Properties of Materials

- Mechanical Properties
- Electronic properties
- Thermal Properties
- Optical properties
- Magnetic properties

Mechanical Properties

- Strength
- Elasticity
- Plasticity
- Ductility
- Malleability
- Toughness or Tenacity
- Brittleness
- Hardness
- Fatigue
- Creep

Brittleness: Ability of a material to break or shatter without significant deformation when under stress; opposite of plasticity, examples: glass, concrete, cast iron, ceramics etc.

· Compressive strength: Maximum stress a material can withstand before compressive failure (MPa)

· Creep: The slow and gradual deformation of an object with respect to time and constant load.

· Ductility: Ability of a material to deform under tensile load (% elongation)

· Durability: Ability to withstand wear, pressure, or damage; hard-wearing.

· Elasticity: Ability of a body to resist a distorting influence or stress and to return to its original size and shape when the stress is removed

· Fatigue limit: Maximum stress a material can withstand under repeated loading or cyclic load (MPa)

· Hardness: Ability to withstand surface indentation and scratching (e.g. Brinnell hardness number)

- Plasticity: Ability of a material to undergo irreversible or permanent deformations without breaking or rupturing; opposite of brittleness
- Resilience: Ability of a material to absorb energy when it is deformed elastically (MPa); combination of strength and elasticity.
- Stiffness: Ability of an object to resist deformation in response to an applied force; rigidity; complementary to flexibility
- Tensile strength: Maximum tensile stress of a material can withstand before failure (MPa)
- Toughness: Ability of a material to absorb energy (or withstand shock) and plastically deform without fracturing (or rupturing); a material's resistance to fracture when stressed; combination of strength and plasticity
- Yield strength: The stress at which a material starts to yield plastically (MPa)
- Young's modulus: Ratio of linear stress to linear strain (MPa)

Electronic Properties

- Free electron theory
- Fermi energy
- Density of states
- Band theory
- Semiconductors
- Hall effect
- Dielectric
- Piezo
- Ferro
- Pyroelectricity

Free electron theory

- The **theory** was originally proposed in 1900 to describe and correlate the electrical and thermal properties of metals.
- Later, quantum mechanics became the basis for the **theory** of most of the general properties of simple metals such as sodium, with one **free electron** per atom, magnesium with two, and aluminum with three.

Fermi Energy

- **Fermi energy** is often defined as the highest occupied energy level of a material at absolute zero temperature. In other words, all electrons in a body occupy energy states at or below that body's Fermi energy at 0K.
- The fermi energy is the different in energy, mostly kinetic. In metals this means that it gives us the velocity of the electrons during conduction. So during the conduction process, only electrons that have an energy that is close to that of the fermi energy can be involved in the process.
- This concept of Fermi energy is useful for describing and comparing the behaviour of different semiconductors.

Density of States

- The density of states (DOS) is essentially the number of different states at a particular energy level that electrons are allowed to occupy, i.e. the number of electron states per unit volume per unit energy.
- Bulk properties such as specific heat, paramagnetic susceptibility, and other transport phenomena of conductive solids depend on this function.
- DOS calculations allow one to determine the general distribution of states as a function of energy and can also determine the spacing between energy bands in semi-conductors

Band theory

- **Band theory**, in solid-state physics, theoretical model describing the states of electrons, in solid materials, that can have values of energy only within certain specific ranges.
- The behaviour of an electron in a solid (and hence its energy) is related to the behaviour of all other particles around it. This is in direct contrast to the behaviour of an electron in free space where it may have any specified energy.
- The ranges of allowed energies of electrons in a solid are called allowed bands. Certain ranges of energies between two such allowed bands are called forbidden bands—i.e., electrons within the solid may not possess these energies.
- The band theory accounts for many of the electrical and thermal properties of solids and forms the basis of the technology of solid-state electronics.

