Elementary Physics

BCA 204 Semester II
Even Semester Semester 2020-21

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Syllabus (04 Credits)

UNIT-1: Mechanics

UNIT-2: Electromagnetism

UNIT-3: Laser

UNIT-4: Fiber Optics

UNIT-5: Semiconductors

UNIT-1: Mechanics

Unit 1: Mechanics

Units and dimensions; Newton's laws; Conservation of linear momentum; Conservative and non-conservative force; Concept of potential energy; Work energy theorem; Periodic and oscillatory motion; Simple harmonic motion: Time period, Frequency, Phase and phase constant, Energy in simple harmonic motion.

Newton's Laws of Motion:

- There are three laws of motion also called Newton's Laws of Motion that describe the motion of particle(s) and the forces acting on it. These three laws are considered as the backbone of classical mechanics.

- **1 Law of Inertia**: Unless forced, a body does not change its state (of constant motion or rest). OR
  The first law states that an object at rest will stay at rest, and an object in motion will stay in motion unless acted on by a net external force.

  Mathematically, $d\underline{v}/dt = 0$ if sum of $\underline{F} = 0$

Newton's Laws of Motion:

- **Newton's Second Law**: The second law states that the rate of change of momentum of a body over time is directly proportional to the force applied, and occurs in the same direction as the applied force:

  Mathematically, $\underline{F} = d\underline{p}/dt$

  $\underline{p} = m\underline{v}$ $\Rightarrow \underline{F} = d(m\underline{v})/dt$

  $\Rightarrow \underline{F} = m\, d\underline{v}/dt$ (if m is constant)

  $\Rightarrow \underline{F} = m\, \underline{a}$ (a is acceleration)

If mass is constant during the motion, the law can also be stated as: the acceleration produced in a body is directly proportional to the force applied on it.

Newton's Laws of Motion:

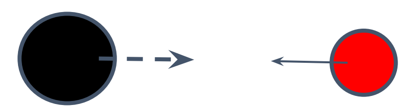
➢ **Newton's Third Law (Law of action-reaction):** Every action has an equal and opposite reaction. OR
The third law states that all forces between two objects exist in equal magnitude and opposite direction:

$\underline{F}_{BA} = - \underline{F}_{AB}$

Before the collision

mass: m_A m_B

Forces: F_{AB} F_{BA}



Conservation of Linear Momentum:

- Linear momentum of a system remains conserved in an elastic collision. It means that the total momentum of a system before and after a collision remains the same.

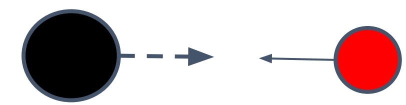
- This property can be exploited in a collision in order to calculate an unknown parameter.

- Consider two particles of mass m_A and $m_{B'}$ moving with the initial velocities of u_A and $u_{B'}$ colliding with each other:

Before the collision

mass: m_A m_B

velocity: u_A u_B



After the collision

velocity: v_A v_B

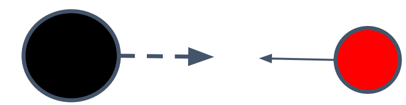
Conservation of Linear Momentum:

- Before the collision
  - mass m_A and m_B
  - initial velocities of u_A and u_B
  - Total Momentum = $m_A u_A + m_B u_B$
- After the collision
  - mass m_A and m_B,
  - final velocities of v_A and v_B
  - Total Momentum = $m_A v_A + m_B v_B$

Before the collision

mass: m_A m_B

velocity: u_A u_B



After the collision

velocity: v_A v_B

➢ Applying conservation of linear momentum:

- Momentum before = momentum after
- $\boxed{m_A u_A + m_B u_B = m_A v_A + m_B v_B}$

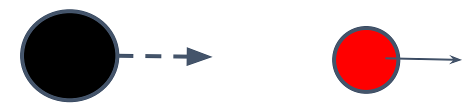
Conservation of Linear Momentum:

- **Example 1: A body of mass m was moving with a velocity of 10 m/s collides with a body of half the mass and moving with a velocity of 5 m/s in the same direction. Find out the velocity of the first body, if after the collision the lighter body is moving with 10 m/s in the direction of its earlier motion.**
- **Applying conservation of linear momentum:**
  - Momentum before = momentum after
  - $m(10) + 0.5m(5) = mv_A + 0.5m(10)$
  - $10 + 2.5 = v_A + 5$
  - $v_A = 12.5 - 5 = 7.5$ m/s

Before the collision

m 0.5 m

10 m/s 5 m/s

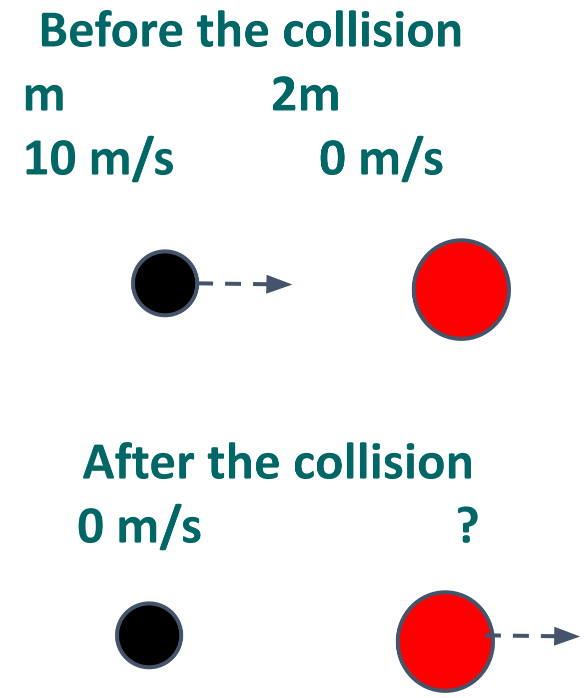


After the collision

? 10 m/s

Conservation of Linear Momentum:

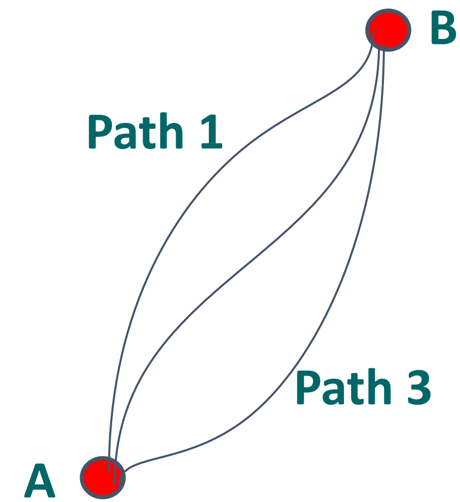
- **Quiz/Example 2: A body of mass m was moving with a velocity of 10 m/s collides with a body of double the mass at rest. Find out the velocity of the heavier body if after the collision the lighter body stops moving.**
- **Applying conservation of linear momentum:**
  - **Momentum before = momentum after**
  -



Conservative Forces:

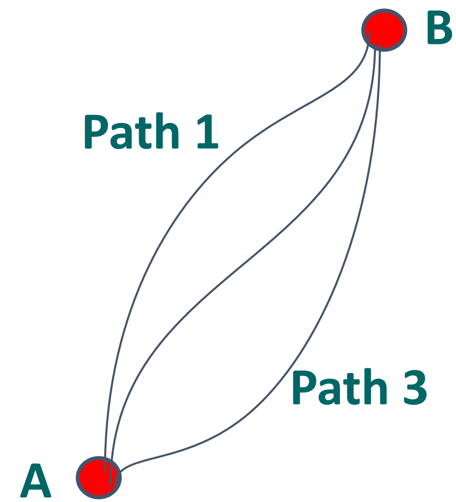
- If work done on a particle under a force in moving it from a point A to a point B is path independent, then the force is called a conservative force. Example:
  - Gravitational force, Coulombic force, usually all non-frictional forces

- In the diagram, there are three paths shown for reaching point B from point A
  - $W_{A \text{ to } B \rightarrow 1} = \int_{\rightarrow 1} f.dr$



Conservative Forces:

- In the diagram, there are three paths shown for reaching point B from point A
  - $W_{\text{A to B-->1}} = \int_{\text{-->1}} f.dr$
  - $W_{\text{A to B-->2}} = \int_{\text{-->2}} f.dr$
  - $W_{\text{A to B-->3}} = \int_{\text{-->3}} f.dr$

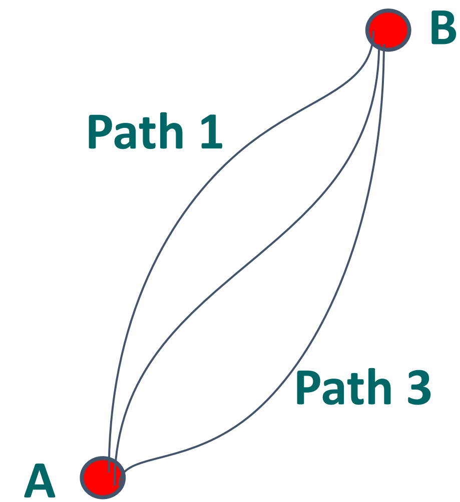


- If $W_{\text{A to B-->1}} = W_{\text{A to B-->2}} = W_{\text{A to B-->3}}$ then the force f is called a conservative force.

Non-Conservative Forces:

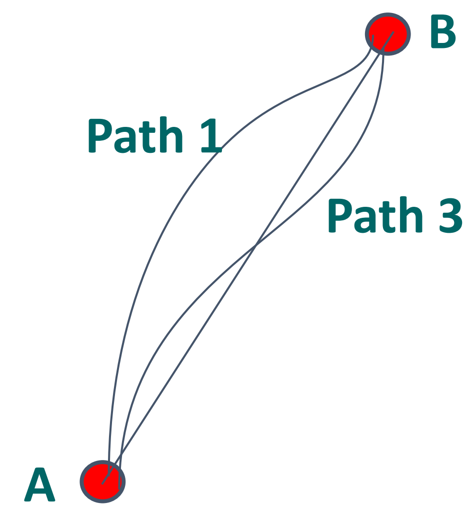
- If work done on a particle under a force in moving it from a point A to a point B is path dependent, then the force is called a non-conservative force. Example:
  - friction
  - viscous force

- In the diagram, there are three paths shown for reaching point B from point A
  - $W_{A\ to\ B\text{-->}1} = \int_{\text{-->}1} f.dr$



Non-Conservative Forces:

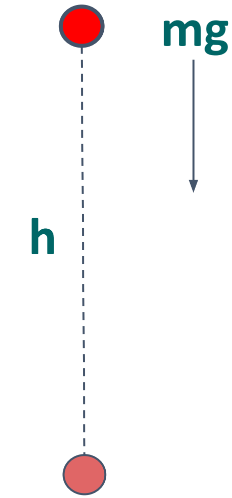
- In the diagram, there are three paths shown for reaching point B from point A
    - $W_{A\ to\ B\text{-->}1} = \int_{\text{-->}1} f.dr$
    - $W_{A\ to\ B\text{-->}2} = \int_{\text{-->}2} f.dr$
    - $W_{A\ to\ B\text{-->}3} = \int_{\text{-->}3} f.dr$



- If $W_{A\ to\ B\text{-->}1} \neq W_{A\ to\ B\text{-->}2} \neq W_{A\ to\ B\text{-->}3}$ then the force f is called a non-conservative force. Usually in non-conservative forces, longer path requires more work.

Work Energy Theorem:

- Work done on any particle/system due to the force(s) acting on it is equal to the gain in its kinetic energy
  - Work done by force(s) = Gain in KE



- Example: Consider a particle of mass m at height h from the ground. If the particle is released, find out the KE and the velocity of the particle just before hitting the ground.

- The gravitational force mg is acting on the particle. If the particle is released, the gravitational force will work on the system:

  Work done = force . displacement = mg . h = mgh

Work Energy Theorem:

- Initial KE was 0

- According to the work energy theorem

  Gain in KE = work done on the particle

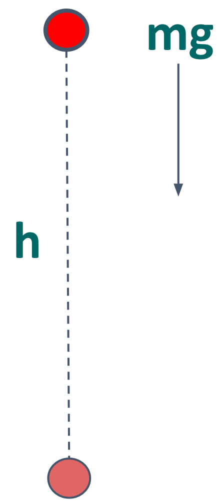
  Final KE - Initial KE = m g h

  $$\boxed{\text{Final KE} = m\,g\,h}$$

- Velocity just before hitting the ground:-

  $$(½)\, m\, v^2 = m\, g\, h$$

  $$\boxed{v = \text{sqrt}(2\, g\, h)}$$



Work Energy Theorem:

- **Example: A ball of 500 gm travelling with a velocity of 108 km/h was hit by a hammer, causing the velocity of the ball to be double of its earlier velocity in the same direction. considering no other energy loss, calculate the work done by the hammer.**

108 km/h
= 108*1000/(60*60) m/s
= 30 m/s

Work done = Final KE - Initial KE

$= (\frac{1}{2})\, m\, [\, (60)^2 - (30)^2]$

$= (\frac{1}{2})\, (\frac{1}{2})\, [\, 90 * 30]$

$= 45 * 15$

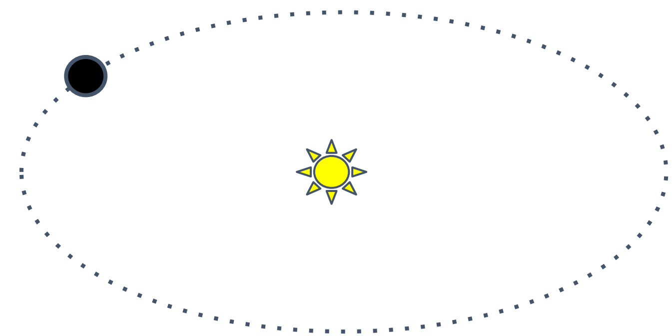
$= 675$ J

Periodic Motion:

- Motion which repeats itself after a fixed period of time is called a periodic motion.

- The path of periodic motion may be symmetric or asymmetric, as long as it repeats the path in a fixed period of time.

- Example: motion of a planet around the sun, clock, etc.



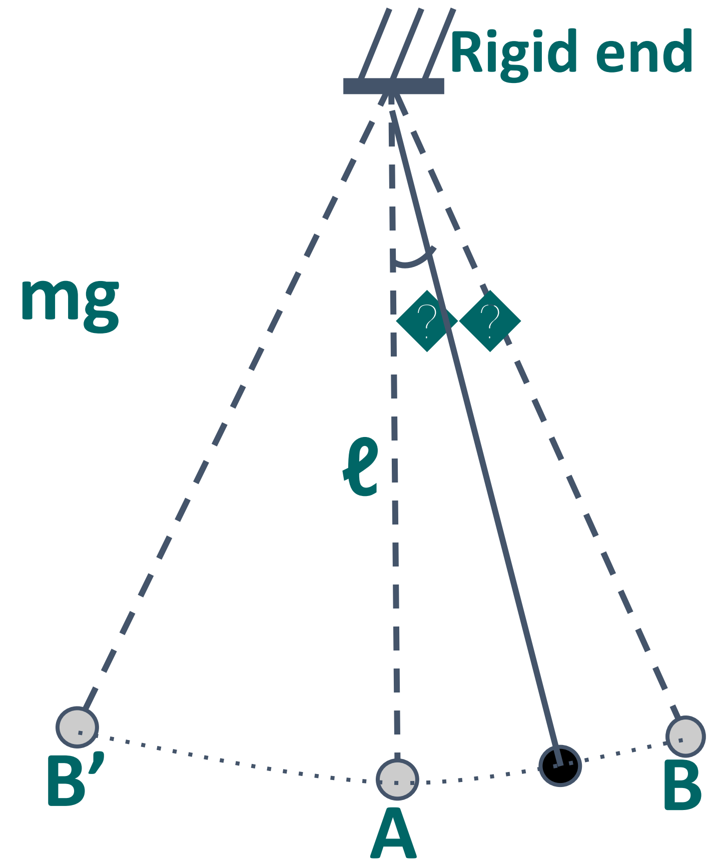
The motion of a planet around the sun

Oscillatory Motion:

- If a system executes to-and-fro motion about a fixed mean point with a fixed time period of the oscillation, the motion is termed as an oscillatory motion.

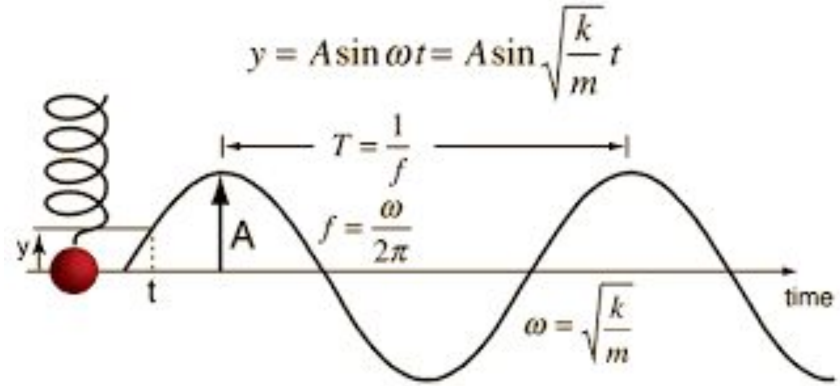
- All oscillatory motions are periodic, but not all periodic motions are oscillatory motions.

- Example: Loaded spring, simple pendulum, etc.



Harmonic Oscillatory Motion:

- When oscillatory motion of a system can be expressed in terms of harmonic functions (sine or cosine), the motion is termed a harmonic motion.
  - $y = A\cos(\omega t + \phi)$



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- All SHM are harmonic motions but all harmonic motions may not necessarily be SHM.

- Example: Loaded spring, simple pendulum, etc.

Simple Harmonic Motion (SHM):

- A specific category of motion in which,

    - The restoring force is always directed towards the fixed or mean point.
    - To-and-from motion about a fixed mean point. (Oscillatory)

    - the motion of the system can be expressed in terms of harmonic functions (Harmonic Oscillatory)

    $$y = A\cos(\omega t + \phi)$$

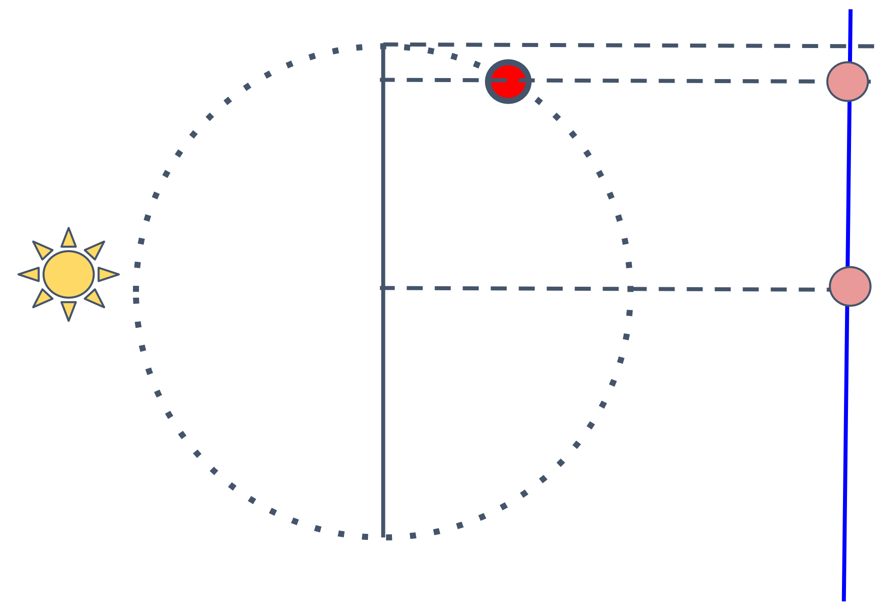
    - The restoring force is proportional to the displacement (y) and opposite in direction (Simplified, so call it that way)

    $F \propto -y \quad ===> \quad F = -k\,y \qquad$ (k constant of proportionality)

Simple Harmonic Motion (SHM):

- **An ideal SHM**
  - consider a particle moving with a constant angular velocity ω on a circle of radius R.
  - Consider the projection of particle's motion on y axis from the centre of the circle.
  - The motion of the projected point is executing a SHM with amplitude R

$$y = R\cos(\omega t + \phi)$$



Simple Vs Complex Harmonic Motion:

- We discussed earlier that the fundamental requirement for Harmonic motion to be considered as SHM is
  - Restoring force ∝ the displacement

    $F = -k\,y$ (k constant of proportionality)

- In reality, this would be true only in an ideal case and there are always non-linear terms (square, cube, etc.) present in the equation that governs this motion. In general terms, it should somewhat resemble:
  - $F = k_1\,y + k_2\,y^2 + k_3\,y^3 + k_4\,y^4 \ldots$

    where k_1, k_2, k_3, k_4 etc are constants, the minus sign can be absorbed in k

Simple Vs Complex Harmonic Motion:

- Consider we worked on the motion of a particle $F_{SHM} = k\,y$, but later found out that the true nature is somewhat complex with equation $F_{CHM} = ky + k_2\,y^3$ where k_2 is another constant. If $k_2 = k$, then find out F_{SHM}/F_{CHM} values for (a) $y = 0.5$; (b) $y = 0.1$; (c) $y = 0.05$

Displacement	F_{SHM}	F_{CHM}	F_{SHM}/ F_{CHM}
0.50	k(0.5)	k(0.625)	80%
0.10	k(0.10)	k(0.101)	99%
0.05	k(0.05)	k(0.050125)	99.75%

A harmonic motion can be approximated as SHM, if the amplitude of oscillation is small.

