiconductors crystal lattice so as to increase the number of carriers.
- For raising electrical conductivity, semiconductors are mixed with either pentavalent impurity such as Antimony (Sb), Arsenic (As) and Phosphorus (P) or trivalent impurity such as Indium (In), Gallium (Ga) or Boron (B).

***n*-type Semiconductors:**

- If Phosphorous with 5 valence-band electrons is added, it will give an extra e^- which will freely move around and leave of a positively charged nucleus.





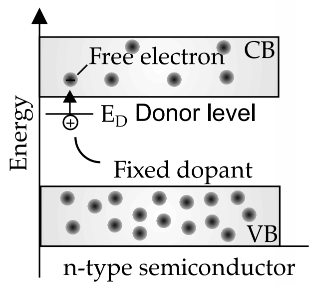
- The crystal is electrically neutral, known as "*n*-type" material with negative carriers where concentration of donor atoms is 10^{15} cm^{-3} ~ 10^{20} cm^{-3} having mobility $\mu_n \approx 1350\,\text{cm}^2/\text{V}$

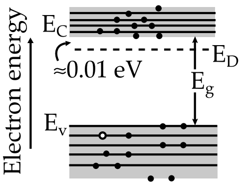
Energy Diagram of *n*-type Semiconductor:

- On doping a semiconductor with pentavalent impurity like Antimony (Sb) or Arsenic (As), extrinsic semiconductor so obtained is known as *n*-type.
- *n*-type semiconductor has a large number of free electrons known as majority (charge) carriers and a small number of holes known as minority (charge) carriers.

$$n_e >> n_h$$

- Impurity atom in an *n*-type semiconductor is called donor as it generates new energy level below the conduction band, known as E_D.

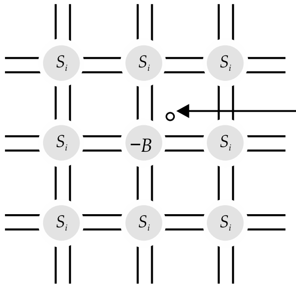


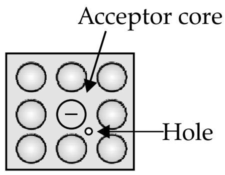


Energy bands for *n*-type semiconductor at T > 0 K

***p*-type Semiconductors:**

- If a Boron atom with 3 valence band electrons is added, it accepts e^- and gives extra holes (h^+) to move freely which leaves behind a negatively charged nucleus.





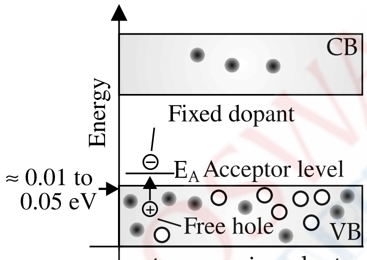
- The crystal is electrically neutral known as "*p*-type" silicon in which concentration of acceptor atoms ~10^{28} cm^{-3} where hole movement needs breaking of bond thereby giving low mobility, where, $\mu_p \approx 500$ cm^2/V.

Energy Band Diagram of *p*-Type Semiconductor

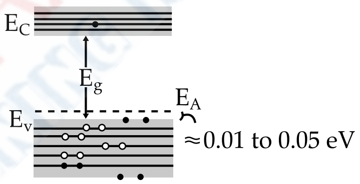
- On doping a semiconductor with trivalent impurity like Indium (In) or Gallium (Ga), extrinsic semiconductor so obtained is known as *p*-type.
- *p*-type semiconductor has large number of holes known as majority (charge) carriers where number of free electrons is less known as minority (charge) carriers.

$$n_h >> n_e$$

- Impurity atom in a *p*-type semiconductor is known as acceptor atom.
- In *p*-type, extra holes in band gap allows excitation of valence band electrons which leaves mobile holes in valence band.
- Large number of holes in covalent bond is created in crystal with trivalent impurity.
- In extrinsic semiconductors $n_e \neq n_h$ but $n_e.n_h = n_i^2$



p-type semiconductor



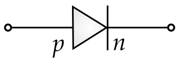
Energy bands for *p*-type semiconductor at *T* > 0 K

- **Energy band:** Range of energies that an electron may possess in an atom.
- **Valence Band:** Range of energy levels possessed by valence electrons.
- **Conduction Band:** Range of energy levels possessed by conductive (free) electrons.
- **Forbidden Band:** Energy band in between the conduction band and valence band.