Semiconductors

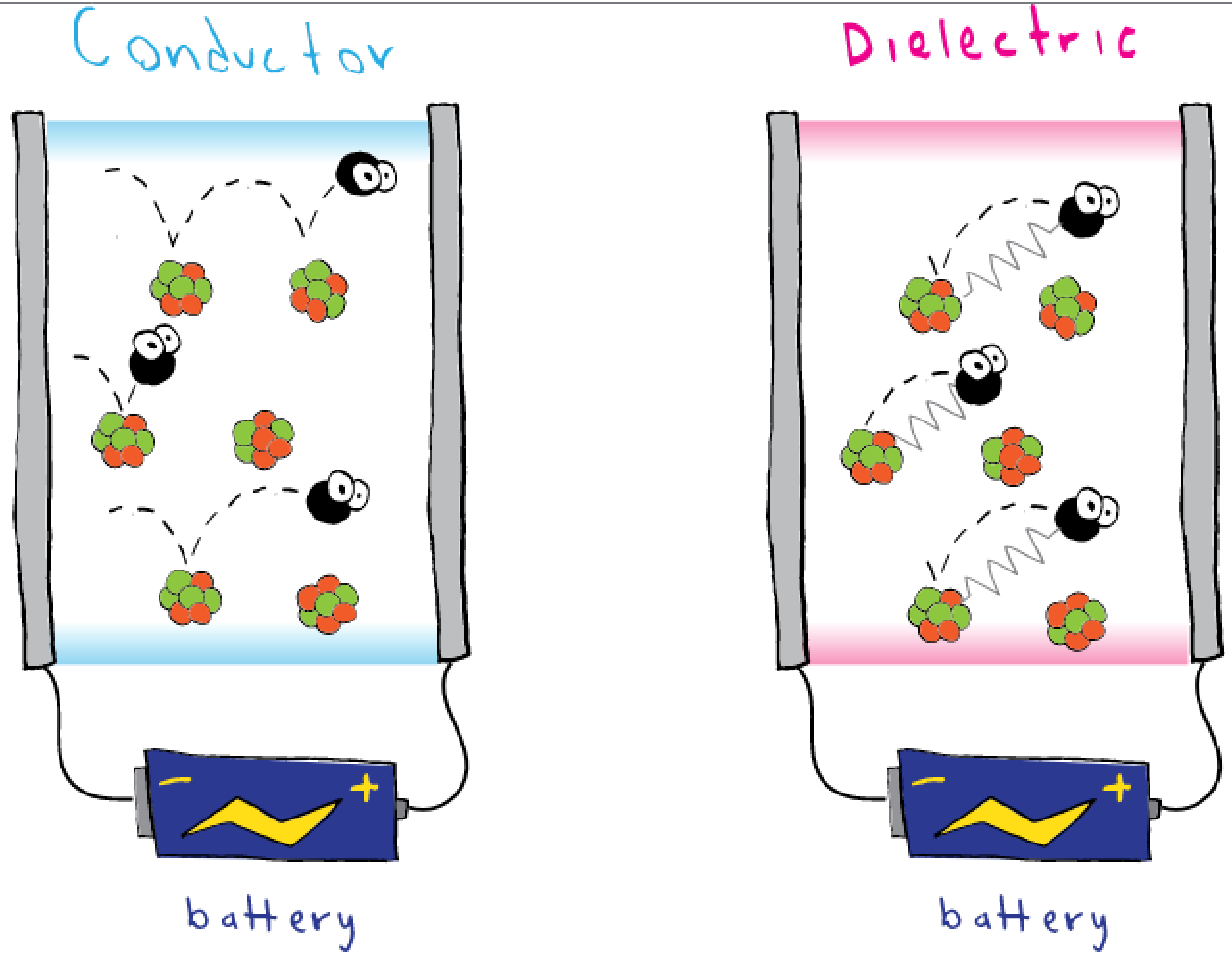
- Semiconductors are materials which have a conductivity between conductors (generally metals) and nonconductors or insulators (such as most ceramics).
- Semiconductors can be pure elements, such as silicon or germanium, or compounds such as gallium arsenide or cadmium selenide.
- In a process called doping, small amounts of impurities are added to pure semiconductors causing large changes in the conductivity of the material.
- Due to their role in the fabrication of electronic devices, semiconductors are an important part of our lives.

Hall Effect

- The Hall effect is the movement of charge carriers through a conductor towards a magnetic attraction. The phenomenon is named for Edwin Hall, who discovered the effect in 1879.
- The Hall effect causes a measurable voltage differential across the conductor such that one side is positively charged and the other negatively.
- The effect is manipulated and measured in the functioning of many electronic devices including joystick-like controls, compasses in smartphones, magnetometers, sensors and current-measuring devices.

Dielectric

- **Dielectrics** are materials that don’t allow current to flow.
- A **dielectric** (or **dielectric material**) is an electrical insulator that can be polarized by an applied electric field.
- When a dielectric is placed in an electric field, electric charges do not flow through the material as they do in an electrical conductor but only slightly shift from their average equilibrium positions causing **dielectric polarization**.
- Because of dielectric polarization, positive charges are displaced in the direction of the field and negative charges shift in the opposite direction.
- This creates an internal electric field that reduces the overall field within the dielectric itself.


Conductor
Dielectric
−
+
battery
−
+
battery

Piezo

- **Piezoelectricity** is the electric charge that accumulates in certain solid materials (such as crystals, certain ceramics, and biological matter such as bone, DNA and various proteins) in response to applied mechanical stress.
- The word *piezoelectricity* means electricity resulting from pressure and latent heat.
- It is derived from the Greek πιέζειν *piezein*, which means to squeeze or press, and ἤλεκτρον *ēlektron*, which means amber, an ancient source of electric charge.
- Piezoelectricity was discovered in 1880 by French physicists Jacques and Pierre Curie.[4]
- The piezoelectric effect is understood as the linear electromechanical interaction between the mechanical and the electrical state in crystalline materials with no inversion symmetry.

Ferro

- **Ferroelectricity** is a characteristic of certain materials that have a spontaneous electric polarization that can be reversed by the application of an external electric field.
- All ferroelectrics are pyroelectric, with the additional property that their natural electrical polarization is reversible.
- The term is used in analogy to ferromagnetism, in which a material exhibits a permanent magnetic moment.