Value of k in SHM:

- Consider a particle of mass m displaced to "$y = y_1$" from the mean/rest "$y= 0$" position and it started executing SHM ($y = R\cos\omega t$). Find out k in terms of m and ω

  - $\underline{F} = -k\,\underline{y} = m\,\underline{a} = m\,d^2\underline{y}/dt^2$
  - $d^2\underline{y}/dt^2 = -(k/m)\,\underline{y}$
  - $-R\,\omega^2\cos\omega t = -(k/m)\,R\cos\omega t$
  - $\omega^2 = k/m$
  - $\boxed{k = m\omega^2}$

$y = R\cos\omega t$

$d\underline{y}/dt = R(-\sin\omega t)\,d(\omega t)/dt$

$d\underline{y}/dt = R(-\sin\omega t)\,\omega\,(1)$

$d\underline{y}/dt = -\omega R\sin\omega t$

$d^2\underline{y}/dt^2 = (-\omega R)\cos\omega t\,d(\omega t)/dt$

$d^2\underline{y}/dt^2 = (-\omega R)\cos\omega t\,\omega\,(1)$

$d^2\underline{y}/dt^2 = -\omega^2 R\cos\omega t$

Potential Energy in SHM:

- Consider a particle of mass m displaced to "$y = y_1$" from the mean/rest "$y = 0$" position and it started executing SHM. Find out the potential energy of the system at "$y = y_1$".

  - In SHM: $\underline{F} = -k\,\underline{y}$
  - Potential Energy gained = work done on the system = W

  Potential Energy gained = $\int_{0 \text{ to } y1} \underline{F} \cdot \underline{dy}$

  Potential Energy gained = $-k \int_{0 \text{ to } y1} \underline{y} \cdot \underline{dy}$ = $-k \int_{0 \text{ to } y1} (\cos(0))\, y dy$

  Potential Energy gained = $-k \int_{0 \text{ to } y1} y\, dy$ = $-(k/2)\, [y^2]_{0 \text{ to } y1}$

  Potential Energy gained = $-(k/2)\, y_1^2$

$$\boxed{\text{Potential Energy} = (½)ky^2 = (½)m\omega^2 y^2}$$

Kinetic Energy in SHM:

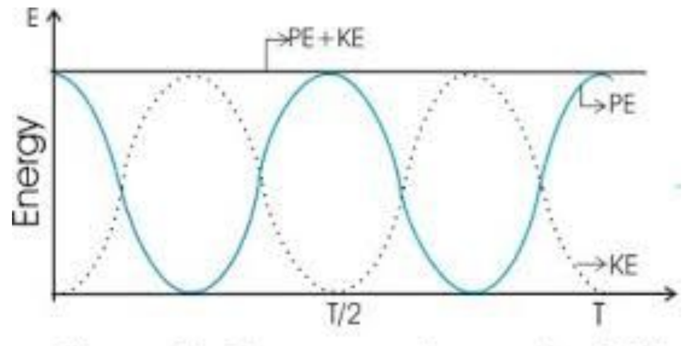
- Consider a particle of mass m displaced to "$y = y_1$" from the mean/rest "$y = 0$" position and it started executing SHM ($y = R\cos\omega t$). Find out the KE

  - $KE = (½)m\,\underline{v}^2 = (½)m\,(dy/dt)^2$
  - $KE = (½)m\,(R\omega \sin\omega t)^2 = (½)m\,[R^2\omega^2 \sin^2\omega t]$
  - $KE = (½)m\,[R^2\omega^2 (1 - \cos^2\omega t)] = (½)m\,[R^2\omega^2 - (R\omega\cos\omega t)^2]$
  - $KE = (½)m\,[R^2\omega^2 - \omega^2(R\cos\omega t)^2] = (½)m\,\omega^2\,[R^2 - y^2]$

  - $\boxed{KE = (½)m\,\omega^2\,[R^2 - y^2]}$

Total Energy in SHM:

➢ Consider a particle of mass m displaced to "$y = y_1$" from the mean/rest "$y= 0$" position and it started executing SHM ($y = R\cos\omega t$). Find out the TE



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- Total Energy = KE +PE
- Total Energy = $(½)m\,\omega^2 [R^2 - y^2] + (½)m\omega^2 y^2$
- Total Energy = $(½)m\,\omega^2 R^2 - (½)m\,\omega^2 y^2 + (½)m\omega^2 y^2$
- $\boxed{\text{Total Energy} = (½)m\,\omega^2 R^2}$

This means that the total energy in SHM remains constant at any given point of time.

UNIT-2 Electromagnetism

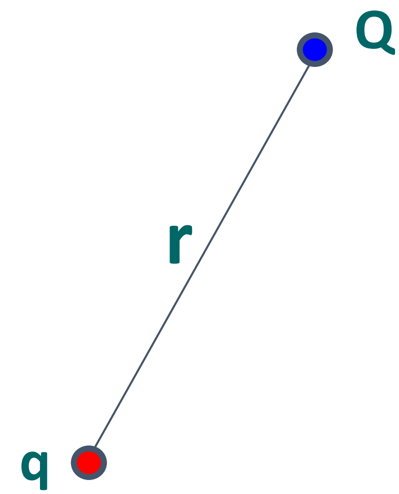
Unit 2: Electromagnetism

Coulomb's law; Superposition principle; Concept of electric field and electric potential: Gauss's law, Simple applications of Gauss's law; Electric Current and current density: Ohm's law, Combination of resistors in series and parallel; Salient features of electromagnetic spectrum.

Coulomb's Law:

- According to Coulomb's Law, the force on a charge Q due to a point charge q (at rest) at a distance r away is:

  - Proportional to Q : $\underline{F} \propto Q$
  - Proportional to q : $\underline{F} \propto q$
  - Proportional to $1/r^2$: $\underline{F} \propto 1/r^2$
  - Combining the three: $\underline{F} \propto qQ/r^2$
  - $\boxed{\underline{F} = A\, Qq/\underline{r}^2}$



Metallic sphere

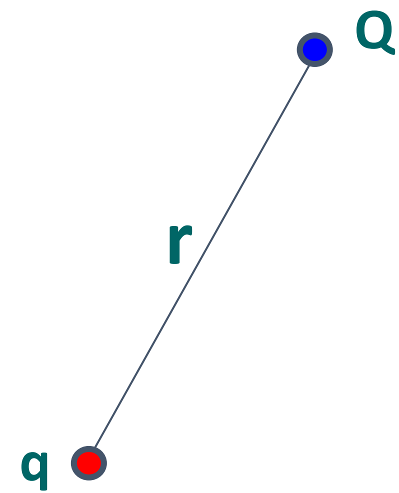
Coulomb's Law:

- where A is the constant of proportionality and in SI units it is written as $A = 1/(4\pi\epsilon_o)$
  ϵ_o being the permittivity of the free space. The value of ϵ_o in SI units is $8.85 \times 10^{-12}\ C^2/(Nm^2)$

- The force on a test charge Q due to a single point charge q (at rest) at a distance r away is given by Coulomb's Law:

  $$\boxed{\underline{F} = 1/(4\pi\epsilon_o)\ Qq/\underline{r}^2}$$

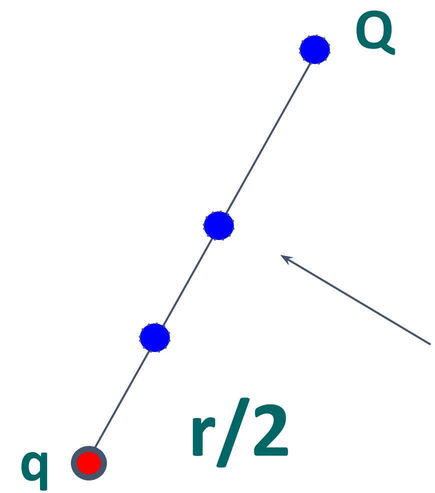
  where ϵ_o is the permittivity of free space.



Coulomb's Law:

➢ **Example: F is the coulomb's force exerted by a charge q on a test charge Q when the separation between them is r. Find out the value of the coulomb force, when the separation is: (A) reduced to half and (B) increased twice**

$\underline{F} = 1/(4\pi\epsilon_o)\ Qq/\underline{r}^2$



(a) $\underline{F}_A = 1/(4\pi\epsilon_o)\ Qq/(\underline{r/2})^2 = 1/(4\pi\epsilon_o)\ 4Qq/\underline{r}^2$

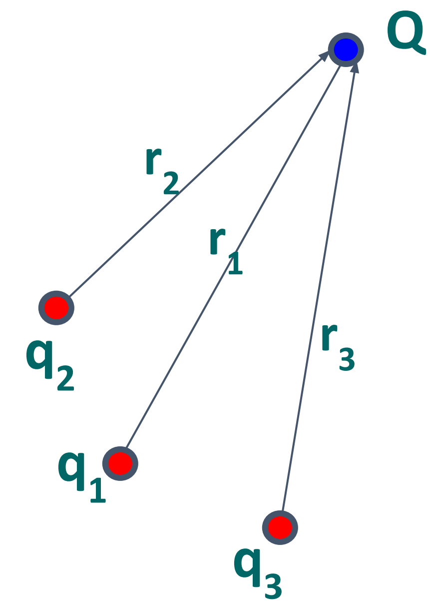
$\underline{F}_A = 4\ [1/(4\pi\epsilon_o)\ Qq/\underline{r}^2] \qquad = 4\underline{F}$

(b) $\underline{F}_A = 1/(4\pi\epsilon_o)\ Qq/(2\underline{r})^2 = 1/(4\pi\epsilon_o)\ Qq/4\underline{r}^2$

$\underline{F}_A = (1/4)\ [1/(4\pi\epsilon_o)\ Qq/\underline{r}^2] \quad = \underline{F}/4$

Superposition Principle:

➢ The interaction between any two charges is completely unaffected by the presence of other charges. This means that to determine the force on a test charge Q, we can compute individual forces F_1, F_2, .. due to charges q_1, q_2, … The net force F on Q would be the sum of $F_1 + F_2 + \ldots$



➢ $\boxed{F = F_1 + F_2 + \ldots}$

➢ $F = 1/(4\pi\epsilon_o) \quad [\, Qq_1/r_1^{\,2} + Qq_2/r_2^{\,2} + \,..]$

Electric Field:

- A field of influence by a point charge q in its vicinity, where another test charge Q experiences a coulombic force (attractive or repulsive) is called an electric field $\underline{E}$ by the charge q.

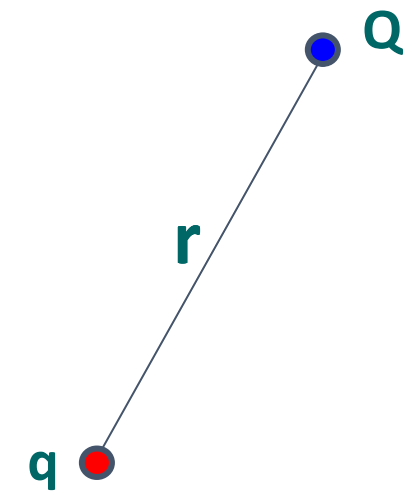
$$\boxed{\underline{E} = 1/(4\pi\epsilon_o)\ q/\underline{r}^2}$$

If we recall the Coulomb's Law

$$\underline{F} = 1/(4\pi\epsilon_o)\ Qq/\underline{r}^2 \qquad = Q\ [1/(4\pi\epsilon_o)\ q/\underline{r}^2]$$

$$\underline{F} = Q\ [1/(4\pi\epsilon_o)\ q/\underline{r}^2]$$

$$\boxed{\underline{F} = Q\ \underline{E}} \qquad \Rightarrow \boxed{\underline{E} = \underline{F}/Q}$$



Gauss's Law:

- **Maxwell's equations: A succinct version of entire electromagnetism is contained in four fundamental equations that are called Maxwell's equations.**

- **1.** $\boxed{\oint \underline{E} \,.\, d\underline{S} = q_{inc}/\epsilon_o \qquad \ldots(1)}$ **(Gauss's Law)**

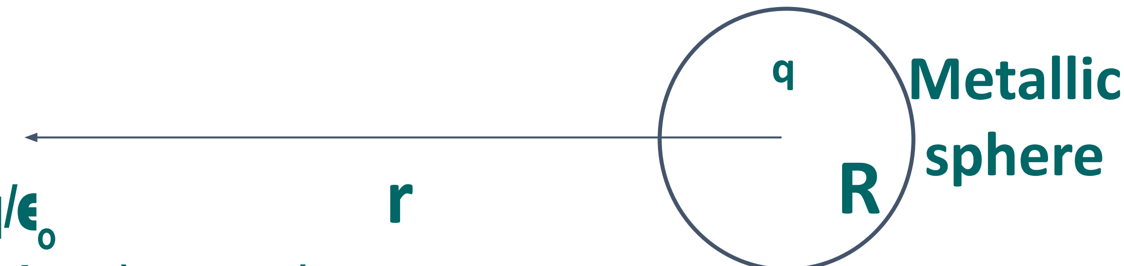
The above equation is also called Gauss's Law in electrostatics. The equation implies that an electric field is produced by electric charges.

- **This law is helpful in finding out the magnitude of the electric field in a situation of symmetric geometry.**

Applications of Gauss's Law:

- **Example:** Consider a small charge q inside a metallic sphere of radius R, find out the field at distance r (>>R).

Consider an imaginary sphere of radius (just smaller than) r, due to symmetry the magnitude of E filed would be same everywhere



$\oint \underline{E} \cdot d\underline{S} = q/\epsilon_o$

$|\underline{E}| \oint \underline{n} \cdot d\underline{S} = q/\epsilon_o$

$|\underline{E}|$ (Area of the sphere) $= q/\epsilon_o$

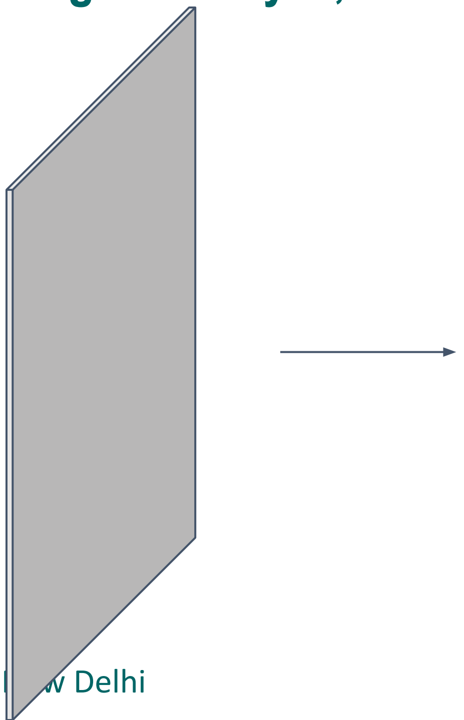
$|\underline{E}|\, 4\pi r^2 = q/\epsilon_o$

$$\boxed{|\underline{E}| = 1/(4\pi\epsilon_o) \quad (q/r^2)}$$

Applications of Gauss's Law:

- **Example:** Consider a small charge q inside a metallic sphere of radius R, find out the field at distance r (>>R).

- **Example:** Consider an infinite thin metal sheet of charge density σ, find out the field at distance d from the sheet.

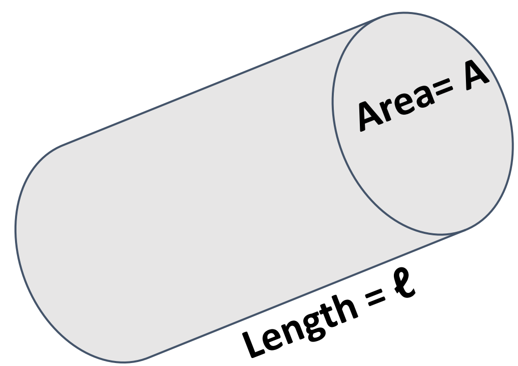


Electrical Conductivity

- Electrical conductivity (σ) is an intrinsic property of any material. It is Inverse of electrical resistivity (also called specific resistivity ϱ). Consider a conductor with cross sectional area A and length l, having resistance R

$\sigma = 1/\varrho$

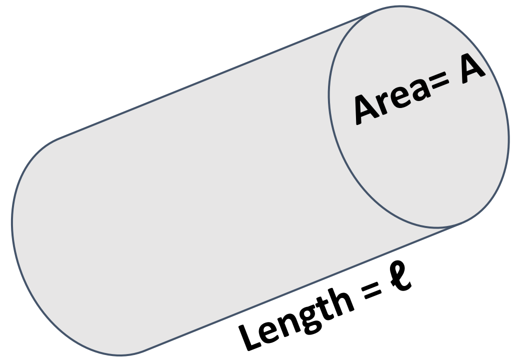
and $\varrho = R\,\ell/A$

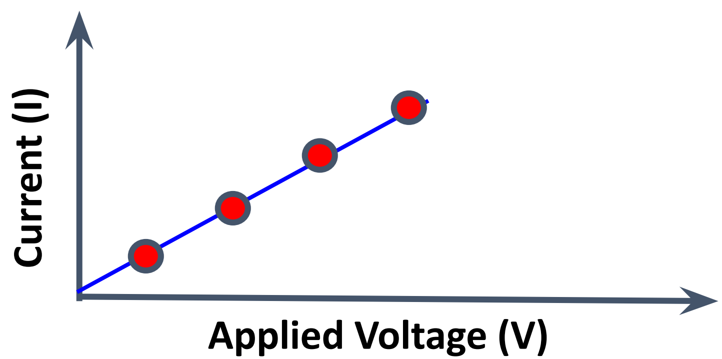


Ohm's Law:

- Current in a conductor is linearly proportional to the voltage applied across it: I ∝ V
- I = V/R

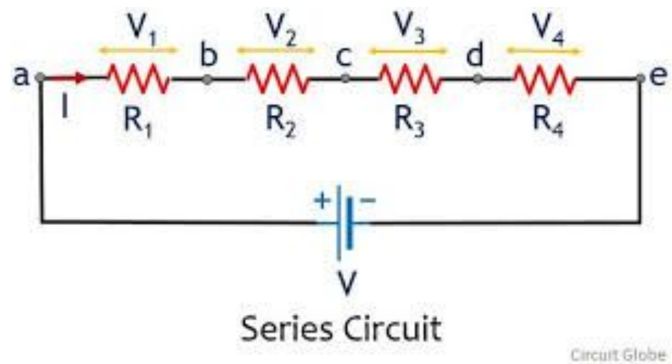
The inverse of the constant of proportionality is called Resistance (R) of the conductor.





Resistors in Series:

- Overall resistance of multiple resistors connected in a series (R) $= R_1 + R_2 + R_3 + R_4$ and so on



Circuitglobe.com

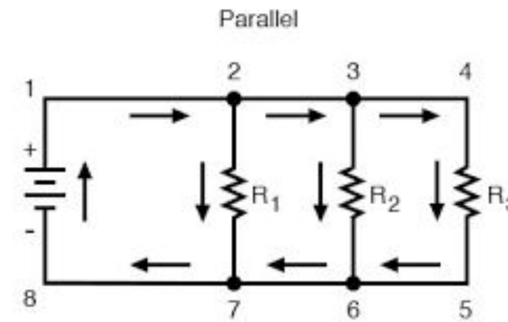
- Example find out the overall resistance of a circuit if 4 resistors of 100 Ω, 200 Ω, 400 Ω and 600 Ω are connected in series.

R= 100 + 200 + 400 + 600 Ω

R= 1300 Ω

Resistor in parallel:

- Overall resistance (R) of multiple resistors connected in parallel
  $(1/R) = 1/R_1 + 1/R_2 + 1/R_3$ and so on



Allaboutcircuits.com

- Example find out the overall resistance of a circuit if 3 resistors of 200 Ω, 300 Ω and 600 Ω are connected in parallel.

$1/R = 1/200 + 1/300 + 1/600\ \Omega$

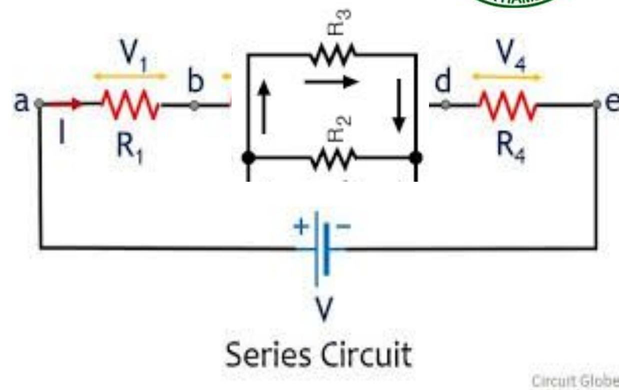
$1/R = (3+2+1)/600\ \Omega$

$1/R = 1/100\ \Omega$

$R = 100\ \Omega$

Combination of Resistors:

- ➢ Example find out the overall resistance of a circuit if 2 resistors 200 Ω, 100 Ω and a combination of 2 resistors in parallel are connected in series. The two resistors in parallel are of value 300 Ω and 600 Ω.