Semiconductor Diodes and Applications

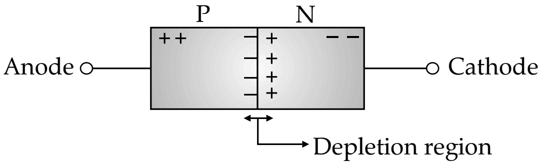
Diode

- Diode is an electronic device consisting of a junction of *p*-type and *n*-type semiconductors. It is represented as:



Semiconductor diode

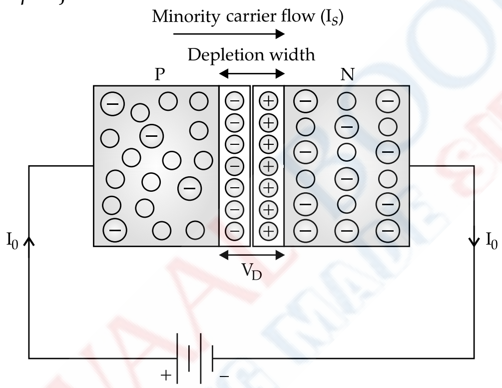
- Semiconductor diodes were first semiconductor electronic devices which is a common type of diode that is made of crystalline piece of semiconductor material with *p–n* junction across its terminals.



- When a *p*-type semiconductor material is suitably joined to *n*-type semiconductor, the contact surface is called a *p-n* junction.
- It is an electrical device that allows current only in one direction. The direction of the arrow is the direction of current when it is forward biased.
- At junction, electrons and holes diffuse to form the diffusion current.
- A *p-n* junction layer is also called the depletion layer. A potential barrier is created at junction due to diffusion current. It acts as a barrier for majority charge carriers.
- The potential barrier helps the minority charge carriers to flow. A drift current is formed which is opposite in direction of the diffusion current.
- Under equilibrium conditions, diffusion current is equal to the drift current and net current is zero as both are in opposite directions.
- There are many types of semiconductor diodes such as:
- Avalanche diodes, Gunn diodes, Light Emitting Diodes (LED), Photodiodes, etc.
- Semiconductor diode can be made either from Silicon or Germanium and each differs in size and properties.

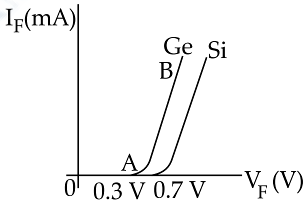
Forward Bias

- When an external voltage is applied, where negative terminal of battery is connected to *n*-side while positive terminal of battery is connected to *p*-side, the barrier potential will get reduced and more current can flow across the junction that decreases the *p-n* junction width.



forward biased p-n junction

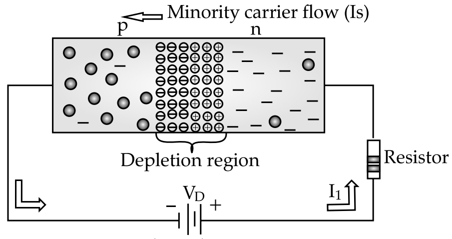
- The positive terminal of battery repels majority carriers, holes in *p*-region while negative terminal repels electrons in *n*-region which pushes them towards the junction.
- Here, an increase in concentration of charge carriers near the junction is observed, where recombination takes place thereby reducing width of depletion region.



- Due to the rise in forward bias voltage, depletion region continues to reduce its width, which results in more and more recombination process.

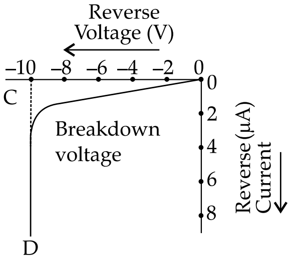
Reverse Bias

- If an external voltage is applied in reverse direction where positive terminal of battery is connected to *n*-side while negative terminal of battery is connected to *p*-side, then barrier potential will increase and minority charge carriers will flow across the junction.



Reverse biased p-n junction

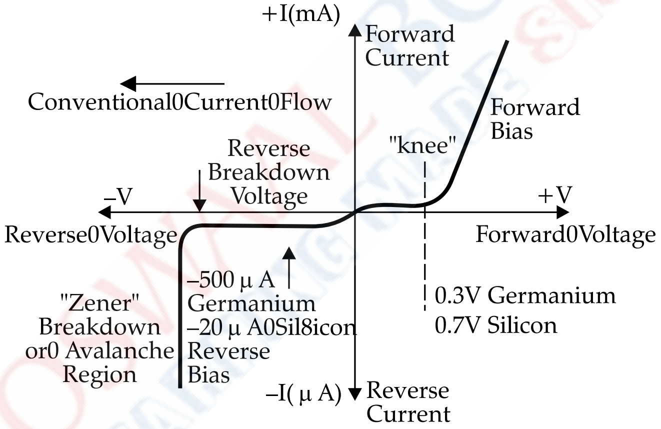
- In this, the current will be quite small and is independent of external voltage.
- Beyond certain voltage, diode will break down with Avalanche breakdown mechanism or Zener breakdown mechanism.
- Here, negative terminal of battery will attract majority charge carriers, holes in *p*-region and positive terminal attracts electrons in *n*-region which pulls them away from the junction.
- As a result of this, there will be a decrease in concentration of charge carriers near junction which increases the width of depletion region.