Pyroelectricity

- **Pyroelectricity** can be described as the ability of certain **materials** to generate a temporary voltage when they are heated or cooled.
- The change in temperature modifies the positions of the atoms slightly within the crystal structure, such that the polarization of the **material** changes.

Thermal Properties

- Specific heat
- Thermal conductivity
- Thermal expansion
- Thermoelectricity

Heat capacity

- A solid material's potential energy is stored as its heat energy.
- Temperature of a solid is a measure its potential energy.
- External energy required to increase temperature of a solid mass is known as the material's *heat capacity*. it is defined as its ability to absorb heat energy.

$$C = \frac{dQ}{dT}$$

- Heat capacity has units as J/mol-K *or* Cal/mol-K.

Specific heat

- For comparison of different materials, heat capacity has been rationalized.
- *Specific heat* is heat capacity per unit mass. It has units as J/kg-K *or* Cal/kg-K.
- With increase of heat energy, dimensional changes may occur. Hence, two heat capacities are usually defined.
- Heat capacity at constant pressure, C_p, is always higher than heat capacity at constant volume, C_v.
- C_p is ONLY marginally higher than C_v.
- Heat is absorbed through different mechanisms: lattice vibrations and electronic contribution.

Thermal expansion

- Increase in temperature may cause dimensional changes.
- Linear *coefficient of thermal expansion* (α) defined as the change in the dimensions of the material per unit length.
- Changes in dimensions with temperature are due to change in inter-atomic distance, rather than increase in vibrational amplitude.

Thermal conductivity

- *Thermal conductivity* is ability of a material to transport heat energy through it from high temperature region to low temperature region.
- Heat energy transported through a body with thermal conductivity k is

$$Q = kA\frac{\Delta T}{\Delta l}$$

- Heat is transported in two ways – electronic contribution, vibratioanl (phonon) contribution.
- In metals, electronic contribution is very high. Thus metals have higher thermal conductivities. It is same as electrical conduction.

Thermoelectric

- **Thermoelectric** materials show the **thermoelectric** effect in a strong or convenient form.
- The **thermoelectric** effect refers to phenomena by which either a temperature difference creates an electric potential or an electric potential creates a temperature difference.

Magnetic Properties

- Those materials in which a state of magnetisation can be induced are called magnetic materials.
- Such a materials create a magnetic field in the surrounding space.
- Study of magnetic properties is necessary because the science of magnetism explains many aspects of the structure and behaviour of the matter.

Magnetic Properties

- Magnetism
- Para-magnetism
- Diamagnetism
- Ferro and ferrimagnetism

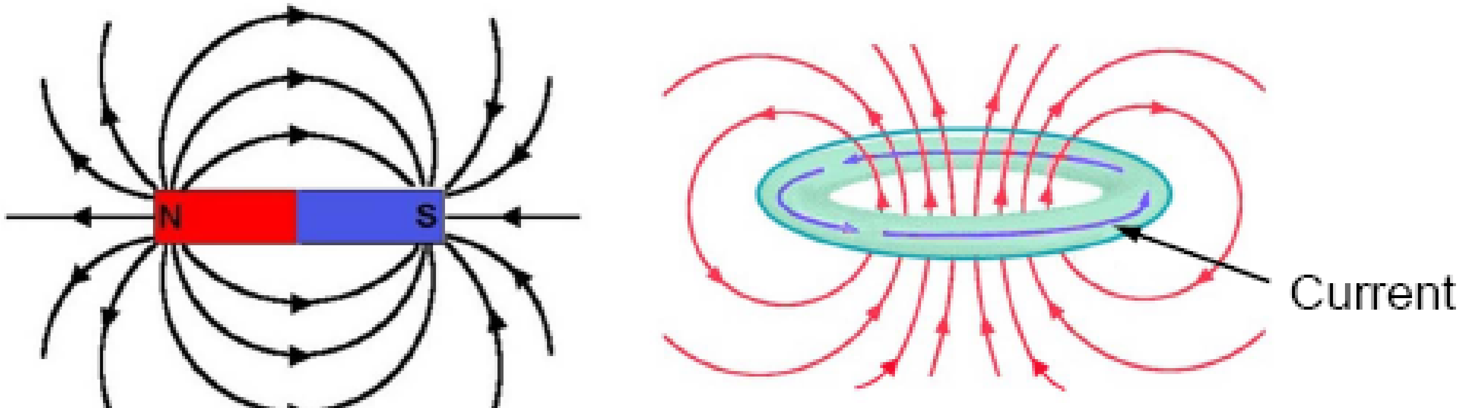
Magnetic field

➢Magnetic field is a force which is generated due to energy change in a volume of space.

➢A magnetic field is produced by an electrical charge in motion e.g. current flowing in a conductor, orbital movement and spin of electrons.