R1 = 200 Ω; R2 = 300 Ω; R3 = 600 Ω; R4 = 100 Ω

First we need to calculate the overall resistance from the two resistors in parallel:

$1/R = 1/R2 + 1/R3 \quad \Rightarrow \quad 1/R = 3/600 \quad \Rightarrow \quad R = 200\ \Omega$

Total Resistance of the circuit = R1+ R + R4

= 200 + 200 + 100 Ω

= 500 Ω

Allaboutcircuits.com

EM Spectrum

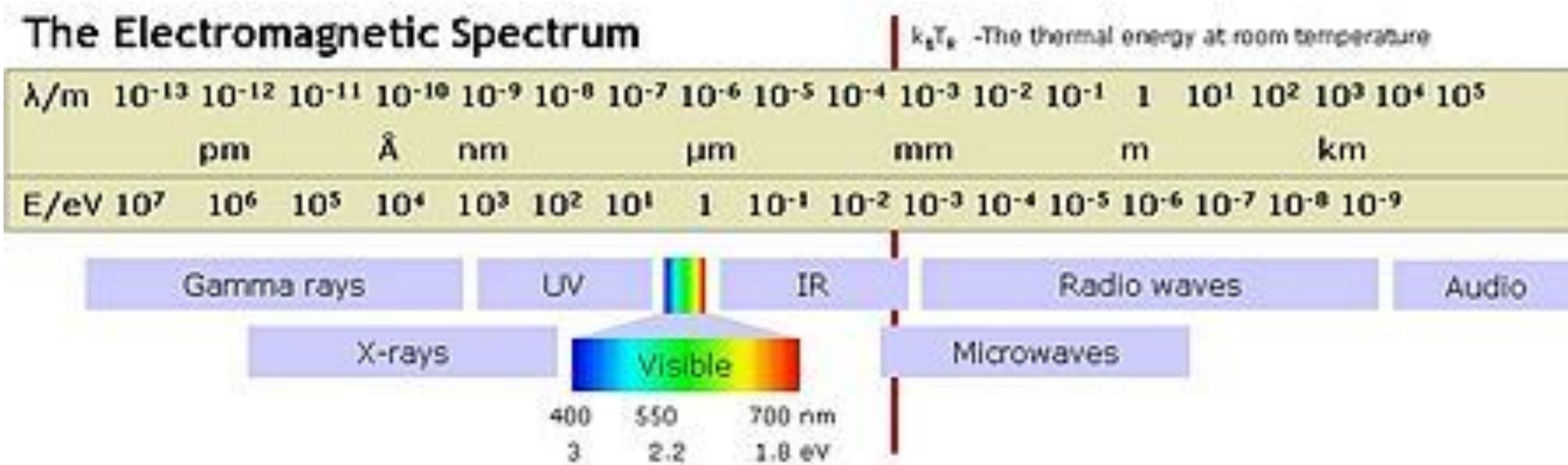
- Visible part of the spectrum is the most common and popularly known EM radiation. Usually the wavelength classified in the range of (violet/blue) 400 nm to 700 nm (red).

- Visible spectrum is popularly known as consisting of VIBGYOR colours. In terms of energy, 3 eV (violet/blue) to 1.8 eV (red).

- Infrared -> lesser than red (in energy).
- Ultraviolet -> Higher than violet (in energy).

- Ultraviolet -> Visible (VIBGYOR) -> Infrared

EM Spectrum



The Electromagnetic Spectrum. Image courtesy: **wikipedia.com**

EM Spectrum

- X-ray photons are higher in energies than UV/Visible light but are lower than gamma rays.

- Wavelength and energy (as well as Frequency) have inverse relationship. Meaning: λ(UV/Visible) > λ(X-ray) > λ(gamma-ray)

- Energies of X-rays are in the range 100 eV to 10,000 eV. Typical energy of an x-ray photon is 1 keV and wavelength 1 nm.

- Visible (2 eV, ~600 nm); UV (20 eV, ~50 nm); X-ray (1 keV, ~1 nm); and gamma-ray (1 MeV, ~0.001 nm)

Energy Calculation in eV

- EM waves travel with the velocity of $c = 3 \times 10^8$ m/s

- EM photons energy wavelength relationship
  - $\boxed{E \text{ (in Joule)} = hc/\lambda}$ (SI unit) where
    - h is Planck's constant = 6.6×10^{-34} J/s
    - c (speed of light) = 3×10^8 m/s
    - to convert energy in eV divide by the charge of electron (1.6×10^{-19} C)and change wavelength in nm by multiplying energy with 10^9, the expression becomes: $\boxed{E \text{ (in eV)} = 1240/\lambda \text{(in nm)}}$

Energy Calculation in eV

- For a reference band gap: Si (~1.1 eV); Ge(~0.7 eV)

- Example 1: Energy of light with wavelength 620 nm (yellow-orange light)
  - E = 1240/620 = 2 eV

- Example 2: Energy of light with wavelength 413 nm (Blue-violet)
  - E = 1240/413 ~3 eV

- Quiz: Calculate Energy of light with wavelength 750 nm (Red)

Energy Calculation in eV

$$\boxed{\lambda(\text{in nm}) = 1240/\ E\ (\text{in eV})}$$

- **Example 2: Find wavelength of UV radiation with energy of 20 eV.**
  - λ(in nm) = 1240/20 = 62 nm

- **Example 3: Find wavelength of X-ray radiation with energy of 100 eV.**
  - λ(in nm) = 1240/100 = 12.4 nm

- **Example 4: Find wavelength of X-ray radiation with energy of 1240 eV.**
  - λ(in nm) = 1240/1240 = 1 nm (Mg Kα standard anode 1253.7 eV)

- **Example 5: Find wavelength of gamma-ray with energy of 5 MeV.**
  - λ(in nm) = $1240/(5\ \text{x}10^6)$ = $2.48\ 10^{-4}$ nm

Numerical Example

- An excited electron at an atomic level with the binding energy of -25 eV, relaxes to a stable atomic level with binding energy of -125 eV. Find out the wavelength of the photon released during the relaxation process. Also comment in which part of the EM spectrum such photons would be placed.

- $E1 = -25$ eV; $E2 = -125$ eV; λ =?; Part of EM = ?

  $\Delta E = E1 - E2 = 100$ eV

  Energy conservation demands: $\Delta E = hc/\lambda$

  $\lambda(\text{in nm}) = hc/\Delta E(\text{in eV}) = 1240/100 = 12.4$ nm

The λ and the process implies it is in X-ray part of the EM spectrum.

Assignment 1

- An excited electron at an atomic level with the binding energy of E1, relaxes to a stable atomic level with binding energy of -170 eV. Find out the value of E1 if the wavelength of the photon released during the relaxation process is 8 nm.

- An excited e^- at an atomic level with the binding energy of -10 eV, relaxes to a stable atomic level with binding energy of E2. Find out the value of E2 if the wavelength of the photon released during the relaxation process is 6nm.

- An excited electron at an atomic level with the binding energy of -150, relaxes to a stable atomic level with binding energy of -1352 eV. Find out the wavelength of the photon released during the relaxation process.

Q. 1: MCQ (Attempt all) **(1 x 3)**

A. The overall resistance of two resistors of 300 Ω and 600 Ω connected in parallel is:

(a) 900 Ω (b) 200 Ω

(c) 450 Ω (d) 2 Ω

B. A periodic motion:

(a) is oscillatory (b) is not oscillatory

(c) may or may not be oscillatory (d) none of these

C. A photon with 0.85 eV energy is placed in?

(a) x-ray (b) infra red (c) radio waves (d) UV

Q. 2: Attempt any two questions (about 10 minutes each). **(2 x 3)**

A. F is the coulomb's force exerted by a charge q on a test charge Q when the separation between them is r. Find out the ration of the coulomb forces, when the separation is: (i) reduced to ⅓ and (ii) increased three times.

B. A ball of 200 gm travelling with a velocity of 10 m/s was hit by a hammer, causing the velocity of the ball to increase in the same direction. Considering no other energy loss, calculate the increased velocity if the work done by the hammer is 300 J.

C. An electron in an excited state of energy of -12.35 eV, relaxes to a stable atomic level with binding energy of -16.8 eV. Calculate the wavelength of the photon released during the relaxation process. Where such radiation should be placed in the EM spectrum? Would that change if the binding energy of the stable state is 14.95 eV.

Q. 3: Attempt all questions (about 20 minutes each). **(1 x 6)**

A. Starting from the equation y= R sin**ω**t in SHM, demonstrate that the total energy in SHM is invariant

Sessional 1

4 June 2021

15 Marks

UNIT-3: LASER

Unit 3: LASER

Conventional sources of light and LASER, Spontaneous emission, Stimulated Emission, Population inversion, Principle of LASER, Einstein's coefficients, Working of helium-neon and Ruby lasers.

Content

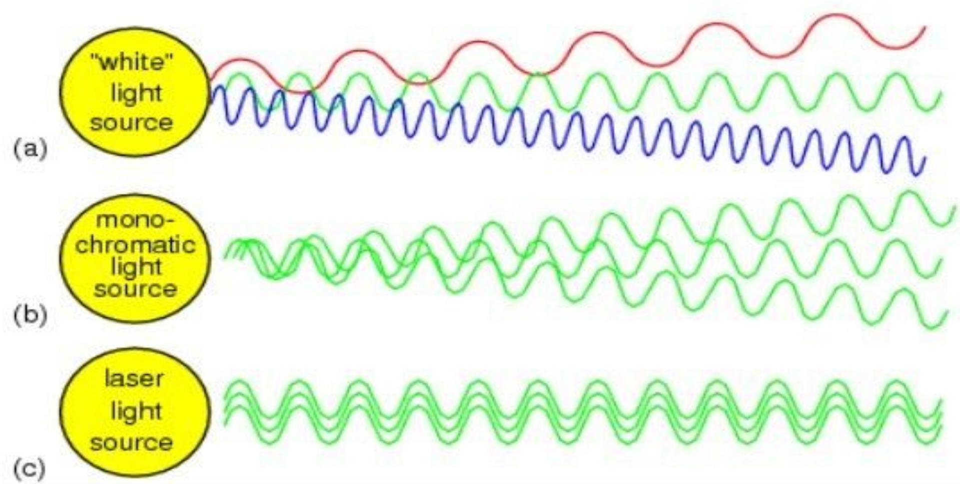
- Conventional vs Laser Light
- Spontaneous Emission
- Stimulated Emission
- Population Inversion
- Working mechanism of a Laser
- Einstein's Coefficients
- He-Ne Laser
- Ruby Laser
- Applications of Lasers

Conventional Light Source

Conventional light is usually:

- **Polychromatic:** the light contains a broad range of **multiple wavelengths**. For example a common tube light contains a good mixture of blue, green, red, etc.

- **Divergent:** the light does not propagate in a specific direction (non directional), but rather diverges as it travels further away.



Courtesy: Quora.com

Conventional Light Source

- **Low Intensity:** the light is usually of low J/cm^2 intensity and isotropic. Usually at a given distance away, the intensity is same for all theta (θ, 0-180°) and phi (ϕ, 0-360°). With the distance, the power substantially drops ($1/r^2$). Doubling the distance would reduce the power four times. Laser source would drop only a few percent in power along the propagation direction even with double or triple the distance. Slight deviation in θ and ϕ from the direction of propagation would nearly diminish the entire intensity.

- **Incoherent:** the light is in a broad mixture of phases or is non-coherent light.

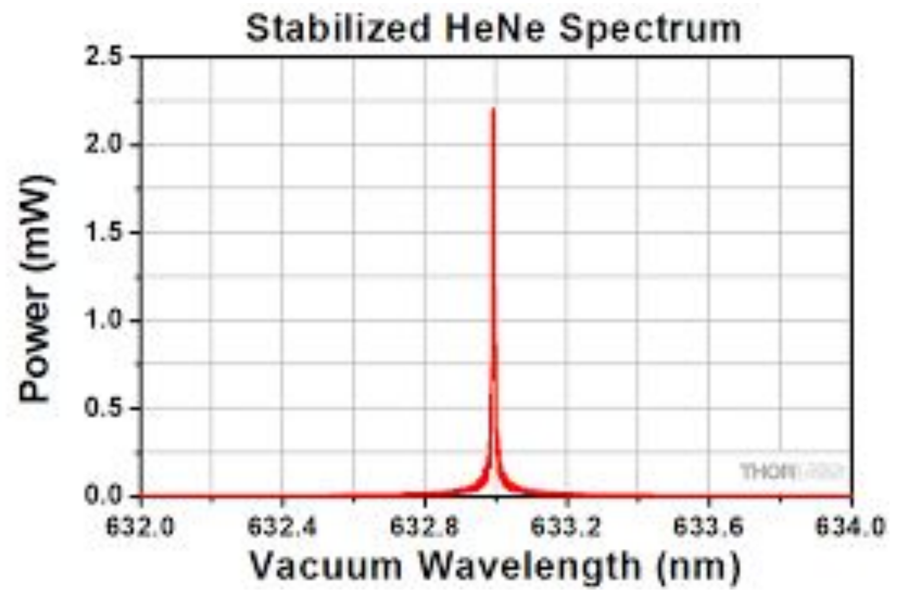
- **Spontaneous Emission:** Consists of spontaneously emitted photons

Laser Light

Laser light is usually:

- **Monochromatic:** the light contains a very narrow range of wavelengths. For example a He-Ne laser is centered around 632.9 nm with FWHM of 0.2 nm to ~10 nm.

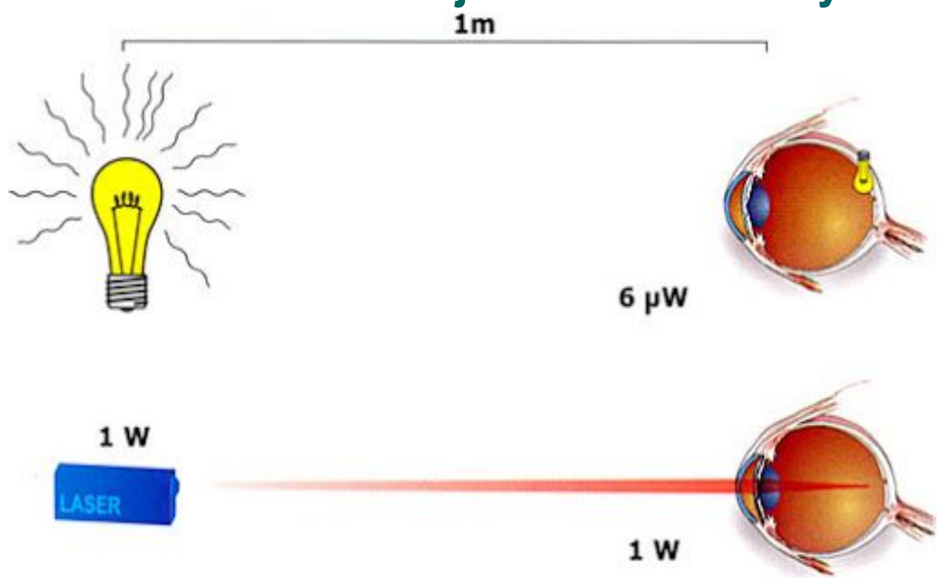
- **Highly directional:** the light propagates in a specific direction with very little divergence.



Courtesy: Thor Lab

Laser Light

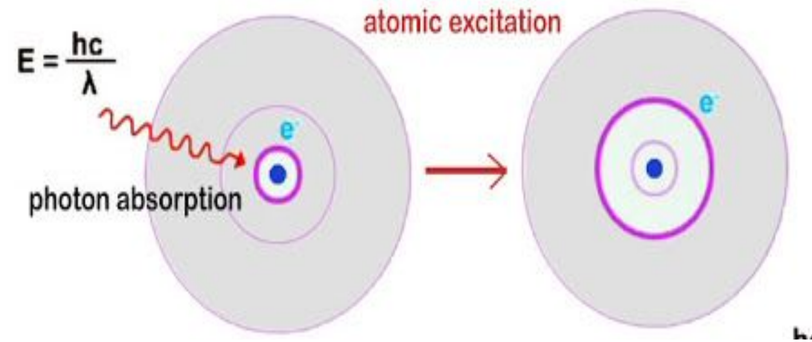
- **High Intensity:** the light is usually of high J/cm^2 intensity
- **Coherent:** the emitted light is in the same phase.
- **Stimulated Emission:** major contribution by stimulated photons



Courtesy: Westernsafety.com

Absorption

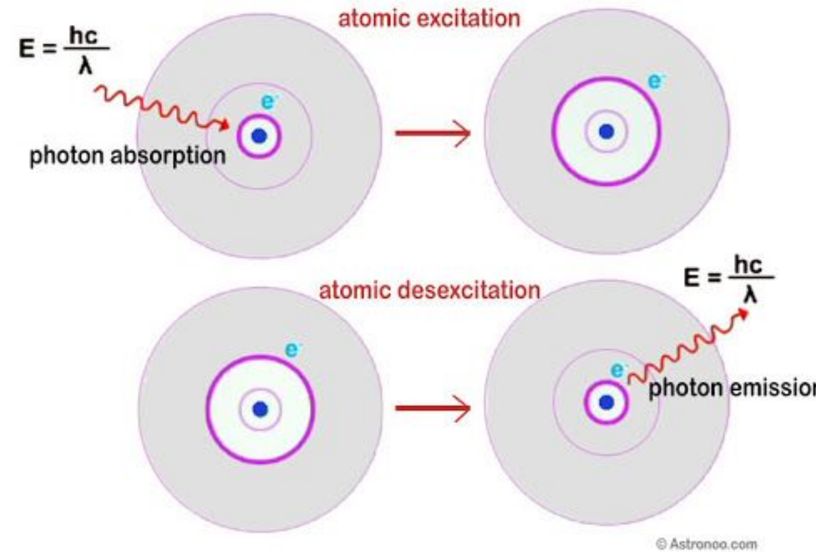
- **Absorption: When a light photon of sufficient energy falls on an electron in the atom, the e^- absorbs the photon and transition itself from ground state to a higher energy (excited) state. There are other ways, such as collision between energetic atoms, through which an e^- can get to an excited state. When an external mean is deliberately created to promote higher percentage of atoms with excited e^{-s} it is called pumping.**



Courtesy: astronoo.com

Spontaneous Emission

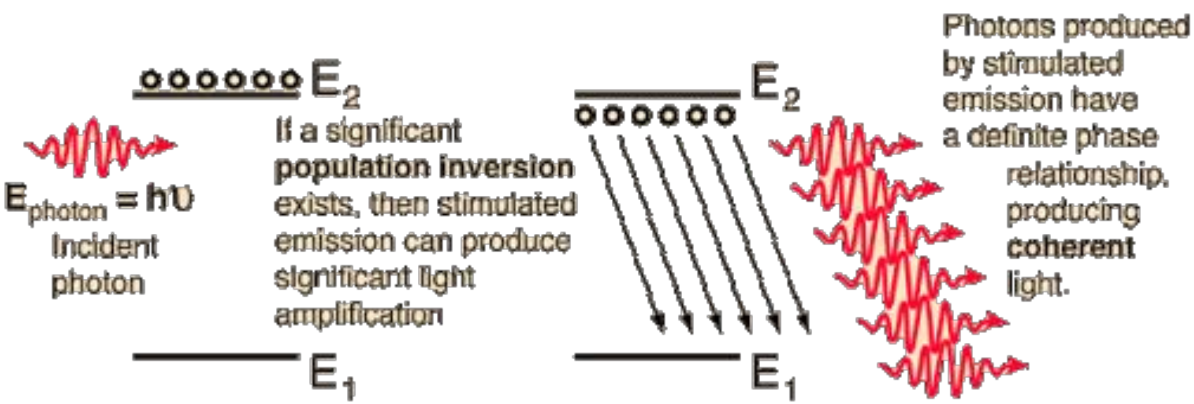
- **Spontaneous Emission: The electron in the higher state spends on average a time equivalent to the excited/higher level lifetime before emitting a photon and getting back to the ground state. Such photon emissions are called spontaneous emission. This process occurs without any external interference. In usual case, any two (or more) spontaneously emitted photons are in different directions and phases.**



Courtesy: astronoo.com

Stimulated Emission

- **Stimulated Emission: Einstein in 1917 pointed out at this possibility of emission. The excited electron (in the higher energy level and before spontaneous emission) may also relax to ground state, when "encouraged/influenced by a photon of the same energy in the vicinity of the excited atom. Thus emitted electron has the same phase and the direction as the external influencing photon. Such emissions are called stimulated emission and are one of the fundamental requirements for a laser to work.**



Courtesy: hyperphysics.com

Population Inversion

- **Pumping**: When an external mean is deliberately created to promote higher percentage of atoms with excited e^{-s} it is called pumping. Pumped atoms have a natural decay rate through which they would spontaneously emit photon and come back to the ground state. In a system where there is a metastable state, atoms would spend more time in excited metastable state before relaxing back to the ground state (through radiative/non-radiative decay).
- If an external source is applied, there would be a rate of pumping of the atoms in a system to the excited state. If the external source/mean is removed all the atoms would come back to the ground state. The rate of pumping to the excited state is obviously higher initially when there are more atoms in ground state and are thus available for pumping and the rate is lower when there are lesser atoms available in the ground state.

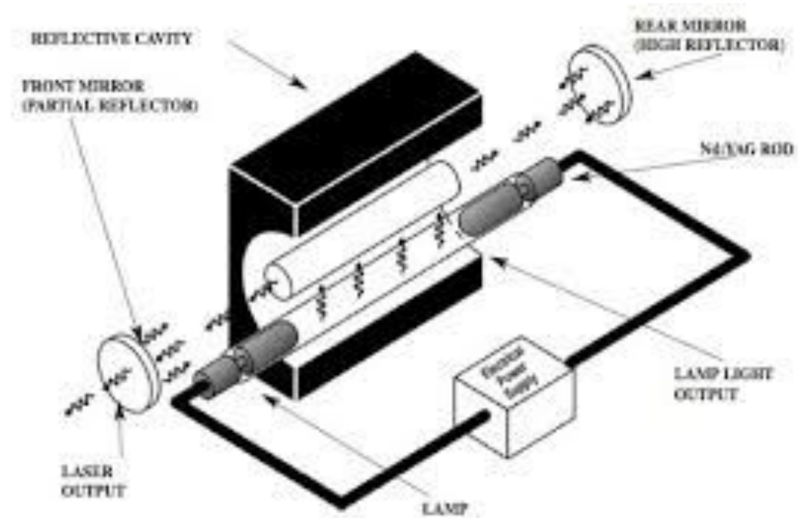
Population Inversion

- Simultaneously, there is a rate at which excited atoms would return back to the ground state (after emitting the photon). By tuning the pumping rate a condition can be achieved where the rate of pumping of atoms is higher than the rate of relaxation.