- A small amount of current flows because of minority carriers known as reverse bias current or leakage current and with the rise in reverse bias voltage, depletion region continues to increase in width without any increase in flow of current.

V-I Characteristics of Diode

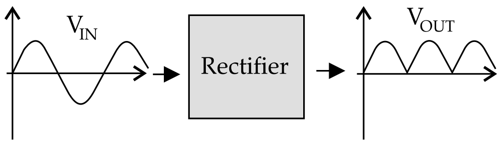
- In V-I characteristics of diode, on voltage axis, "reverse bias" is an external voltage potential that increases the potential barrier while external voltage that decreases the potential barrier is in "forward bias" direction.



- Biasing of diode can be forward biasing or reverse biasing.

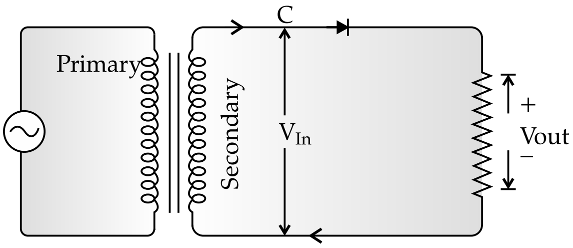
Diode as rectifier

- Rectifier is a circuit that converts AC supply into unidirectional DC supply.

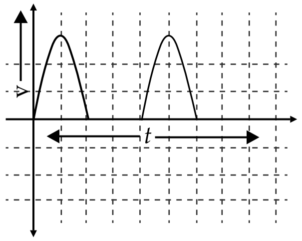


- With rectification, alternating current (AC) gets converted to direct current (DC).
- The bridge rectifier circuits uses semiconductor diodes for converting AC as it allows the current to flow in one direction only.

Half-wave rectifier



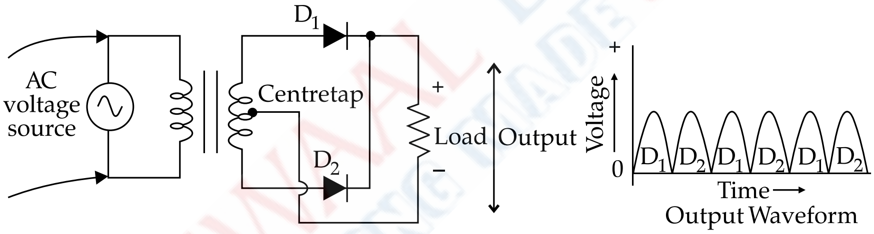
- The half-wave rectifier with a single diode, allows current to flow in one direction.
- Here, AC power source V_{ac} is connected to primary side of transformer, while secondary terminals of transformer are connected to diode and resistor in series.
- If V_{ac} is in positive cycle, a positive voltage is produced on secondary side of transformer.
- The positive voltage forward bias the diode and diode start passing the current. As a result of which the voltage drop across the load.
- If V_{ac} is in negative cycle, then secondary side has negative voltage where diode is reverse biased and does not pass any current.
- Voltage waveform across the load resistor is shown below, where positive side of sinusoidal cycle is present while negative side of sinusoidal cycle has been clamped off.



- The output voltage V_{dc} is similar to the output of battery which is always positive.
- The positive waveform is bumpy as single diode is applied to produce half-wave rectification where one half of AC wave is removed that does not pass through the diode.

Full-wave rectifier

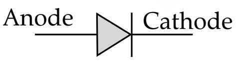
- For rectifying AC power for using both half cycles of sine wave, full wave rectification is used.

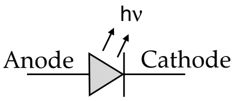


- A simple kind of full-wave rectifier uses centre tap transformers with two diodes.
- In full wave rectification, during first half-cycle, when source voltage polarity is positive (+) on top and negative (-) on bottom, then only top diode conduct, while bottom diode blocks the current. And during second half cycle, when source voltage polarity is negative (–) on top and positive (+) on bottom, only bottom diode will conduct while the top diode blocks the current.

Special purpose *p-n* junction diodes

- Apart from simple *p-n* junction diodes, there are many more types of diodes which are used in various specific applications that take advantage of the behaviour and features.