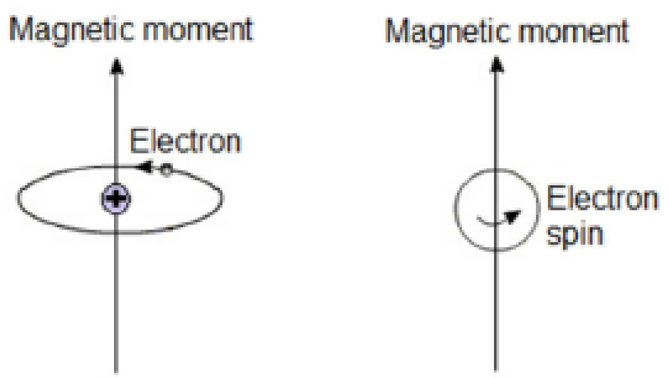
➢The magnetic field can be described by imaginary lines as shown in the figure below for a magnet and a current loop.

Magnetic lines of force



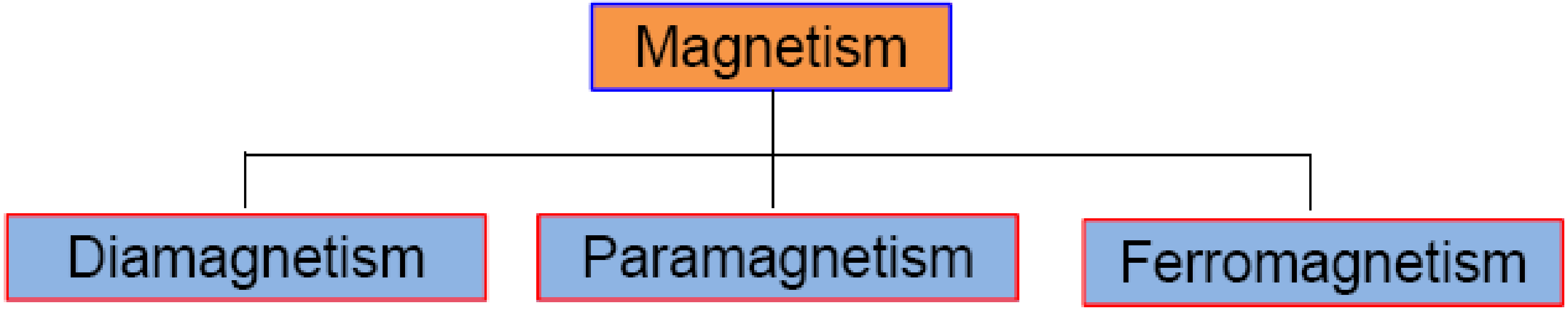
Magnetic moments

- Being a moving charge, electrons produce a small magnetic field having a magnetic moment along the axis of rotation.
- The spin of electrons also produces a magnetic moment along the spin axis.
- Magnetism in a material arises due to alignment of magnetic moments.



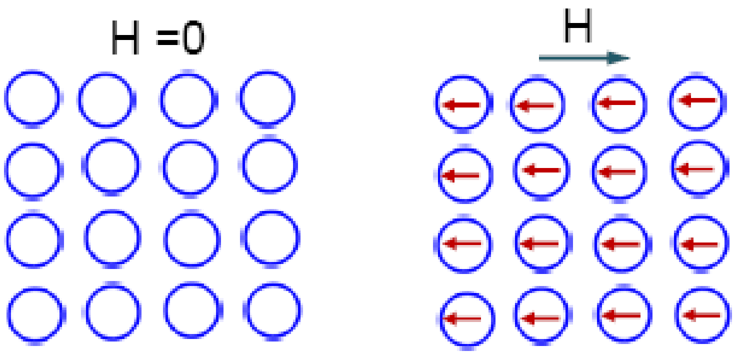
Magnetism

- Depending on the existence and alignment of magnetic moments with or without application of magnetic field, three types of magnetism can be defined.



Diamagnetism

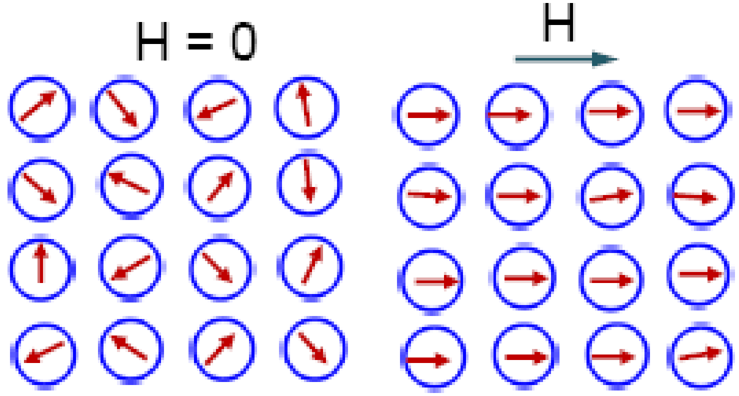
- Diamagnetism is a weak form of magnetism which arises only when an external field is applied.
- It arises due to change in the orbital motion of electrons on application of a magnetic field.
- There is no magnetic dipoles in the absence of a magnetic field and when a magnetic field is applied the dipole moments are aligned opposite to field direction.
- The magnetic susceptibility, χ_m ($\mu_r - 1$) is negative i.e. *B* in a diamagnetic material is less than that of vacuum.