- Population Inversion: The condition (higher pumping than relaxation rate) would bring population inversion in which, in a steady state, there are more excited atoms than relaxed/ground state atoms in any system.
  In another words, "The term population inversion describes an assembly of atoms in which the majority are in energy levels above the ground state; normally the ground state is occupied to the greatest extent"

Population Inversion

- **Optical pumping: There are a number of ways to produce a population inversion. One of them, called optical pumping. In this, an external light source is used some of whose photons have the right frequency to raise ground state atoms to the excited state that decays spontaneously to the desirable metastable state.**



directedlight.com

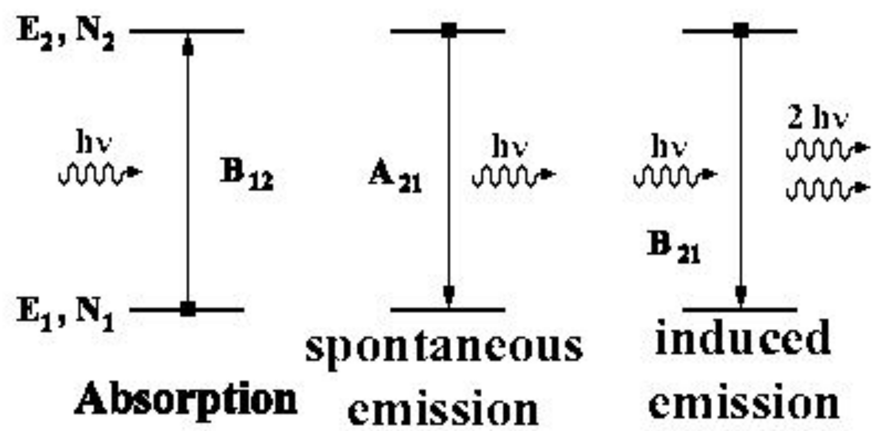
LASER: Light Amplification by Stimulated Emission of Radiation!

Einstein's Coefficients

- These are mathematical quantities describing probability of absorption and emission of light by an atom.

- Coefficients A are related to the rate of spontaneous emission.

- Coefficient B are related to the rate of absorption or stimulated emission.



Quora.com

Einstein's Coefficients

- Consider level E1(ground) and E2 (excited) with number of atoms N1 and N2 in the respective states.

- Spontaneous Emission:
  - $[dN_2/dt]_{spont.} = -A_{21} N_2$
  - $[dN_1/dt]_{spont.} = A_{21} N_2$

- Spontaneous Emission:
  - $[dN_2/dt]_{spont.} = -A_{21} n_2$

- Spontaneous Emission:
  - $[dN_2/dt]_{spont.} = -A_{21} n_2$

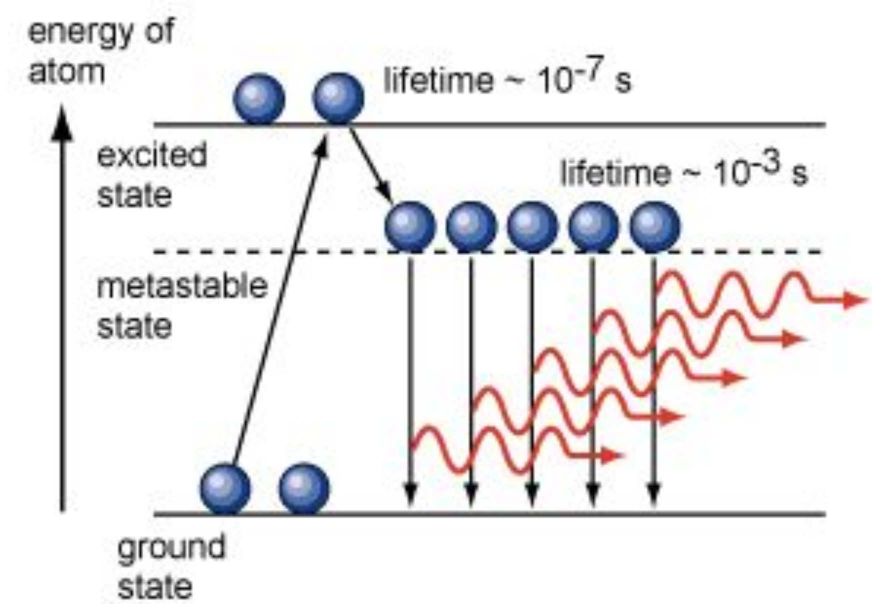
Einstein's Coefficients

- **Absorption:**
  - $[dN_1/dt]_{\text{positive abs}} = -B_{12}\, n_1 \varrho(\nu)$

- **Stimulated Emission:**
  - $[dN_2/dt]_{\text{negative abs.}} = B_{21}\, n_2\, \varrho(\nu)$

Three Level Laser

- **Metastable Excited State: The key to laser is the presence of at least a metastable state whose lifetime may be 10^{-3}(micro) sec than the normal excited state lifetime of 10^{-7} to 10^{-8}(100-10 nano) sec.**



tes.com

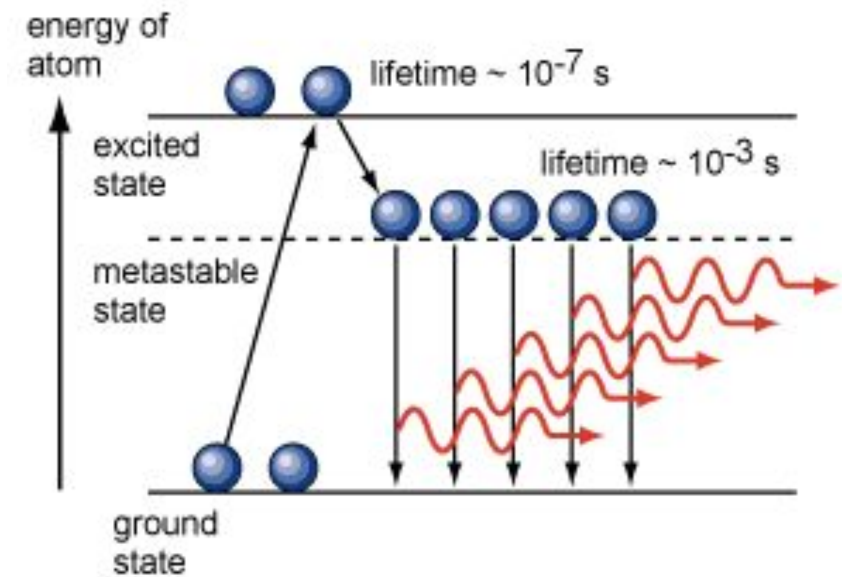
Three Level Laser

➢ In a 3-step laser:

a. ground-state atoms are first pumped to the excited state

b. atoms in excited state rapidly transition to the metastable state within 100 nano-sec by spontaneous emission.

c. an avalanche of coherent photons occurs due to stimulated emission by a photon of same energy (spontaneous or external)



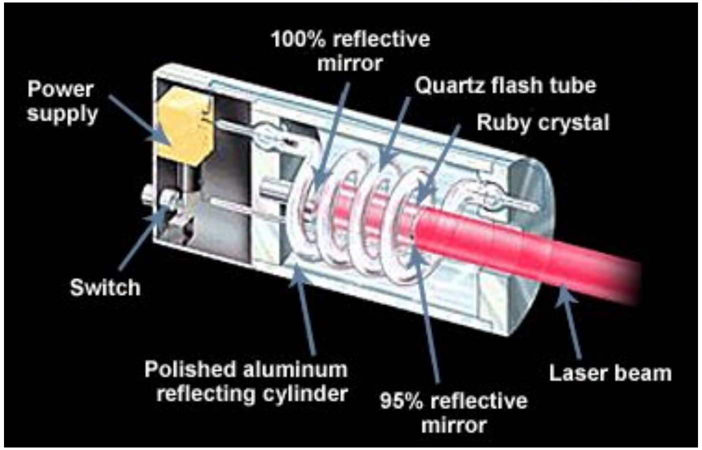
tes.com

Ruby Laser

- The first successful laser, the ruby laser is based on three energy levels in the chromium ion Cr^{3+}.
- A ruby is a crystal of Aluminium oxide (Al_2O_3) in which some of the Al^{+3} ions are replaced by Cr^{+3} ions, which are responsible for the red colour.
- A Cr^{+3} ion has a metastable level whose lifetime is about 0.003 sec.
- A xenon flash lamps excites the Cr^{+3} to an excited state from which they fall to the metastable state.

Ruby Laser

- Photons from the spontaneous decay of some Cr^{+3} ions are reflected back and forth between the mirrored ends of the ruby rod, stimulating other Cr^{+3} ions in the metastable state to radiate.
- After a few microseconds the result is a large pulse of monochromatic, coherent red light (694.3 nm) from the partly transparent end of the rod.
- The rod's length is made precisely an integral number of half wavelengths long, so the radiation trapped in it forms an optical standing wave.

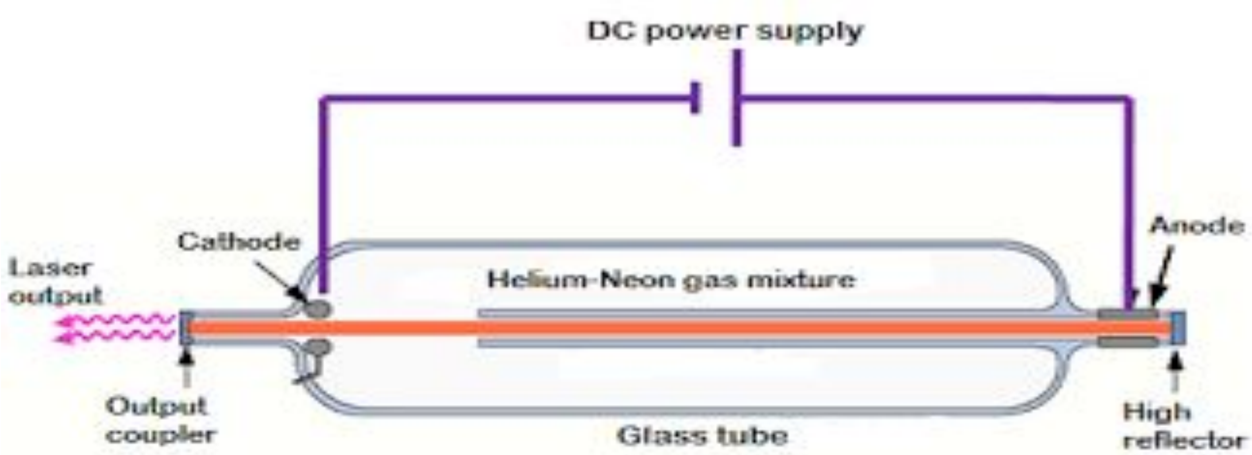


laserfest.com

He-Ne Laser

- Popular and widely used He-Ne gas mixture based laser achieves population inversion in a different way.

- 90% He and 10% Ne at a low pressure of ~1 torr is placed in a glass tube that has parallel mirrors.



physics and radio electronics.com

He-Ne Laser

- The tube length is exactly an integral multiple of half-wavelengths of the laser light.

- An electric discharge is produced in the gas by means of electrodes outside.

- Collisions with electrons from the discharge excites He and Ne atoms to metastable states respectively 20.61 and 20.66 eV above their ground state.

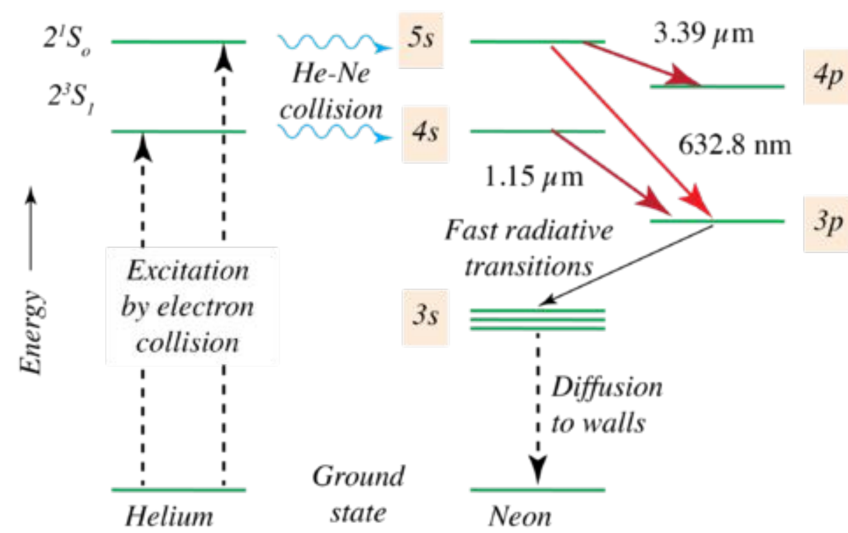
- Due to collisions, some of the excited He atoms transfer their energy to ground state Ne atoms.

He-Ne Laser

- With the additional 0.05 eV energy being provided by the Kinetic energy of the atoms

- The purpose of the He atoms is thus to help achieve a population inversion in the Ne atoms.

- The laser transition in Ne is from the metastable state at 20.66 eV to an excited state at 18.7 eV, with the emission of a 632.8 nm photon.



wikipedia.com

Application

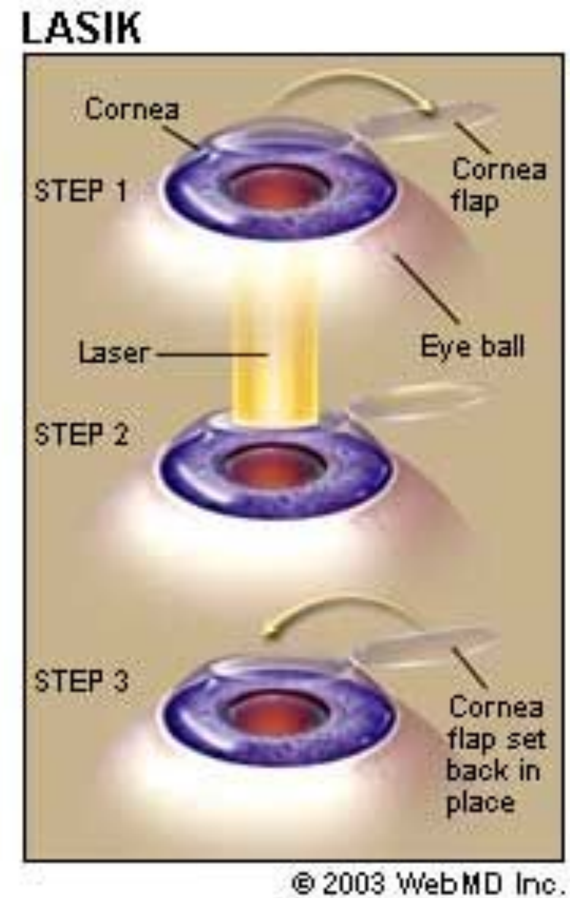
- **Laser Pointer: these lasers are much lower in energy, 5mW output in the product presented here from amazon.com**

amazon.com

Application

- There are many medical applications, where laser is used for removal of tumor, burning of unwanted skin spots, etc.

- LASIK is one of such application, where cornea flap is removed and a laser with a designed wavefront is directed at the eyeball and brings the eye back to normal or corrected eyeball level, thus removing the need for corrective glasses.



Application

- ➢ **Precision sheet cutting fiber laser**
  - **Example from bodor laser** https://youtu.be/WzIV1V1fpcc

- ➢ **High power 20kW precision sheet (20 mm SS) cutting fiber laser**

UNIT-4: Fiber Optics

<u>***Unit 4: Fiber Optics***</u>

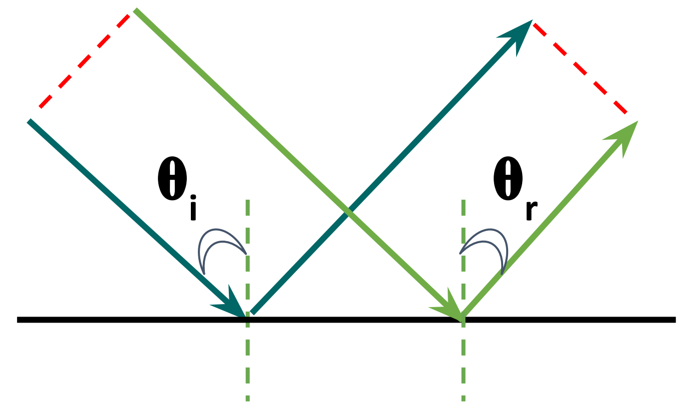
Total internal reflection, Introduction of fiber optics, Numerical aperture, Step index and graded index fibers, Attenuation and dispersion mechanism, Application of optical fibers.

Content

- Reflection, Refraction, Snell's Law
- Critical Angle, Quiz #1
- Total internal reflection, Waveguiding due to TIR
- Optical Fiber: Basic Structure
- Early Development; Advantages
- Working Mechanism, Quiz #2
- Step Index and Graded Index Fiber
- Applications
- Optical Communication

Reflection

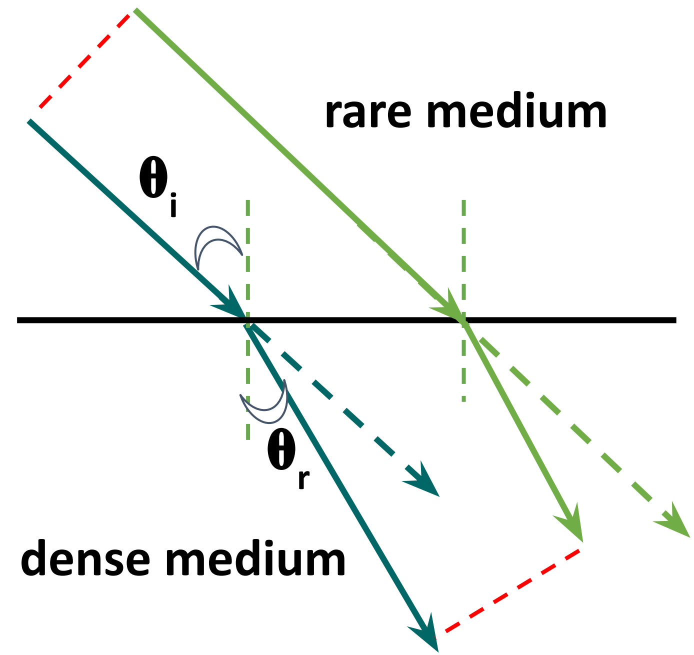
- Consider a plane wave incident on a plane mirror at an angle θ to the normal.
- One edge of the wavefront arrives earlier. Angle of incidence is equal to the angle of reflection. Rays arrive at the mirror surface and reflect back. After a distance the wavefront (ideally) regains the shape of wavefront. There is no path difference and hence no interference pattern (maxima and minima fringes) is observed.
- Try to reflect a torch light off of a plane mirror. The reflected wavefront gains back its shape.



Law of reflection: $\theta_i = \theta_r$

Refraction

- Consider a plane wave incident from a rare medium to a dense medium at an angle θ_i to the normal.
- When the beam inter the dense medium it bends towards the normal (rather than going in a straight line as marked by the dotted lines).
- This phenomenon is called refraction of light, indicating a medium with different refractive index.
- In case of light entering from a dense medium to a rare medium, the refracted light bends away from the normal.



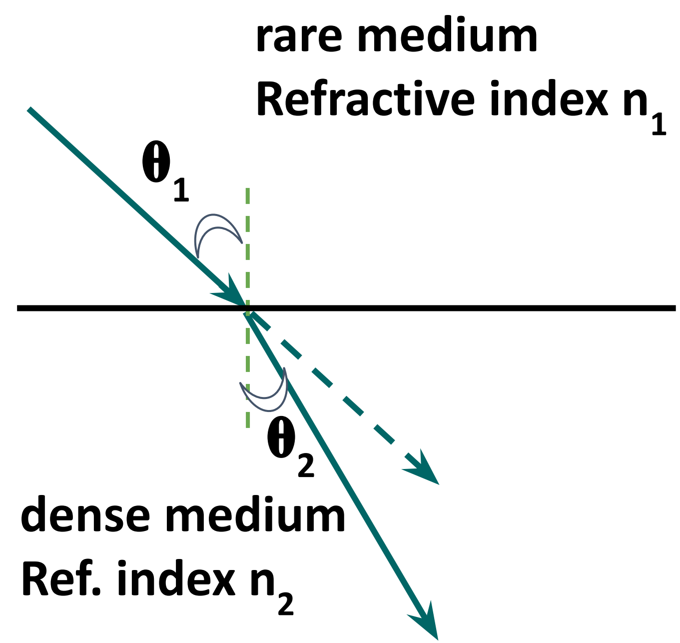
Snell's Law

- This is the relationship governing refraction from one to another isotropic medium. It states that the ratio of the sines of the angles of incidence and refraction of a wave are constant when it passes between two given media.
  - $n_1 \sin\theta_1 = n_2 \sin\theta_2$
- Example: Calculate θ_2 if the light passes from air(n_1 =1) to water (n_2 =1.33) making an angle 45° with the normal.

Ans: $1 \times \sin 45^\circ = 1.33 \times \sin\theta_2$

$\theta_2 = \sin^{-1} [1/(1.33 \times 1.41)]$

$\theta_2 = \sin^{-1} [0.533] = 32.2^\circ$ (less than 45°)



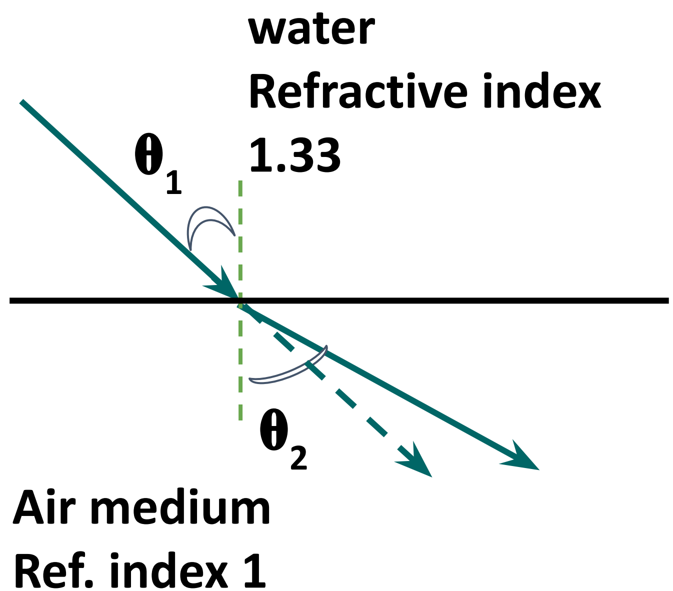
Snell's Law

- Now consider going from a dense to a rare medium, such as from water to air
- Example: Calculate θ_2 if the light passes from water(n_1 =1.33) to air (n_2 =1) making an angle 45° with the normal.