Light–emitting diode

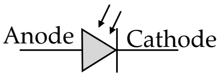
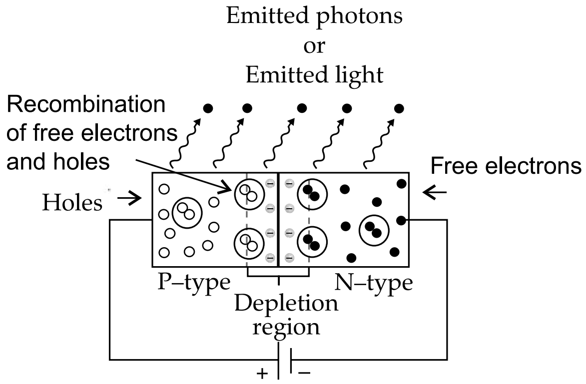


Photo diode

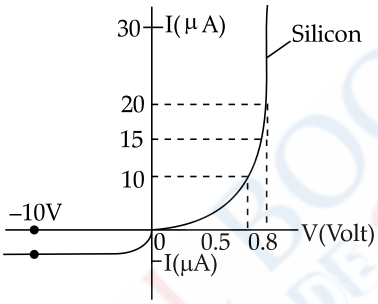
LED

- Light Emitting Diode or LED is most widely used semiconductor diodes among all available types of semiconductor diodes.
- It emits visible light or invisible infrared light when forward biased.
- The LEDs which emit invisible infrared light are used for remote controls.
- It is always in forward biased which make electrons and holes to move fast across the junction and helps in combining constantly by removing one another.
- Electrons which move from *n*-type to *p*-type silicon combine with holes and give energy in the form of light.



➢ Recombination of electrons and holes in depletion region decreases the width of the region which allows more charge carriers to cross the *p-n* junction.

➢ Here, some of the charge carriers from *p*-side and *n*-side will cross the *p-n* junction before they recombine in depletion region.

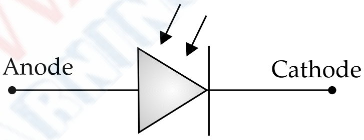


V-I characteristics

Photodiode

➢ Photodiode is a transducer which takes light energy and converts it into electrical energy.

➢ It is a *p-n* junction which consumes light energy to generate electric current.



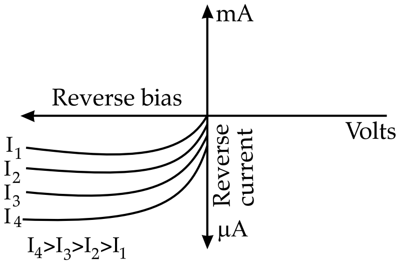
➢ It is referred to as photo-detector, photo-sensor or light detector.

➢ It is specially designed to operate in reverse bias condition where *p*-side is connected to negative terminal of battery and *n*-side is connected to positive terminal of battery.

➢ It is sensitive to light as when light or photons fall on it, it easily converts light into electric current.

➢ In photodiode circuit, current flows from the cathode to anode when exposed to light.

➢ Photodiode is capable of converting light energy to electrical energy and can be expressed as a percentage known as Quantum Efficiency (Q.E.).

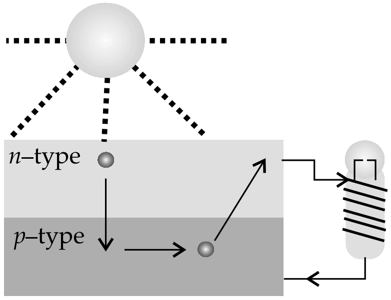


V-I characteristics

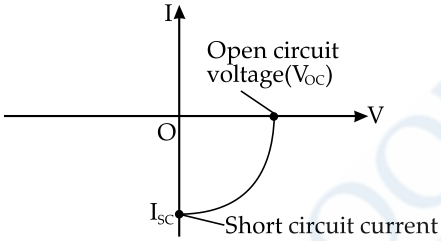
Solar cell

➢ Solar cell is an electronic device which absorbs sunlight and generates emf.

➢ In this, there are *n*-type silicon and *p*-type silicon layers that generates electricity using sunlight so that the electrons can jump across the junction between different types of silicon material.



- When sunlight falls on solar cell, photons bombard the upper surface and generates electron-hole pairs.
- They get separated due to voltage barrier at junction, electrons are swept to n side and holes are swept to p-side.
- Metal contacts hold these electron-hole pairs. Thus, p side becomes positive and n side becomes negative and hence it acts as photo-voltage cell.



V-I characteristics

Mnemonics

Concept : Forward biased P-N Junction.

Football **d**eserve **S**tamina and **low** **r**isk.

- **F** → **F**orward Bias
- **d** → **D**epletion layer
- **S** → **S**hrinks
- **low** → **Low**
- **r** → **R**esistance

In Forward Biased P-n Junction:
(i) Depletion layer shrinks
(ii) Resistance is low

Concepts : Reverse biased P-N Junction.

Rafting **d**eserve **E**nergy and **high** **r**isk.

- **R** → **R**everse Bias
- **d** → **D**epletion layer
- **E** → **E**xpands
- **high** → **HIGH**
- **r** → **R**esistance

In Reverse Biased P-n Junction:
(i) Depletion layer expands
(ii) Resistance is high