Diamagnetic materials:
Al_2O_3, Cu, Au, Si, Zn

Paramagnetism

- In a paramagnetic material the cancellation of magnetic moments between electron pairs is incomplete and hence magnetic moments exist without any external magnetic field.
- However, the magnetic moments are randomly aligned and hence no net magnetization without any external field.
- When a magnetic field is applied all the dipole moments are aligned in the direction of the field.
- The magnetic susceptibility is small but positive. i.e. *B* in a paramagnetic material is slightly greater than that of vacuum.



Paramagnetic materials:
Al, Cr, Mo, Ti, Zr

Ferromagnetism

- Certain materials posses permanent magnetic moments in the absence of an external magnetic field. This is known as ferromagnetism.
- Permanent magnetic moments in ferromagnetic materials arise due to uncancelled electron spins by virtue of their electron structure.
- The coupling interactions of electron spins of adjacent atoms cause alignment of moments with one another.

Ferrimagnetism

- In physics, a **ferrimagnetic** material is one that has populations of atoms with opposing magnetic moments, as in antiferromagnetism.

- However, in ferrimagnetic materials, the opposing moments are unequal and a spontaneous magnetization remains.

- This happens when the populations consist of different materials or ions

Optical properties

- The optical properties of engineering materials are useful in different applications.

  Ex.: domestic, medicine, astronomy, manufacturing.

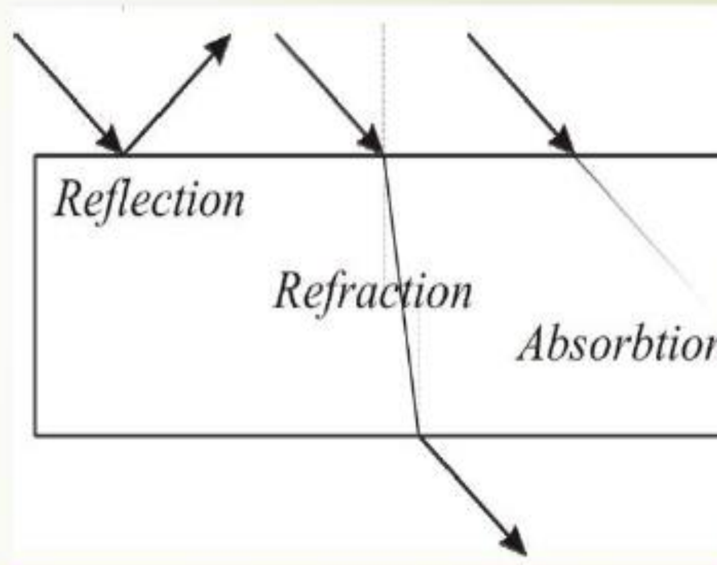
- Materials are classified on the basis of their interaction with visible light into three categories.
- Materials that are capable of transmitting light with relatively little absorption and reflection are called *transparent materials* i.e. we can see through them.
- *Translucent materials* are those through which light is transmitted diffusely i.e. objects are not clearly distinguishable when viewed through.
- Those materials that are impervious to the transmission of visible light are termed as *opaque materials*. These materials absorb all the energy from the light photons.

Optical properties - Metals

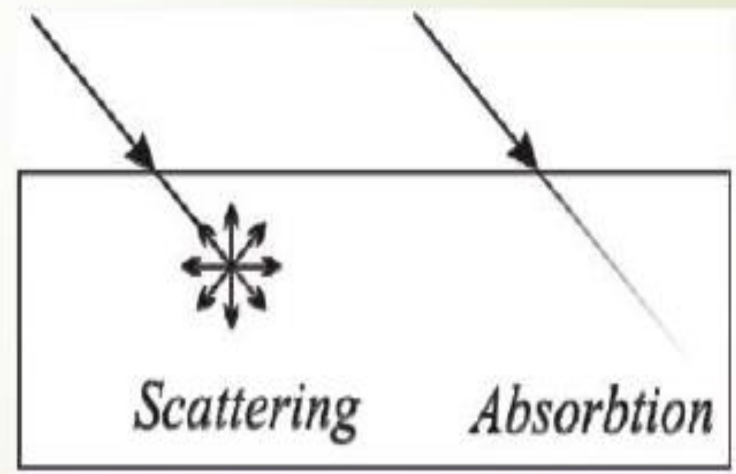
- Metals consist partially filled high-energy conduction bands.
- When photons are directed at metals, their energy is used to excite electrons into unoccupied states. Thus metals are opaque to the visible light.
- Metals are, however, transparent to high end frequencies i.e. x-rays and γ-rays.
- Absorption of takes place in very thin outer layer. Thus, metallic films thinner than 0.1 μm can transmit the light.
- The absorbed radiation is emitted from the metallic surface in the form of visible light of the same wavelength as reflected light. The reflectivity of metals is about 0.95.