  Ans: $1.33 \times \sin 45^\circ = 1 \times \sin\theta_2$

  $\theta_2 = \sin^{-1}[1.33/1.41]$

  $\theta_2 = \sin^{-1}[0.94] = 70.6^\circ$ (more than 45°)



- Think what will happen if we further increase the angle of incidence from dense to rare medium? Can a beam make an angle ≥ 90° to the normal?

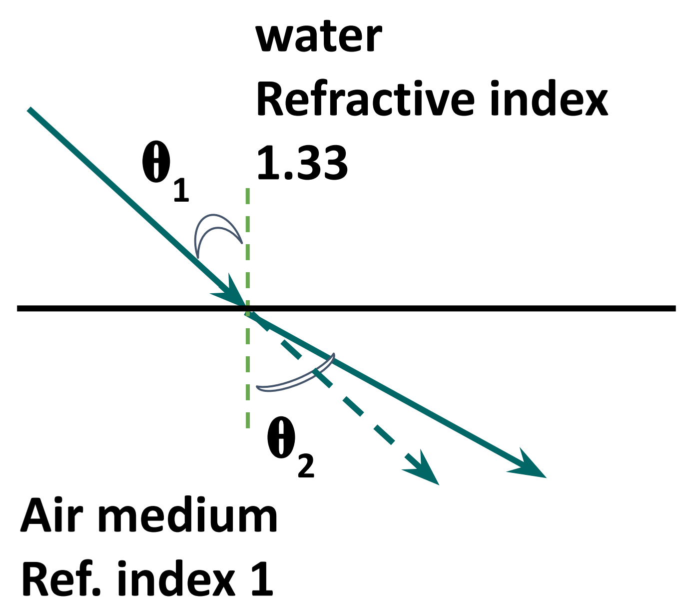
Critical Angle

- Let's increase the angle of incidence by 2°
- Example: Calculate θ_2 if the light passes from water(n_1 =1.33) to air (n_2 =1) making an angle 47° with the normal.

  Ans: $1.33 \times \sin 47° = 1 \times \sin\theta_2$

  $\theta_2 = \sin^{-1} [1.33\ 0.73]$

  $\theta_2 = \sin^{-1} [0.97] = 76.6°$ (more than 45°)



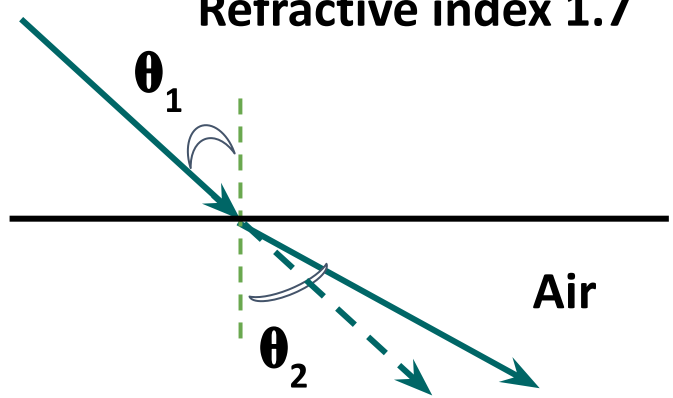
- Critical angle: For what $\theta_1$angle, $\theta_2$would become 90°?

  $1.33 \times \sin\theta_1 = 1 \times \sin 90°$

  $\theta_1 = \sin^{-1} [1/1.33] = 48.75° = \theta_{Critical}$

QUIZ #1

- Find out the critical angle for glass(1.5)-air interface.
- Many polymers used in OLED have refractive index of 1.7 and we want the light produced inside OLED to come out in air. What is the critical angle of incidence below which the light produced inside would come out in air?

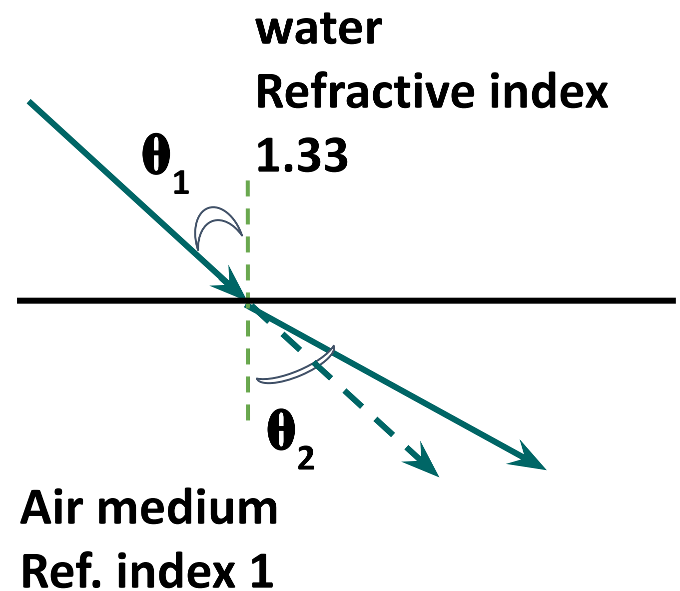


Total Internal Reflection (TIR)

- If the angle of incidence is increased beyond the critical angle, the entire incident light is reflected back in the medium of incidence itself and this phenomenon is called **Total Internal Reflection (TIR)**.

- For water-air interface angle of incidence beyond 48.75° would result in TIR.

- For glass(1.5)-air interface the angle of incidence beyond 41.8° would result in TIR.

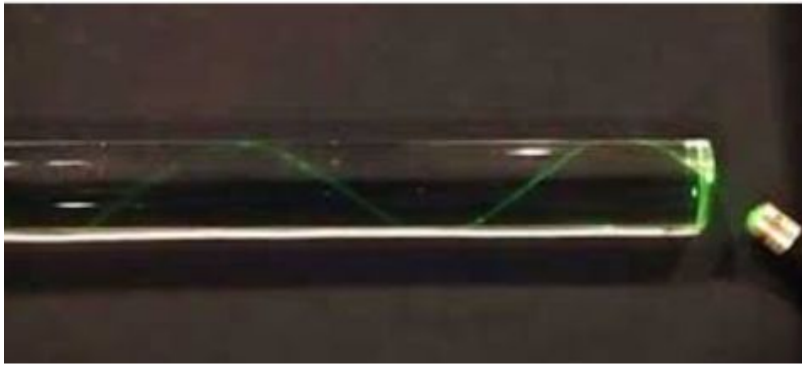


Waveguiding due to TIR

- TIR phenomenon is the backbone of working mechanism of an optical fiber.

- In the image presented, a small (most likely) diode laser is used as an incident light source inside (probably) a glass tube at an angle larger than the critical angle for the material-air interface. Due to TIR, a vivid waveguiding phenomenon is observed.

- In waveguiding, light signals travel from one end of the tube to the other end without any significant loss in signal intensity.



Courtesy: Fiberu.org

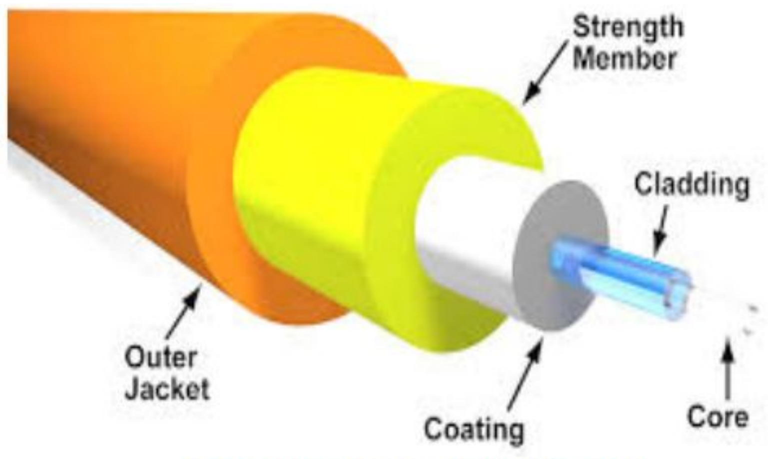
Optical Fiber: Basic Structure

- A high refractive index **core** material, with diameter usually in µm size. Usually made of fused silica/glass (SiO_2)

- Core is covered with a (relatively) lower refractive index material called **cladding**.

- Cladding is covered by a strengthening layer, so that the optical fiber does not break with usual bending/handling .

- A thin outer layer is used as a protective covering for the optical fiber.



Courtesy: Community.fs.com

Early Development: Sir Charles Kao

- Sir Charles Kuen Kao pioneered the development and use of fibre optics in telecommunications. In the 1960s, Kao created various methods to combine glass fibres with lasers in order to transmit digital data, which laid the groundwork for the evolution of the Internet.
- Known as
  - the "Godfather of Broadband",
  - the "Father of Fiber Optics", (Narinder Kapany*)
  - the "Father of Fiber Optic Communications",
- Kao was awarded Nobel Prize in Physics in 2009 for "groundbreaking achievements concerning the transmission of light in fibers for optical communication"

Courtesy: Wiki

Advantages of Optical Fibers

- Optical fibres are very thin and light weight and are much cheaper to produce compared to metal wires.

- Due to TIR, low loss transmission.

- Due to higher frequency (than radio and microwaves), higher information transmission capacity.

- Metal wires are susceptible to interference by stray EM signals, while optical fibres are immune to such disturbance and cross-talks.

- Insulation of two adjoining optical fibres is easier than metal wires.

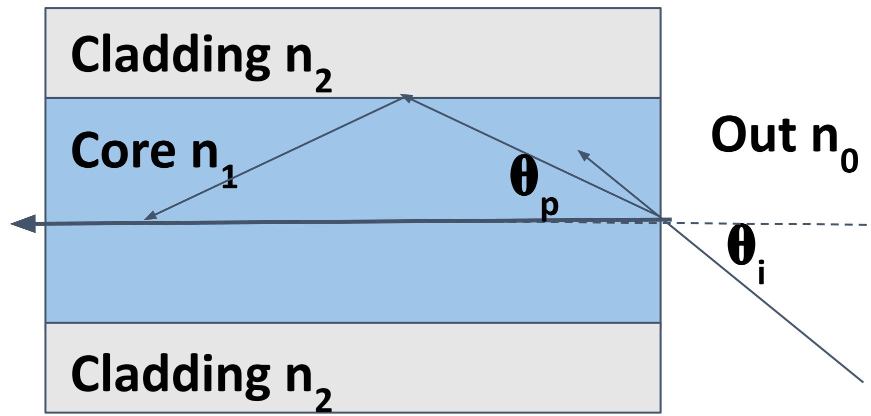
Working Mechanism

- Core with index n_1 (n_{fiber} or n_{core})
- Cladding with index n_2(or $n_{cladding}$)
- For transmission along the fiber

$$\boxed{\begin{array}{l} \cos\theta_p > n_2/n_1 \\ \theta_p > \cos^{-1}(n_2/n_1) \end{array}}$$

- Maximum acceptance angle: θi allowed so that signals can pass through the fiber without a significant loss

$$\theta_{i\_MAX} = \sin^{-1} \mathrm{sqrt}[(n_1^2-n_2^2)/n_0^2]$$

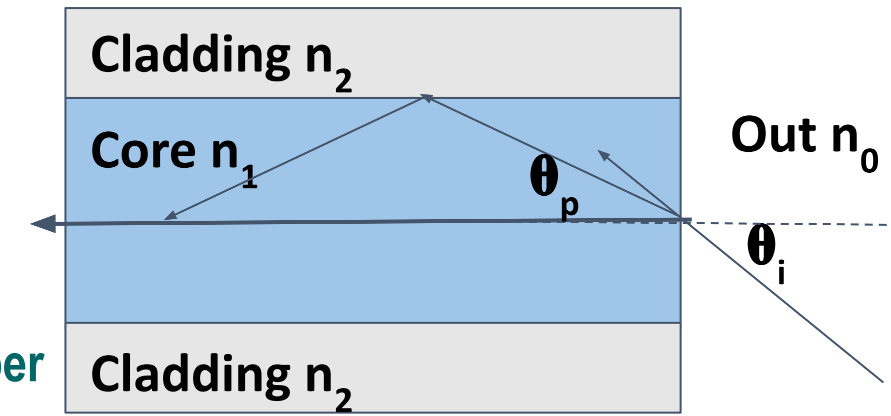


Working Mechanism

- **Numerical Aperture (NA):**

$$NA = \sin\theta_{i\_MAX} = [n_1^2 - n_2^2]$$

$$NA = [n_1 + n_2]\,[n_1 - n_2]$$



- Full Acceptance Angle = $2\theta_{i\_MAX}$
- **Example:** Find NA and $2\theta_{i\_MAX}$ for a fiber with core (1.52) & cladding (1.42)

$$NA = (1.52+1.42)(1.52-1.42) = 2.94 \times 0.1$$

$$NA = 0.294$$

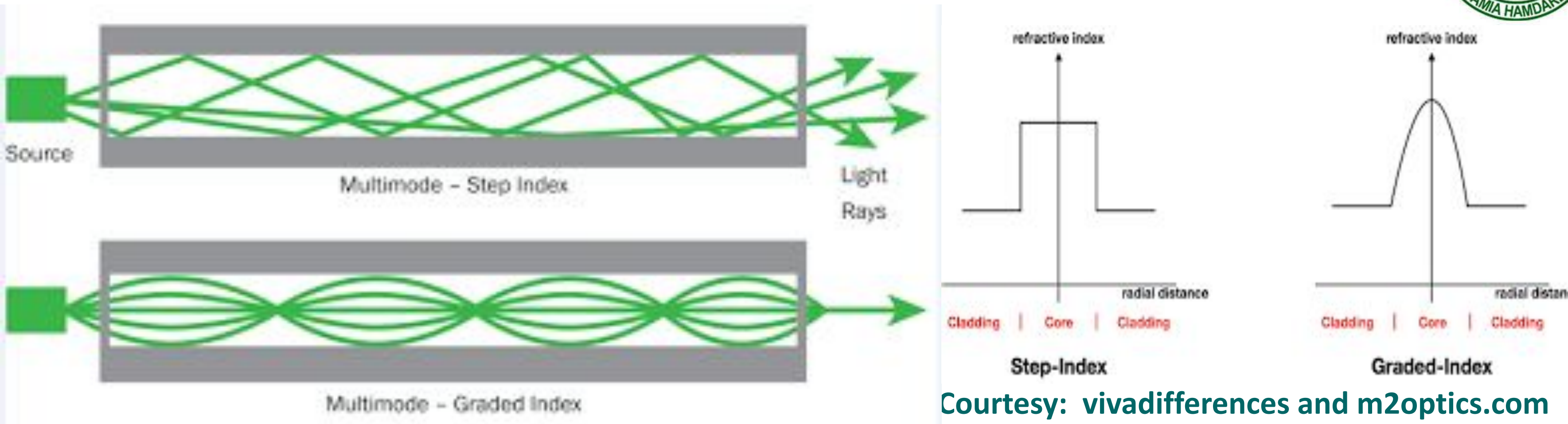
$$2\theta_{i\_MAX} = 2 \sin^{-1} \text{sqrt}(NA) = 2 \sin^{-1} (0.54)$$

$$2\theta_{i\_MAX} = 2 \times 32.8^{o} = 65.7^{o}$$

QUIZ #2

- Find out the critical angle for core(1.6) and cladding (1.4)
- Find out full acceptance angle for core (1.55) and cladding (1.45)

Step Index and Graded Index Fiber



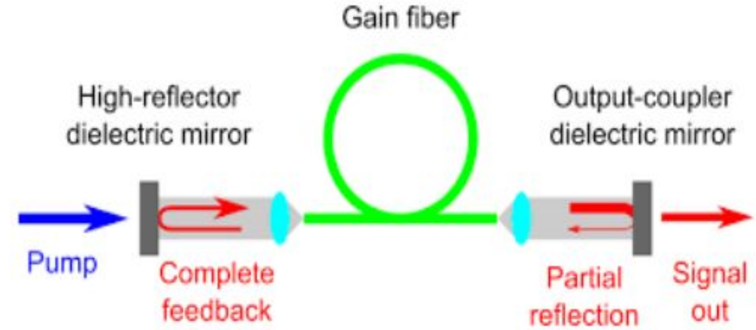
Courtesy: vivadifferences and m2optics.com

- **Step Index Fiber: An abrupt change of index at the core/cladding interface.**

- **Graded Index Fiber: a gradual change in refractive index as one moves from the central axis in core to the cladding material. This allows serpentine modes and travel time is similar to the central mode.**

Applications

- **Communication:**
  - **Mobile**: from the local tower onwards, the mode of communication is dependent on optical fibers.
  - **Broadband internet**: is based on optical fibers.
- **Materials Characterization:**
  - Optical fiber based lasers as a source of laser light for materials characterization.
  - Small diameter tube inspection etc



fiberlabs.com

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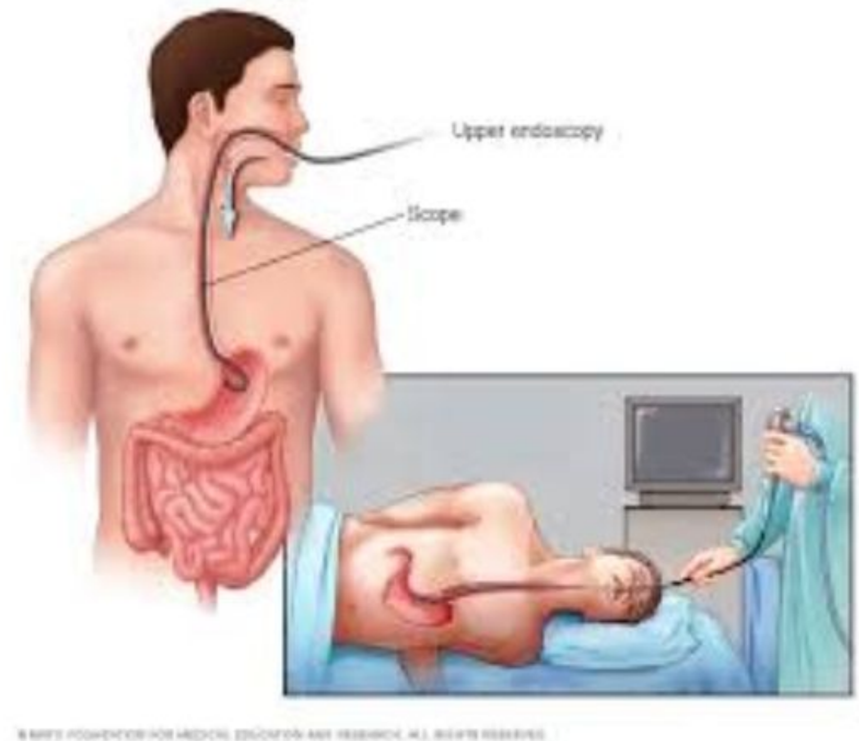
Applications

- **Medical Application (among many a few are):**
  - **Endoscopy/Colonoscopy:** live images of colonoscopy/endoscopy for spotting a tumor/infection/injury are obtained using optical fibers.
  - C



Courtesy: Mayoclinic.org

Sessional 2
2 July 2021
15 Marks

UNIT-5: SEMICONDUCTORS

Unit 5: Elementary Ideas of Semiconductors

Classification of semiconductors: intrinsic and extrinsic semiconductors, Doping, P-type and N-type semiconductors; Band gap: Classification of materials on the basis of band gap, Formation of P-N junction, Depletion width, Forward biased and reverse biased P-N junction, I-V characteristics; Working of Light Emitting Diode (LED) and solar cell.

Types of Semiconductors

Semiconductor

Intrinsic

Low conductivity

insulator at 0K

Extrinsic

High Conductivity

Semiconductor even at 0K

n-type

doping of atoms with 5 e-

in the outer shell: As, Pb

p-type

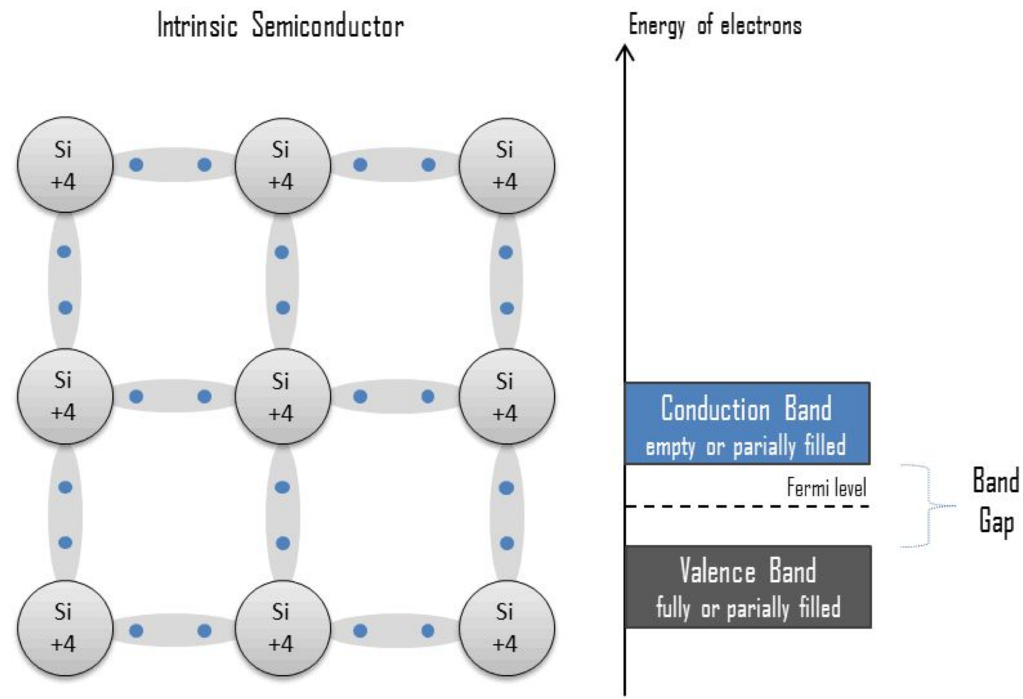
doping of atoms with 3e-

in the outer shell: Al, B

Intrinsic Semiconductor

- Pure semiconductor having no external impurities (or intentional doping of donor or acceptor atoms).

- At 0K temperature, no electrons in the conduction band and no holes in the valence band and hence no conductivity.

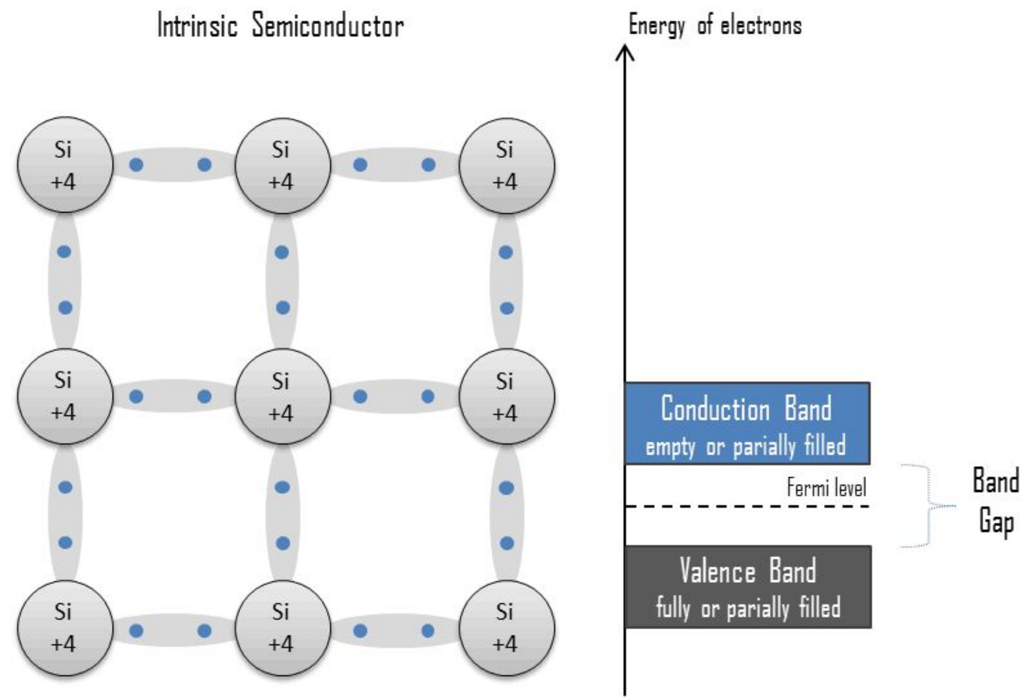


RadiationDosiometry.com

Intrinsic Semiconductor

- ➢ At finite temperature, same number of electrons (in the conduction band) and holes (in the valence band). These charge carriers provide some (low) conductivity.

- ➢ Reference Fermi Level lies exactly in the middle of the band gap.

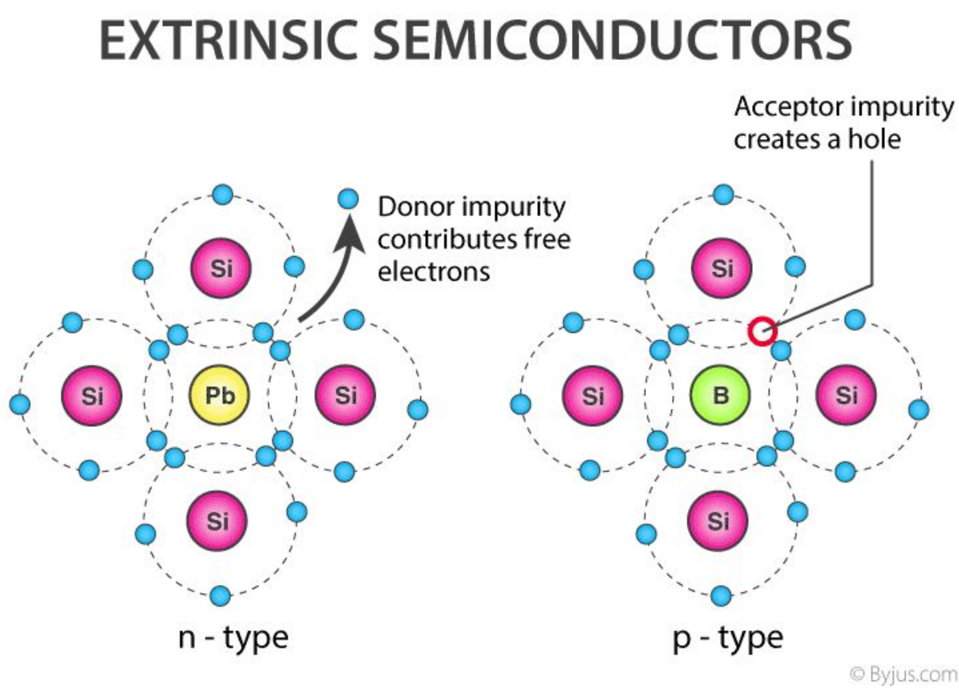


RadiationDosiometry.com

Extrinsic Semiconductor

- Semiconductors having external impurities (due to intentional doping of donor or acceptor atoms).

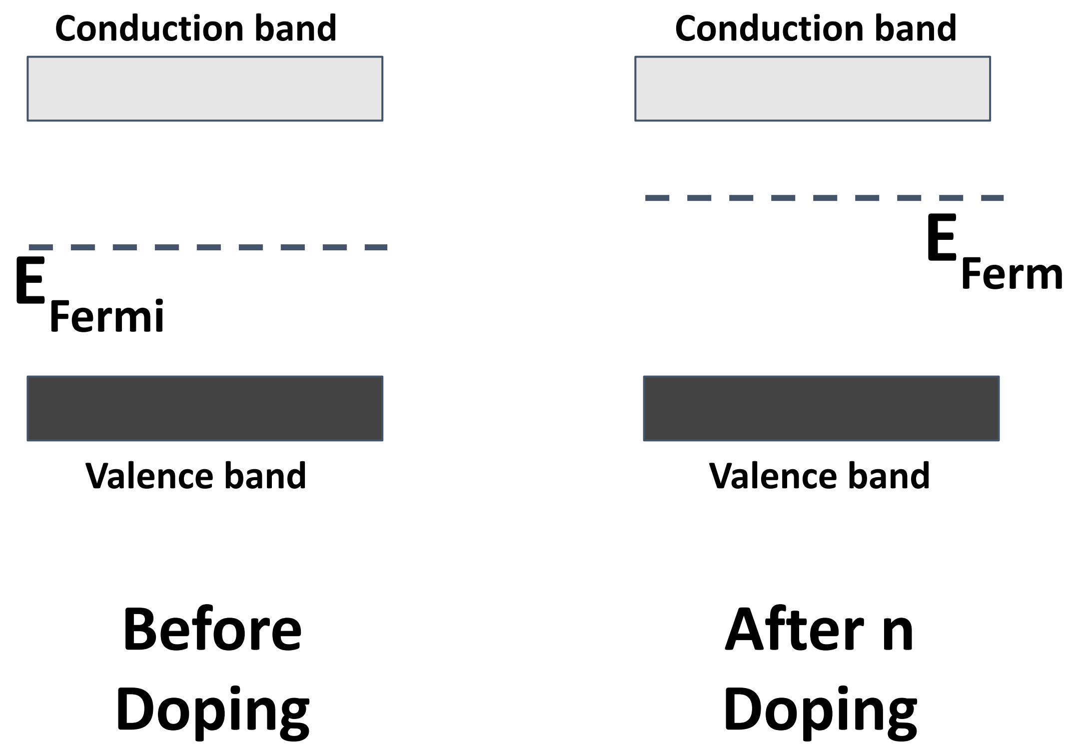
- There are two types of extrinsic semiconductors:P-type and N-type.



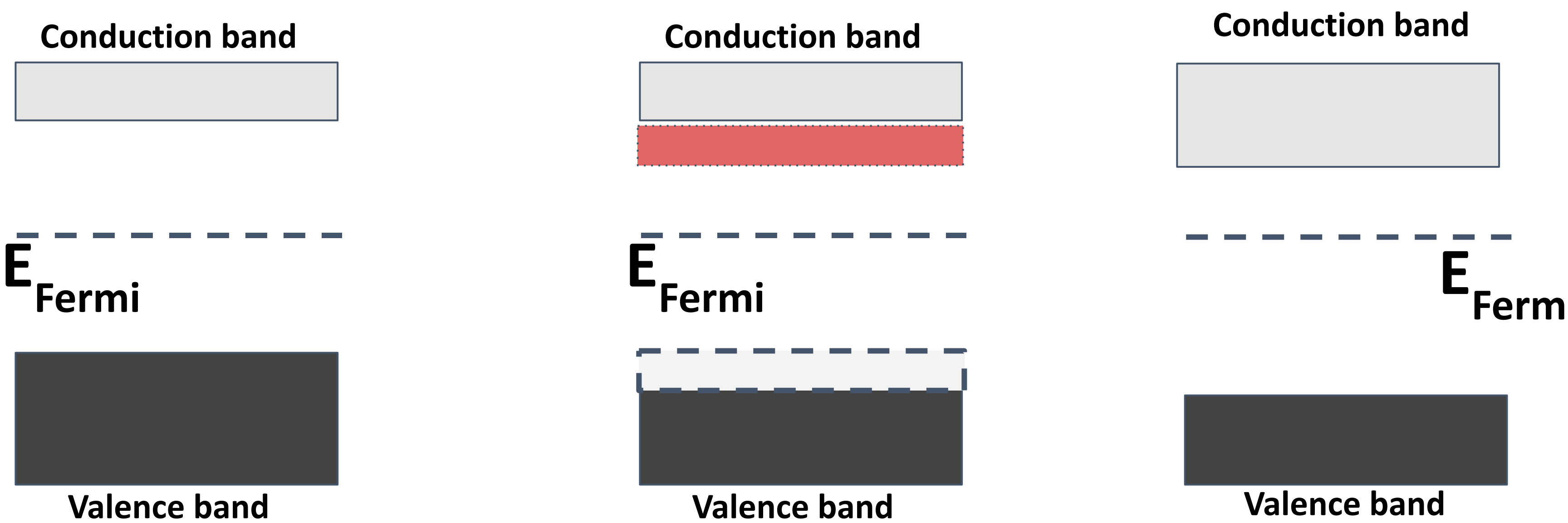
Byju's.com

N-Type Semiconductor

- N-type semiconductor having donor impurities (atoms with 5 electrons in the outer shell) such as As, Pb etc. So, one extra electron is left after fulfilling covalent bonding requirement with Si, which helps in increasing the conductivity.
- Consider the common (and often misunderstood) picture of doping.



N-Type Semiconductor



Before Doping

Levels after n Doping

Final appearance after n Doping

N-Type Semiconductor

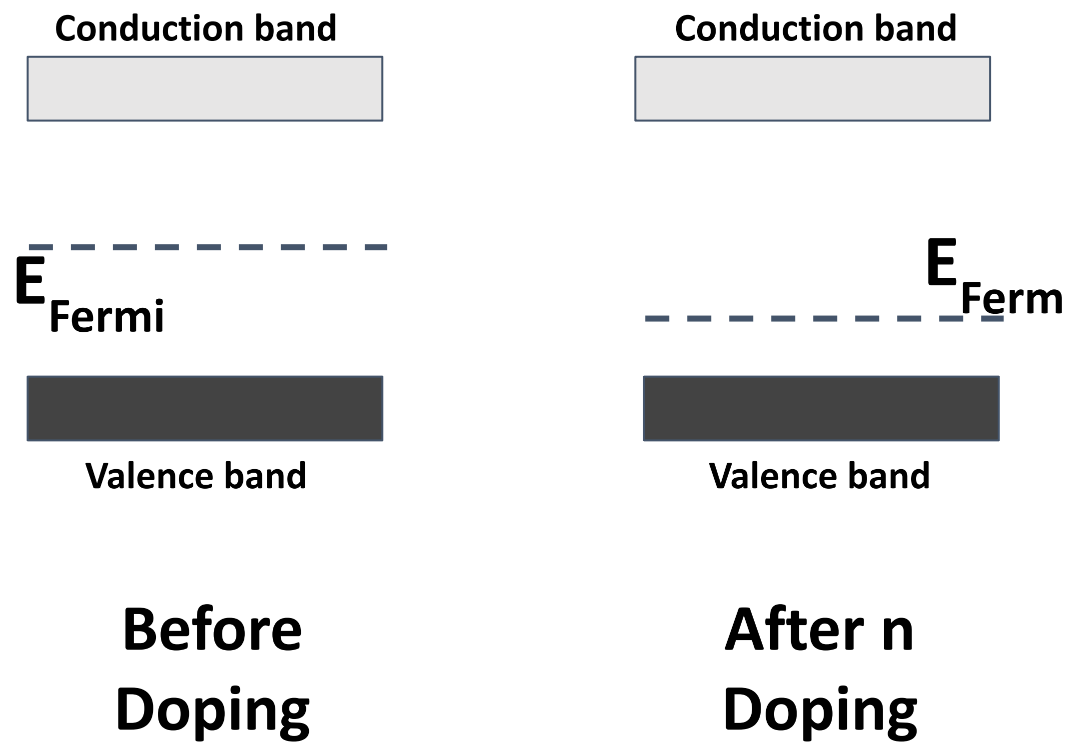
- In the final picture, Fermi level instead of being in the center of conduction band minima and valence band maxima edges, the level becomes closer to the conduction band edge.

- Fermi level is not moving, rather new donor levels are developing near conduction band edge (in N-type doping) and corresponding evolution of valence band edge is occurring. Band gap remains the same.

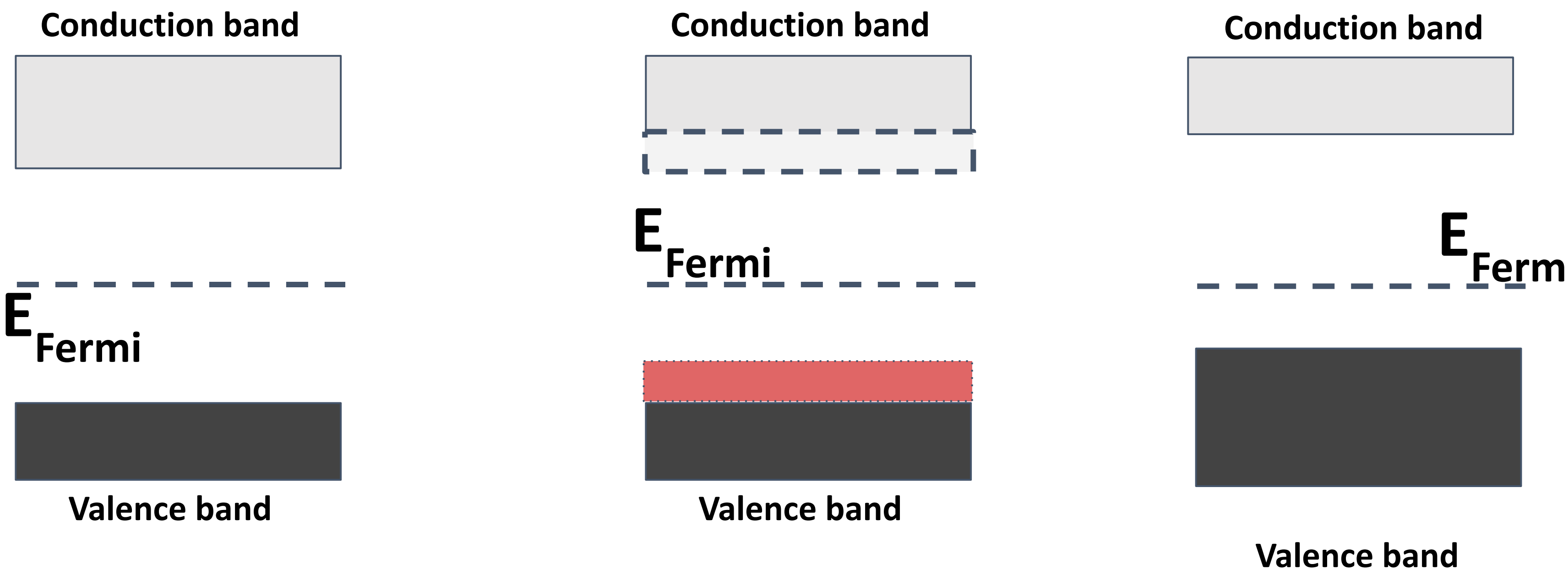
- In such semiconductor there is an asymmetry in the number of holes and electrons present in the material. In n-type semiconductor, there are disproportionately more electrons(arising from donor material) and therefore majority carriers are electrons.

P-Type Semiconductor

- **P-Type semiconductor: acceptor impurities (atoms with 3 electrons in the outer shell) such as Al, B etc. So, one less electron (hole or absence of electron) in fulfilling covalent bonding requirement with Si. Extra holes increase the conductivity of the semiconductor being doped.**



P-Type Semiconductor



Before Doping

New Levels after p Doping

Final after p Doping

P-Type Semiconductor

- In the final picture, Fermi level instead of being in the center of conduction band minima and valence band maxima edges, the level becomes closer to the valence band edge.

- Fermi level is not moving, rather new acceptor levels are developing near valence band edge (in p-type doping) and corresponding evolution of conduction band edge is occurring. Band gap remains the same.

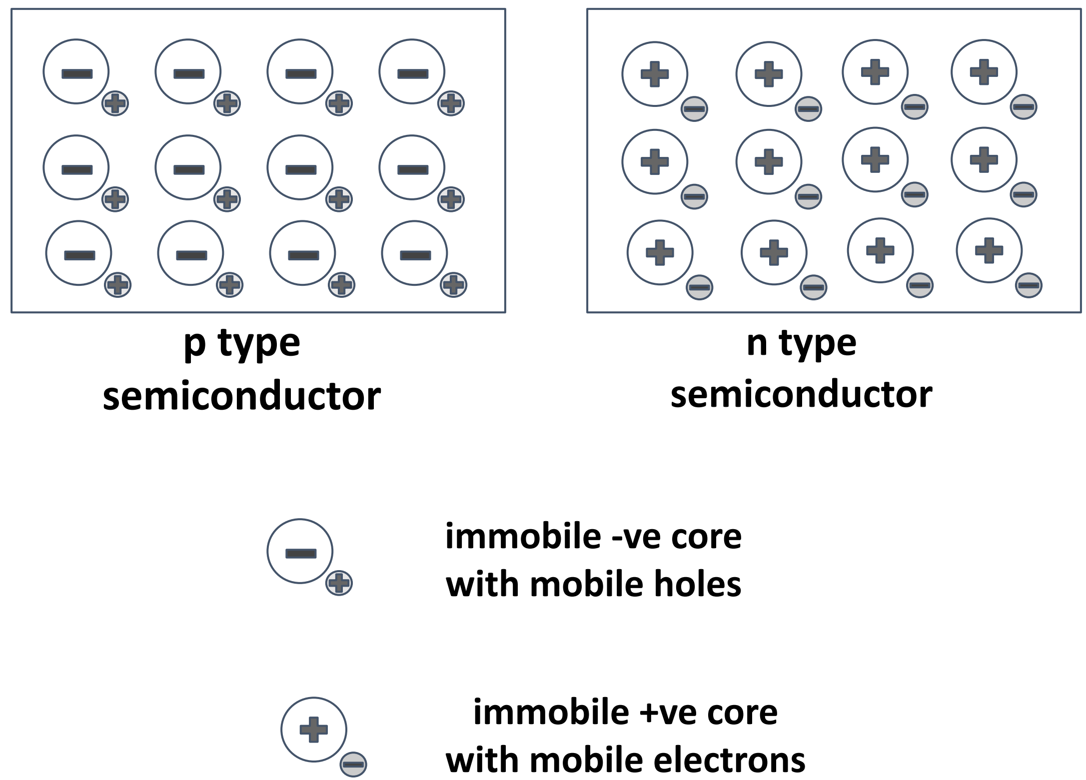
- In such semiconductor there is an asymmetry in the number of holes and electrons present in the material. In p-type semiconductor, there are disproportionately more holes(arising from acceptor material) and therefore majority carriers are holes.

Quiz

Is there any net total charge on p-type (or n-type) semiconductor?