Optical Properties

- Many of the optical properties are closely related to the electrical properties of the material. But as we shall see other factors also come into the picture when dealing with Optical Properties
- OPTICAL = "Operating in or employing in the visible part of the electromagnetic spectrum" **OR** "relating to sight, especially in relation to the action of light".
- The simple picture start by considering a 'ray' of an electromagnetic wave of a single frequency entering a medium from vacuum. This could be **reflected, transmitted (refracted) or absorbed.**



- The reflection could be specular or diffusion.
- From more fundamental perspective., there are only two possibilities of interaction of a medium with electromagnetic radiation
    i. Scattering
    ii. Absorption
- If one considers a wider spectrum of frequencies, the some part of the spectrum could be absorbed while the other frequencies could be scattered.



List of Properties

1) Absorbance – How strongly a chemical attenuates light

2) Birefringence – is the optical property of a material having a refractive index that depends on the polarization and propagation direction of light.

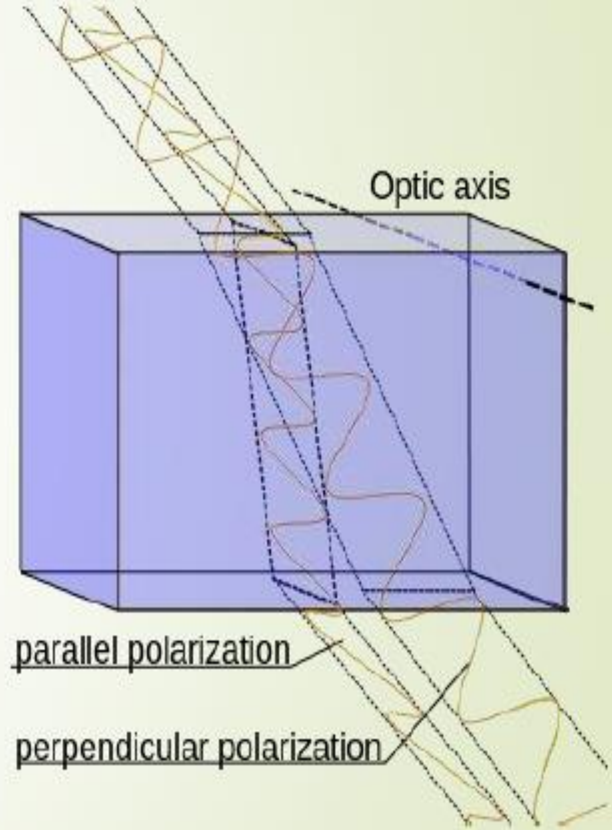
3) Luminosity – It is the amount of electromagnetic energy a body radiates per unit time.

   - It is most frequently measured in two forms :

   I. Visual (visible light only)

   II. Bolometric (Total radiant energy)

4) Photosensitivity – is the amount to which an object reacts upon receiving photons, especially visible light.



5) Refractive Index (n) – is a dimensionless number that describes how light propagates through the medium.

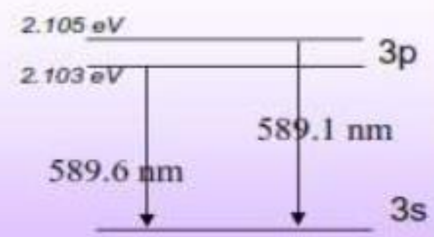
$$n = \frac{c\,(Velocity\ in\ Vaccum)}{V(Velocity\ in\ Medium)}$$

6) Scattering – is a general physical process where some forms of radiation, such as light, sound, or moving particles, are forced to deviate from a straight trajectory by one or more path due to localized no-uniformities in the medium through which they pass.

7) Transmittance – of the surface of a material is its effectiveness in transmitting radiant energy. It is the fraction of incident electromagnetic power that is transmitted through a sample, in contrast to the transmission coefficient, which is the ratio of the transmitted to incident electric field.

Origin of Colour

Origin of colour
- Absorption/emission
- Reflection/Transmission
- Scattering — Blue sky
- Dispersion — Prism
- Interference — Oil films on water, CD, Butterfly wing



- Atomic electronic transitions can give rise to colour : Yellow colour of sodium in flame test

Electro-optics

- **Electro-optics** is a branch of electrical engineering, electronic engineering, materials science, and material physics involving components, devices (e.g. Lasers, LEDs, waveguides etc.) and systems which operate by the propagation and interaction of light with various tailored materials.
- It is essentially the same as what is popularly described today as photonics. It is not only concerned with the "Electro-Optic effect". Thus it concerns the interaction between the electromagnetic (optical) and the electrical (electronic) states of materials.

Magneto-optic effect

- Any one of a number of phenomena in which an electromagnetic wave interacts with a magnetic field, or with matter under the influence of a magnetic field.