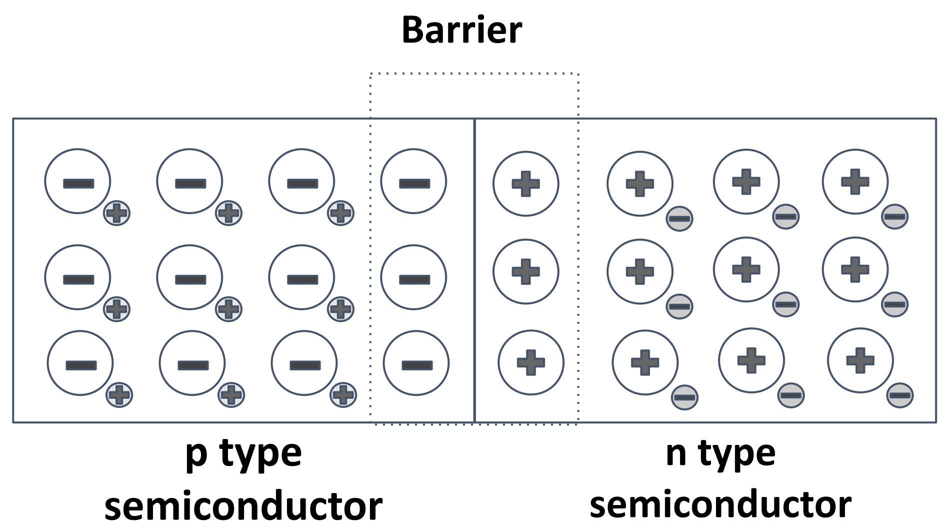
pn Junction

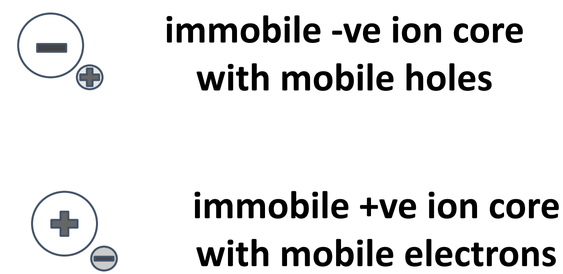
- p-type semiconductor is charge neutral, just +ve holes are charge carriers. It can be considered as an immobile -ve core with mobile holes.
- Similarly, n-type semiconductor can be described.



pn Junction

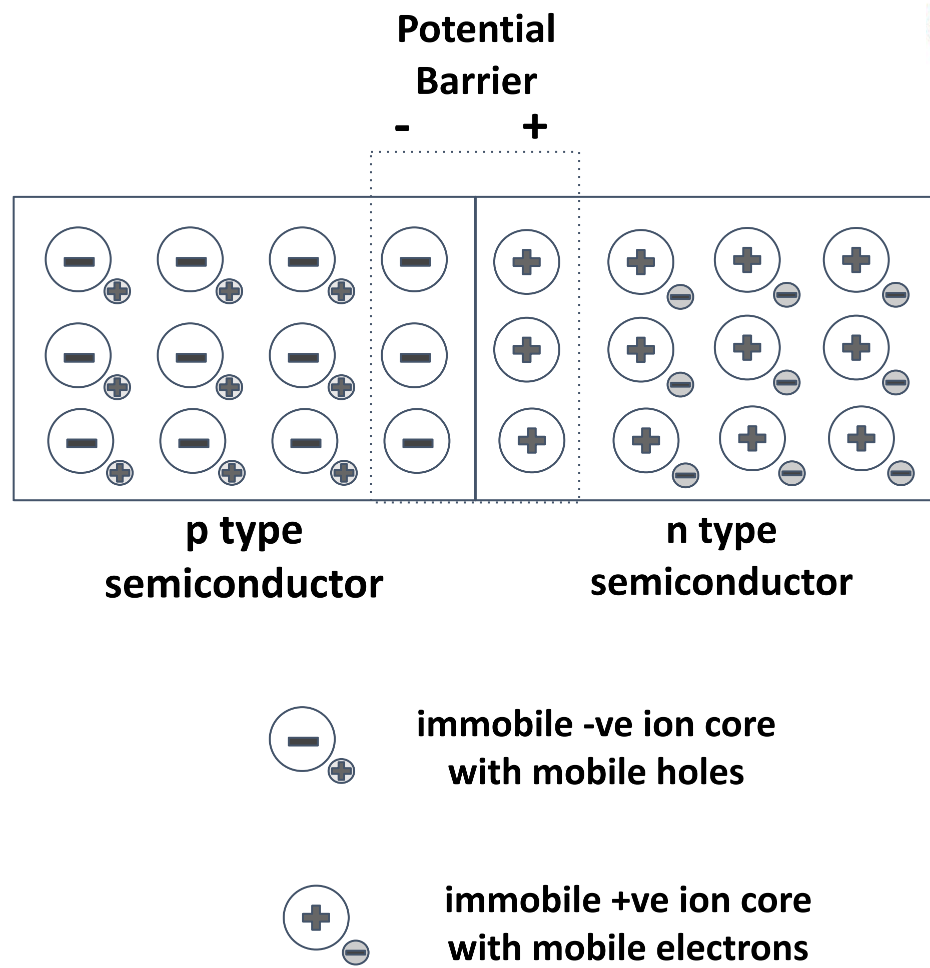
- When the pn junction is formed, mobile holes from p side diffuse to n-side and neutralize with an electron.
- Similarly, mobile electrons from n side diffuse to p-side and neutralize with a hole.
- This process is self limiting.





pn Junction

- Depletion of mobile positive holes across the junction will leave behind -ve core, which will gradually built a negative barrier for electrons diffusing from the other side.
- Similarly, a positive charge will built up on n-side which will stop diffusion of holes from the p side.
- Charge built-up will result in a barrier formation.



pn Junction

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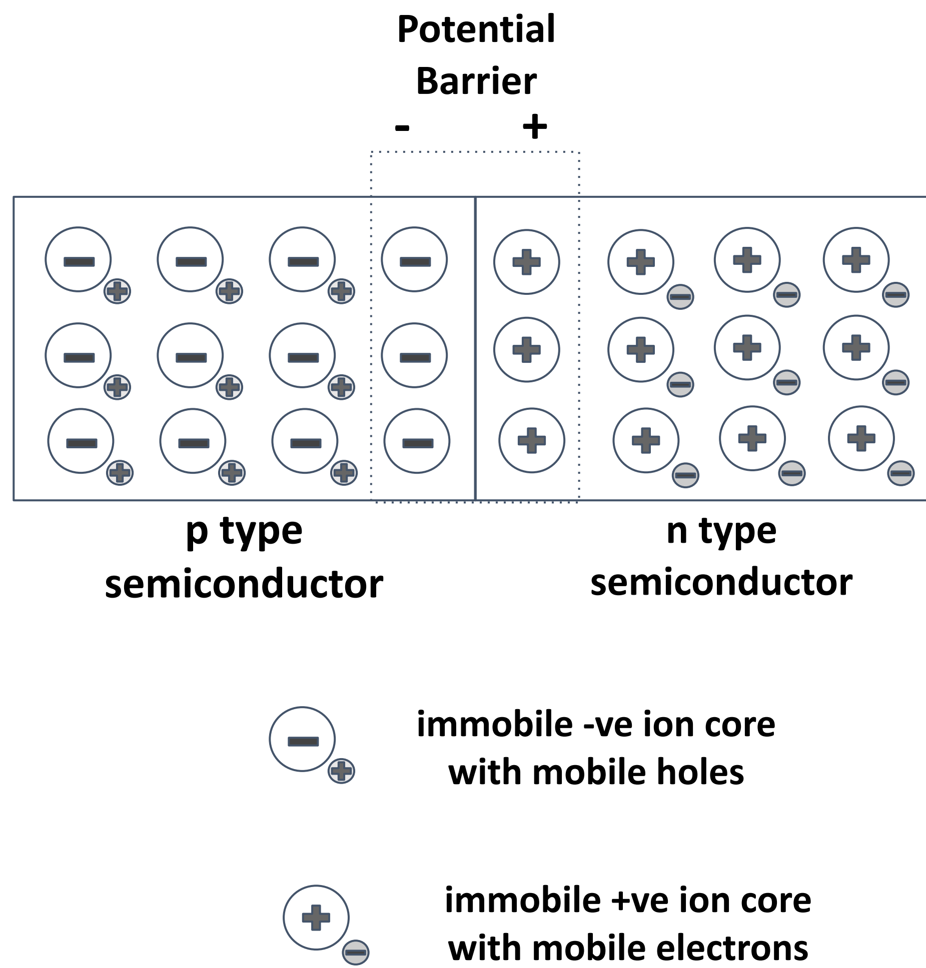
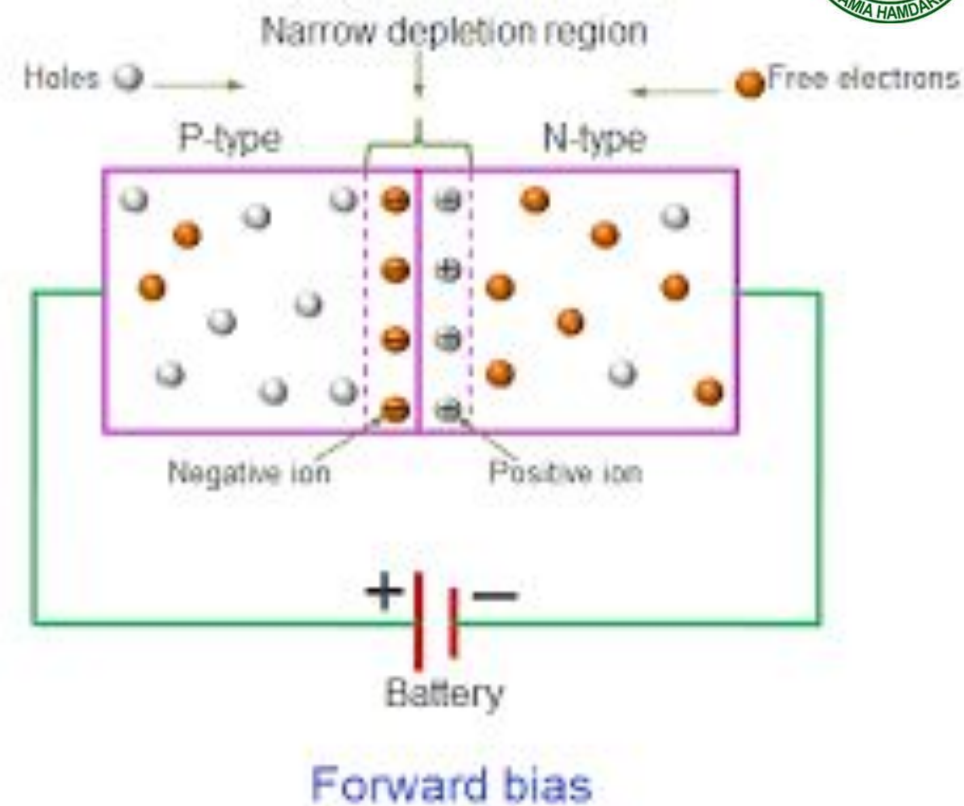


Forward Biased pn Junction

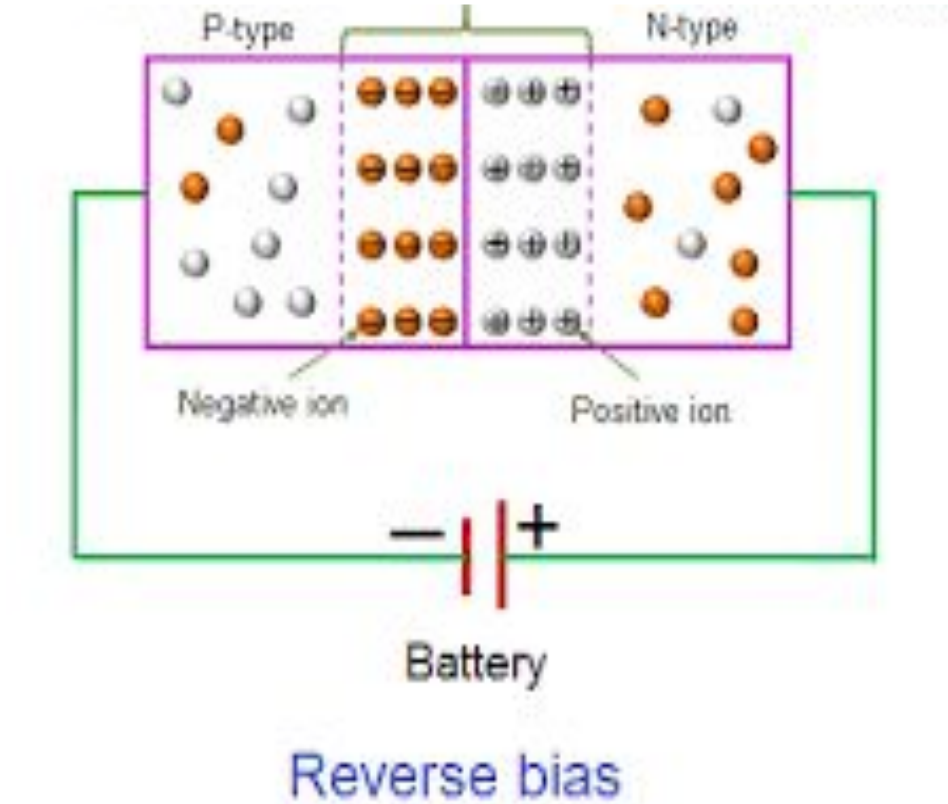
- P-type semiconductor side is connected with the positive terminal and n-type side with the negative terminal of the battery.
- Barrier potential has to be overcome, so before the appropriate voltage is supplied the current flow is negligible.
- Holes in the p-type semiconductor side are pushed towards the junction and electron on the n-side towards the junction.



Physics and radio electronics.com

Reverse Bias pn Junction

- P-type semiconductor side is connected with the negative terminal and n-type side with the positive terminal of the battery.
- Current flow is due minority carriers.
- minority electrons in the p-type semiconductor side are pushed towards the junction and holes on the n-side towards the junction.



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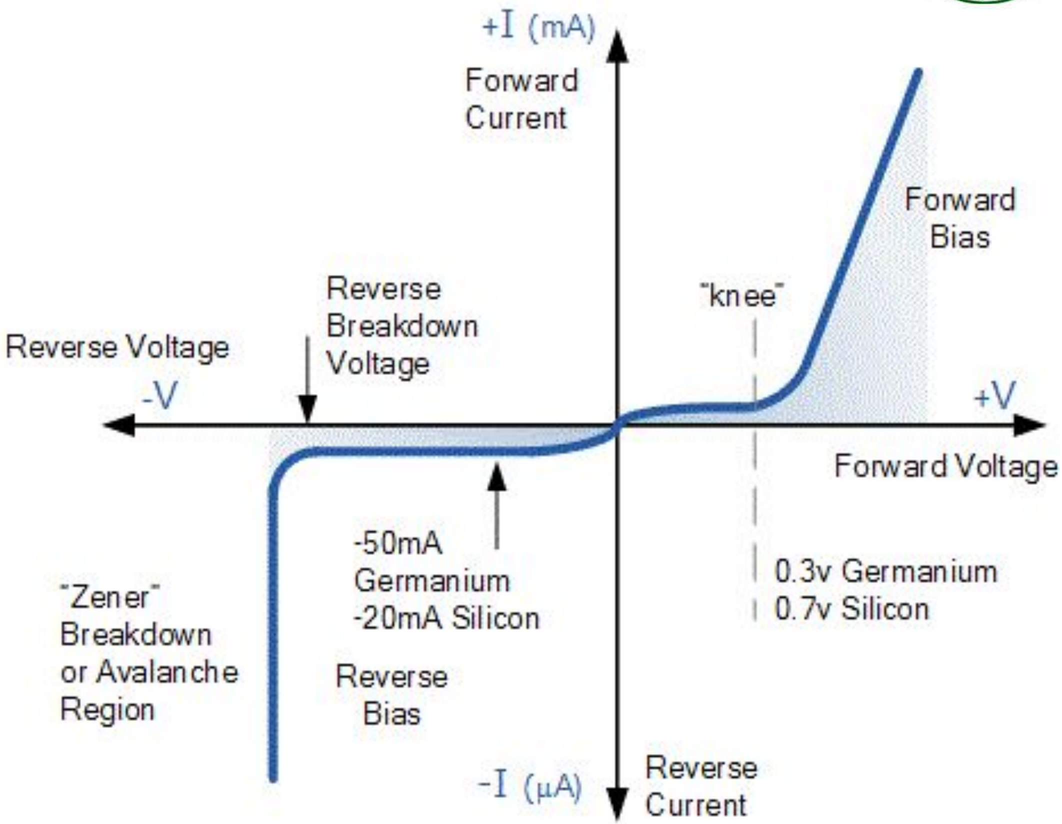
Current Voltage Characteristics

- Knee Voltage: 0.3V(Ge) and 0.7V (Si)
- Forward biased in mA
- Reverse biased usually in micro Amp.
-



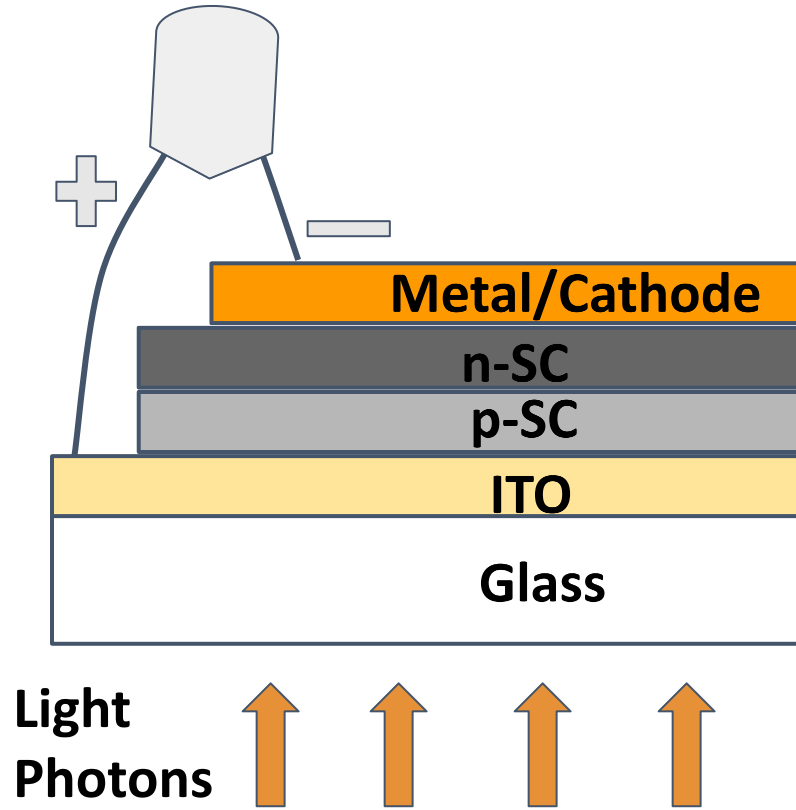
Assignment 1

Current voltage characteristic curve in the forward biased mode has a knee voltage. The current is usually very low before the knee voltage and rises rapidly after the knee voltage. Knee voltage for Si based pn junction is about 0.7V. Does the knee voltage change with the level of doping? Say from 0.1% to 1% doping of acceptor and donor material in Si. Does this change in doping affect the width of depletion region? Explain in detail, with the help of figures.

Solar Cell:

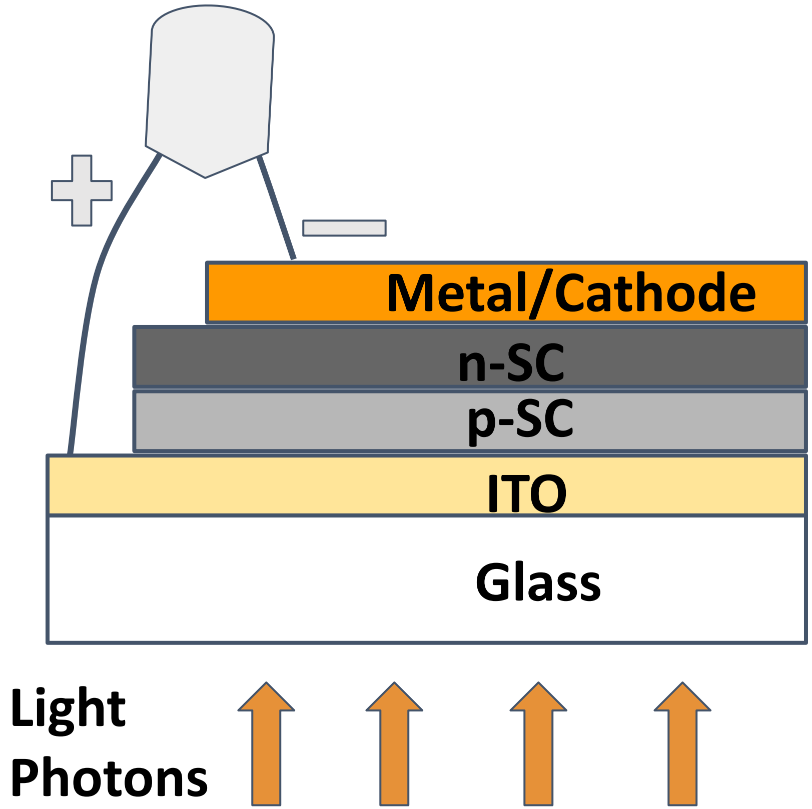
- A solar (or photovoltaic) cell converts photons into charges (both positive and negative), collects at appropriate electrodes and thus generate voltage.

- The generated voltage when connected to a load(light bulb, etc.) a current flows in the circuit.



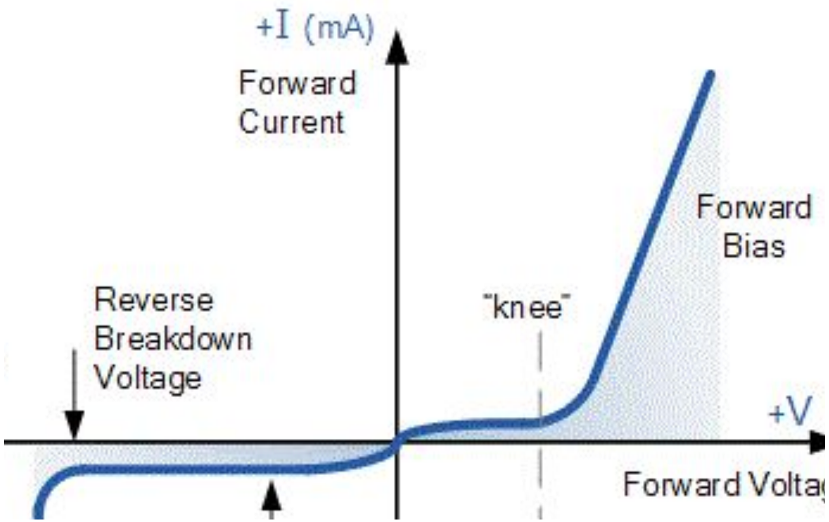
Solar Cell: Structure

- A glass/protective cover sheet (light source side)
- A transparent and conducting electrode (anode): ITO
- A p-type semiconductor
- An n-type semiconductor
- Metal electrode (cathode)



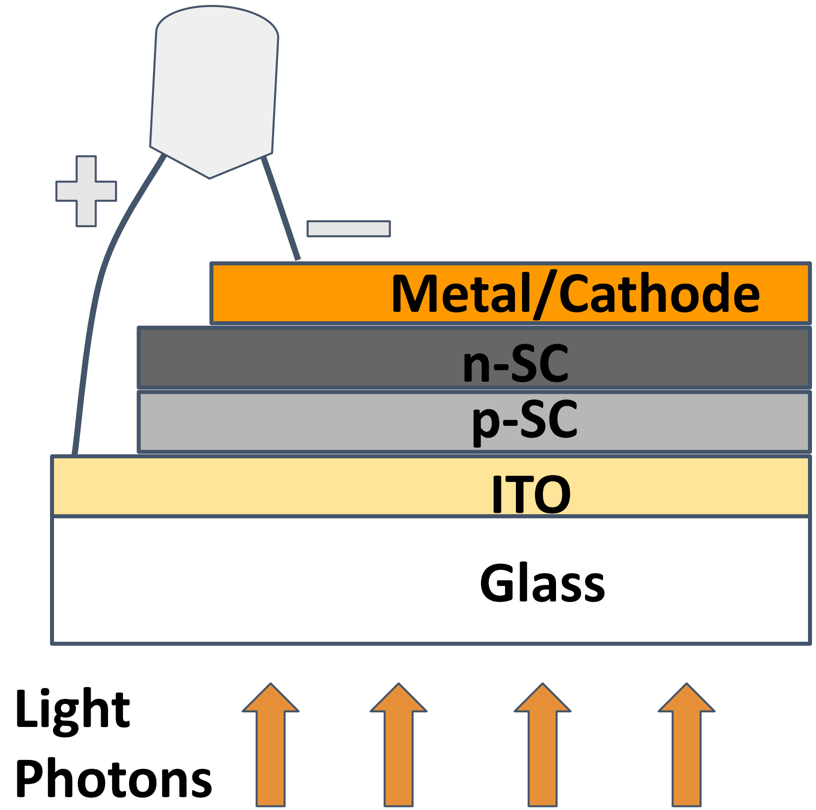
Solar Cell: Without Light

- The structure of a solar cell is exactly like a pn junction.
- If there is no light photons around, it would behave as a normal pn junction diode.
- Characteristics
    - forward bias: small current (mA) with small rise till cut off voltage.
    - reverse bias: very small current (µA).



Solar Cell: Mechanism

- 99% photons (sunlight) would pass through the glass to the next layer.
- Thin ITO layer would pass 95% of photons (of energy less than UV) to the next layer.
- At the end of the day, solar cell generates voltage by absorbing photons. It means that there has to be e- accumulation at cathode and hole accumulation at anode, which can be used to turn on the light.

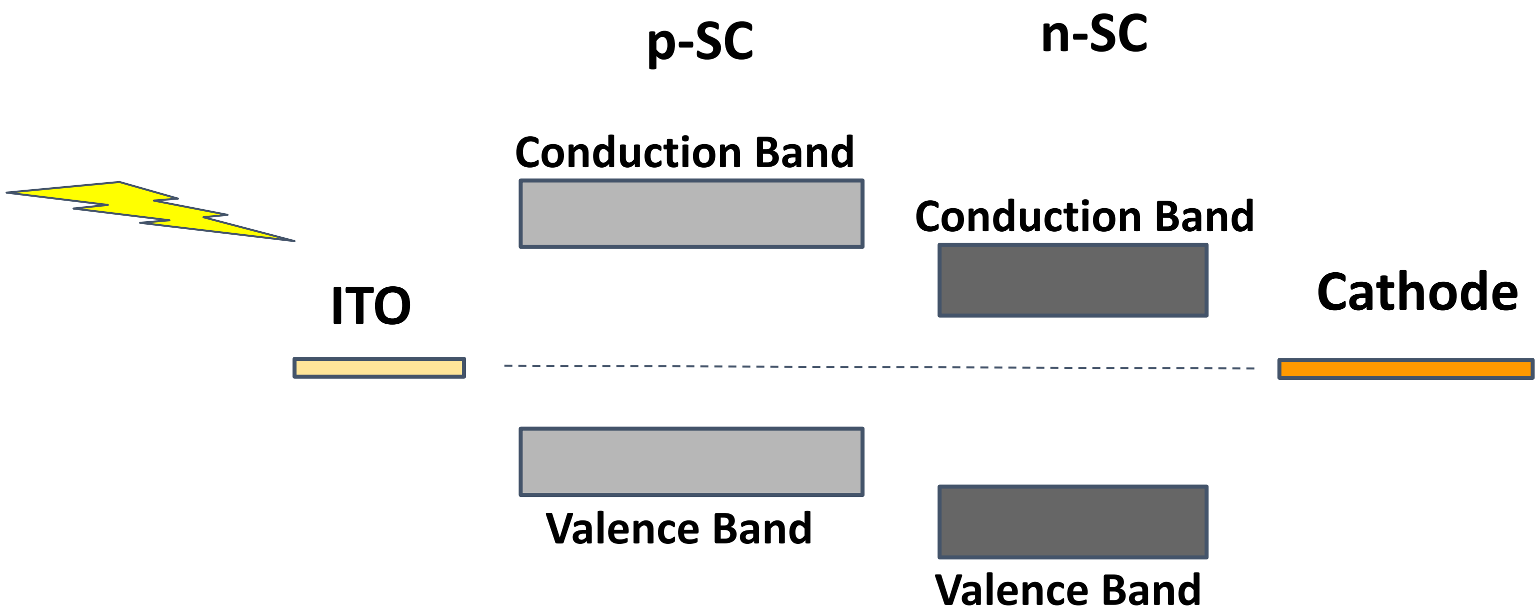


Solar Cell: Mechanism

- **Photon**:
  - a small packet of light energy
  - travels with c(light vel.) in vacuum
  - massless, chargeless, spin 0 particle
- **Exciton**:
  - a correlated pair of electron and hole, so overall charge neutral.
  - Exciton has a certain life time (~micro sec) and binding energy (~0.1 eV)
  - Absorption of photons in a semiconductor usually result in creation of excitons.

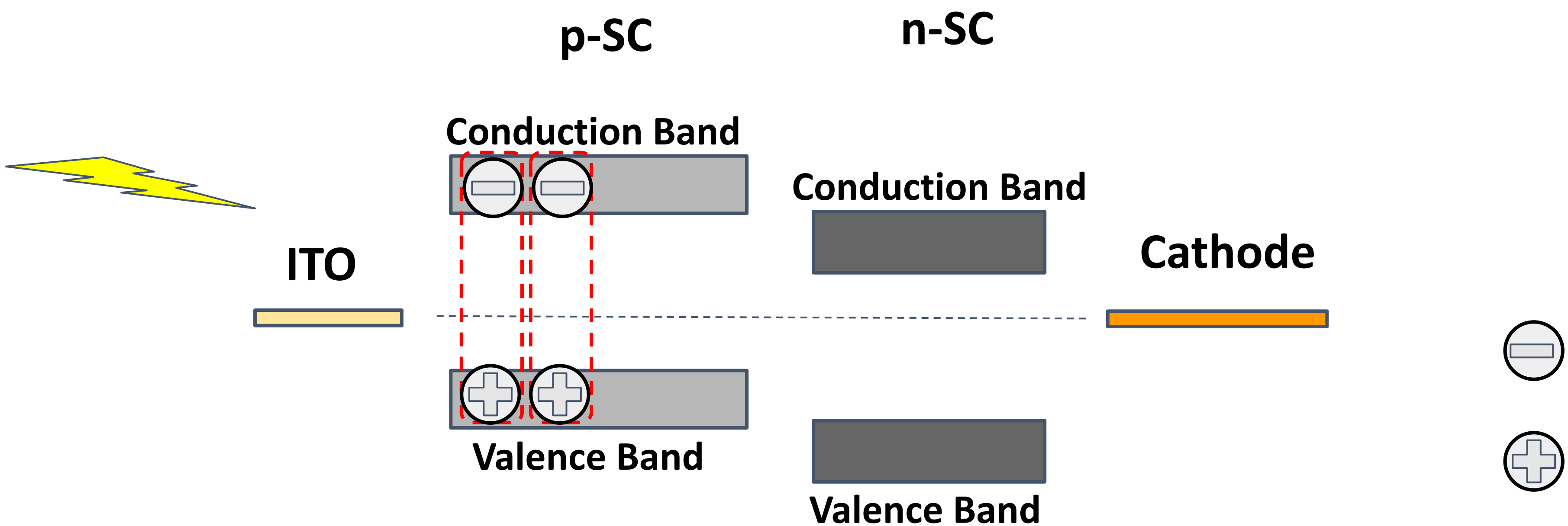
Solar Cell: Band Level Picture

- 99% photons (sunlight) would pass through glass to the ITO layer.
- 95% photons would pass through ITO to the p-type semiconductor layer.
- Absorption of photons would occur mostly in the front (p-SC) layer.



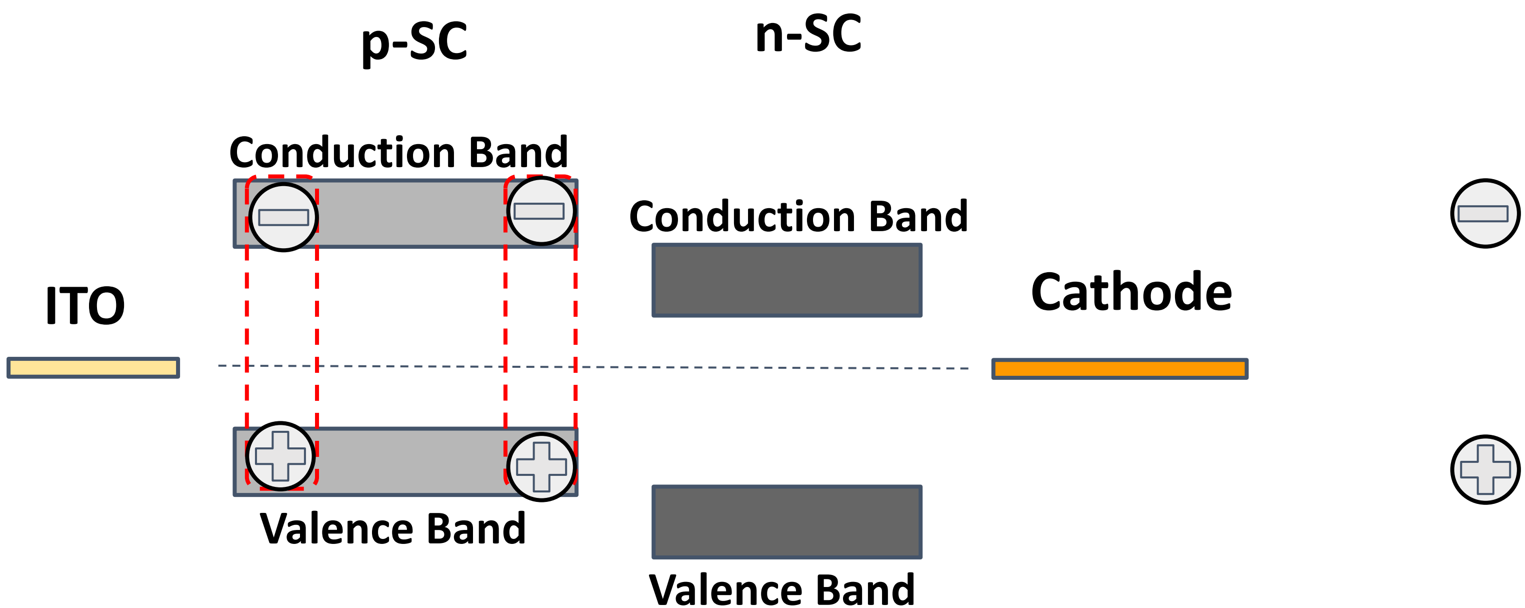
Solar Cell: Band Level Picture

- Absorption of photons would occur in semiconductor layers.
- Absorption of photons in the SC layer generate excitons.
- The density of exciton would be higher at the earlier part of the p-type SC.



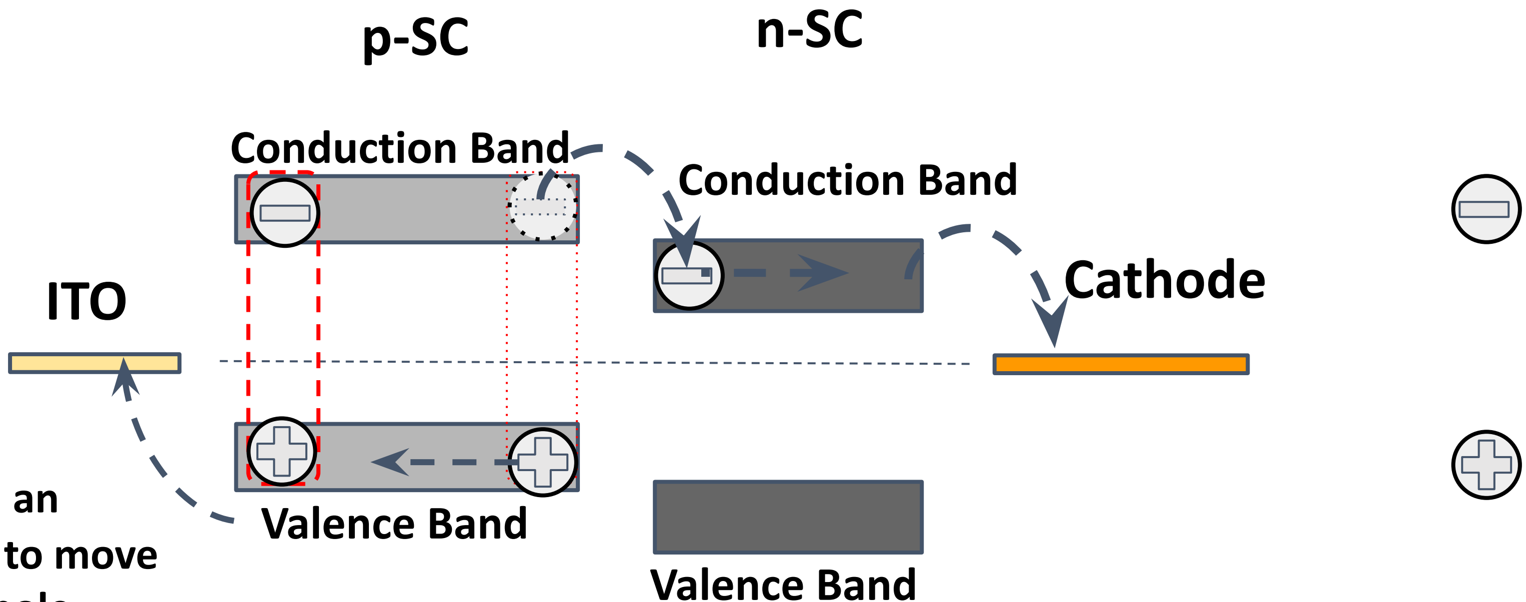
Solar Cell: Band Level Picture

- The density of exciton would be higher at the earlier part of the p-type SC.
- The higher density would result in diffusion of excitons towards the lower density region (pn-junction).



Solar Cell: Band Level Picture

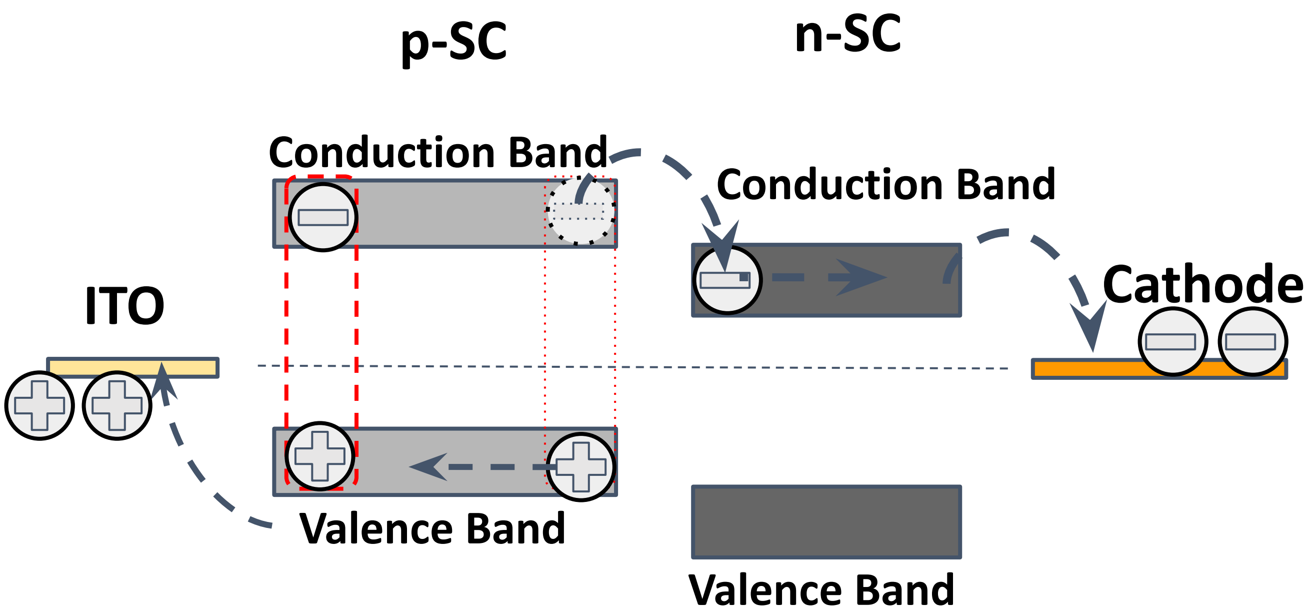
- When an exciton reaches at the pn junction, the electron (in the exciton) finds it energetically favorable to jump to the conduction band of the n-type semiconductor, while the corresponding hole do not find it energetically favorable to jump on the other side. It causes the exciton to break up in e- & h+.



*In energy band an electron prefers to move downward and hole upward

Solar Cell: Band Level Picture

➢ The electron (hole) continue to move towards the cathode (anode) and this process thus results in accumulation of electrons at cathode and holes at anode. The entire process thus generates voltage.



Solar Cell: Efficiency Estimate

- Photon absorption (exciton creation) (η_{abs}) ~ 0.9
- Exciton diffusion (η_{diff}) ~ 0.5
- Exciton dissociation (in electron and hole) (η_{diss}) ~ 0.5
- Charge transfer (electron from p to n side) (η_{CT}) ~ 0.8
- Individual charge diffusion (η_{Cdiff}) ~ 0.8
- Charge collection at cathode and anode (η_{CC}) ~ 0.8

- Total Efficiency $\eta = \eta_{abs} \times \eta_{diff} \times \eta_{diss} \times \eta_{CT} \times \eta_{Cdiff} \times \eta_{CC} = 0.115$ (or 11.5%)

- The above calculation provides a ballpark estimate of the solar cell efficiency. The numbers can of course be very different for different types of cells.

Solar Cell: Device Efficiency

- **Fill factor, FF: It is defined as the ratio of maximum power (P_{max}) and the product I_{sc} x V_{oc}. Higher the FF, better the cell.**

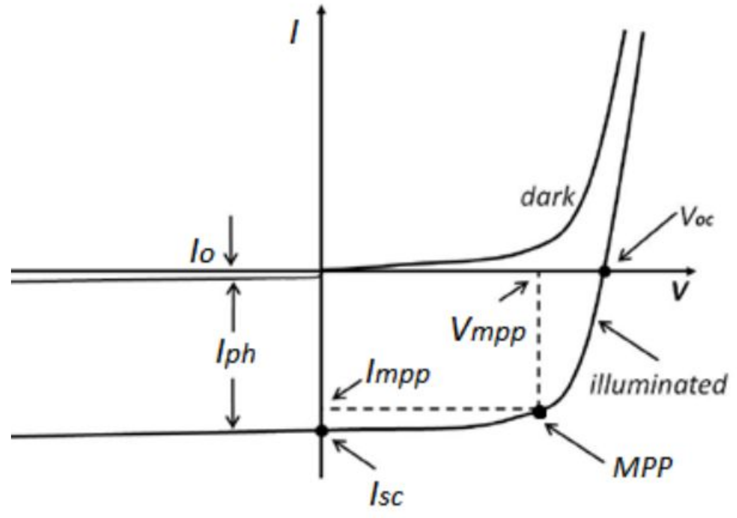
  $$FF = P_{max}/I_{sc} \times V_{oc}$$

  $$FF = I_{mpp} \times V_{mpp}/(I_{sc} \times V_{oc})$$

- **Conversion efficiency, η: The conversion efficiency is calculated as the ratio of the maximum generated power and the incident power.**

  $$\eta = P_{max}/P_{in} = I_{mpp} \times V_{mpp}/P_{in}$$

  $$\eta = J_{sc} \times V_{oc} \times FF/ I_{in}$$



: Determining solar cell parameters from I-V characteristics

Acknowledgement & Further Reading

- Engineering Physics by Malik and Singh.
- Online material available on other educational websites.

Thank You!

PS: **These slides are for educational purpose, if there is any correction or suggestion to improve the content, please send an email to irfanplsr at GMail**