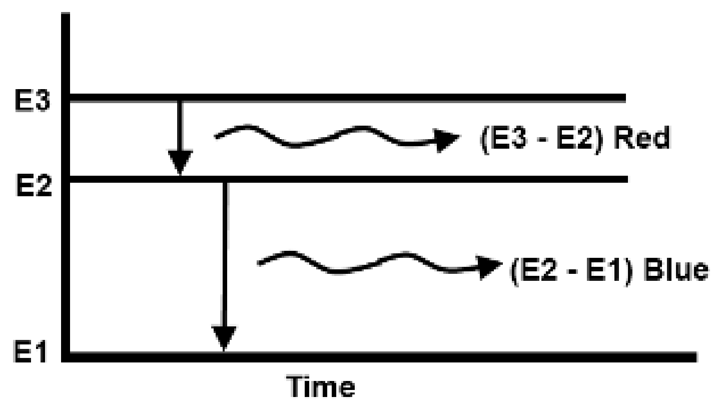
- *Note:* The most important magneto-optic effect having application to optical communication is the Faraday effect, in which the plane of polarization is rotated under the influence of a magnetic field parallel to the direction of propagation. This effect may be used to modulate a lightwave.

Spontaneous and Stimulated Emission

Spontaneous Emission

We know that when an atom absorbs extra energy and goes in excited state. To return to its normal or ground state it emits the absorbed extra energy (photon) at an undetermined time. This unpredictable release of photon energy by an atom is called the spontaneous emission. Spontaneous emission occurs at random and the emission of atom has no relationship to any other atom.

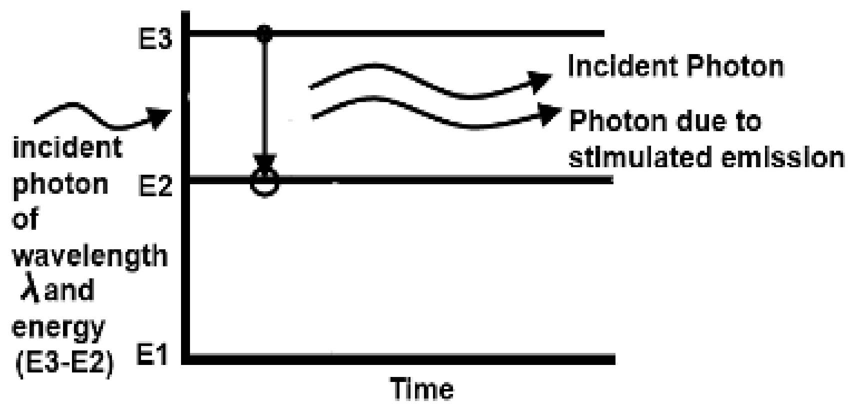
By energy level diagram, the spontaneous emission can be shown as:



Stimulated emission

The stimulated emission occurs when a photon with the correct wavelength approaches to an excited atom. If the excited atom has the energy structure such that an electron can drop to the lower level and release an amount of energy equal to the energy or wavelength of incident photon then photon will be emitted from the excited atom. This photon is identical in all respects to the incident photon. Therefore after stimulated emission, the two photons travel in the same direction, have the same wavelength and are coherent.

By energy level diagram, the stimulated emission can be shown as:



From this diagram it is clear that stimulated emission has increased the number of photons.

Spontaneous emission	Stimulated emission
The transition of an electron from the excited state to the ground state happens as a result of the natural tendency of the electron without the action of any external agent. The radiation produced as a result of such transitions is called as spontaneous radiation.	Stimulated emission of radiation is the process whereby photons are used to generate other photons that have exact phase and wavelength as that of parent photon.
This phenomenon is found in LEDs, Fluorescent tubes.	This is the key process of formation of laser beam.
There is no population inversion of electrons in LEDs.	Population inversion is achieved by various ‘pumping’ techniques to get amplification giving the LASER its name “Light amplification by stimulated emission of radiation.”
No external stimuli required.	Thus stimulated emission is caused by external stimuli.

LASER

What is a laser?

- LASER stands for Light Amplification by Stimulated Emission of Radiation. A laser is a device which produces highly directional light. It emits light through a process called stimulated emission of radiation which increases the intensity of light.
- A laser is different from conventional light sources in four ways: coherence, directionality, monochromacity, and high intensity.
- The light waves of ordinary light sources have many wavelengths. Hence, the photons emitted by ordinary light sources are out of phase. Thus, ordinary light is incoherent.
- On the other hand, the light waves of laser light have only one wavelength. Hence, all the photons emitted by laser light are in phase. Thus, laser light is coherent.
- The light waves from laser contain only one wavelength or color so it is known as monochromatic light.
- The laser beam is very narrow and can be concentrated on a very small area. This makes laser light highly directional.
- The laser light spreads in a small region of space. Hence, all the energy is concentrated on a narrow region. Therefore, laser light has greater intensity than the ordinary light.

Types of lasers

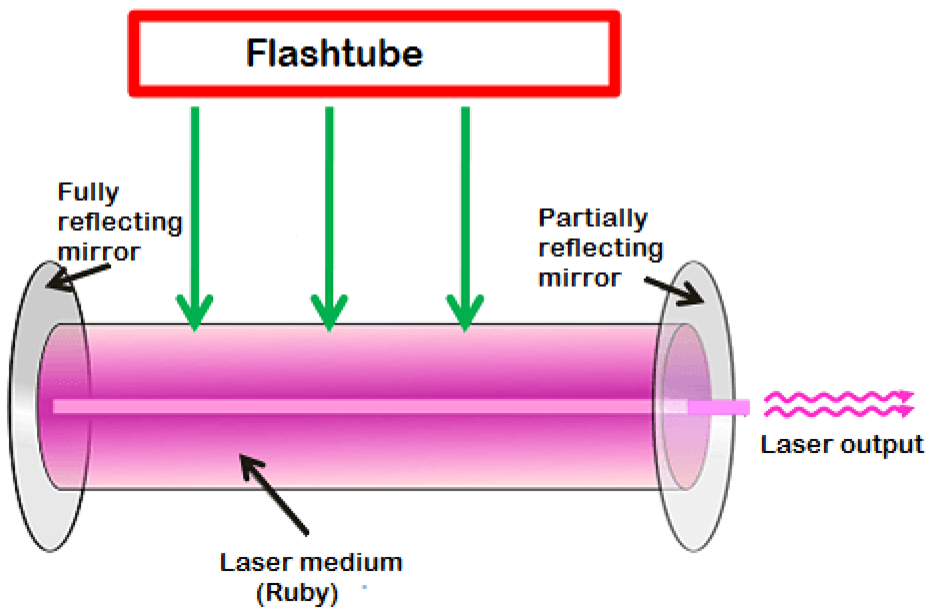
Lasers are classified into 4 types based on the type of laser medium used:

- Solid-state laser
- Gas laser
- Liquid laser
- Semiconductor laser

Solid-state laser

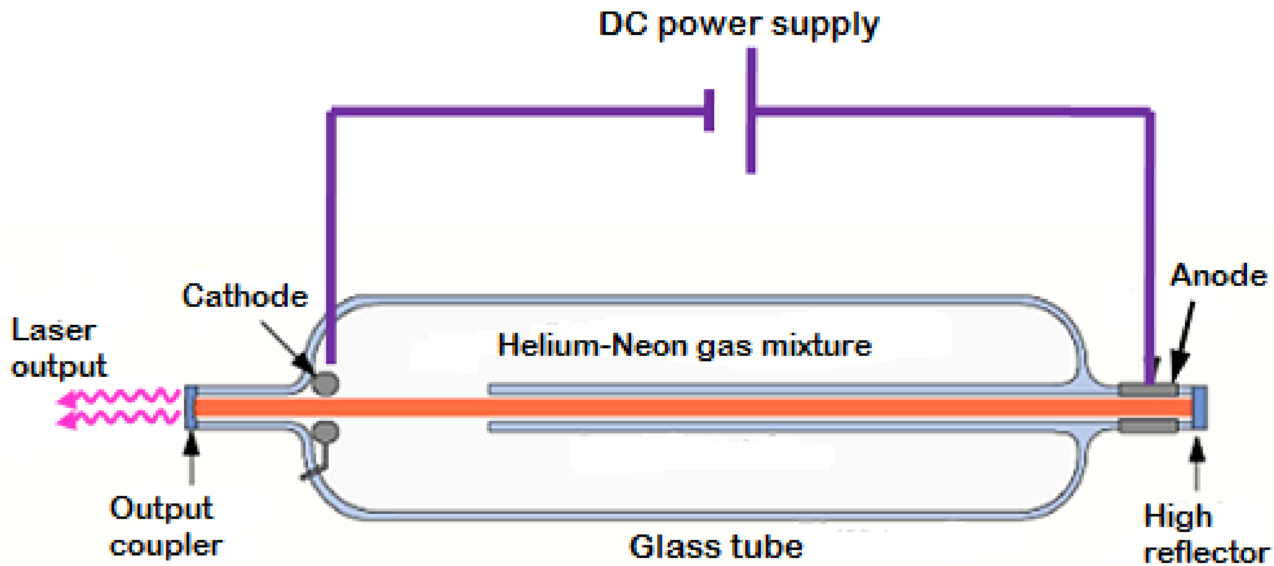
- A solid-state laser is a laser that uses solid as a laser medium. In these lasers, glass or crystalline materials are used.

- Ions are introduced as impurities into host material which can be a glass or crystalline. The process of adding impurities to the substance is called doping. Rare earth elements such as cerium (Ce), erbium (Eu), terbium (Tb) etc are most commonly used as dopants.
- Materials such as sapphire (Al_2O_3), neodymium-doped yttrium aluminum garnet (Nd:YAG), Neodymium-doped glass (Nd:glass) and ytterbium-doped glass are used as host materials for laser medium. Out of these, neodymium-doped yttrium aluminum garnet (Nd:YAG) is most commonly used.
- The first solid-state laser was a ruby laser. It is still used in some applications. In this laser, a ruby crystal is used as a laser medium.



Gas laser

A gas laser is a laser in which an electric current is discharged through a gas inside the laser medium to produce laser light. In gas lasers, the laser medium is in the gaseous state.



- Gas lasers are used in applications that require laser light with very high beam quality and long coherence lengths.
- In gas laser, the laser medium or gain medium is made up of the mixture of gases. This mixture is packed up into a glass tube. The glass tube filled with the mixture of gases acts as an active medium or laser medium.
- A gas laser is the first laser that works on the principle of converting electrical energy into light energy. It produces a laser light beam in the infrared region of the spectrum at 1.15 µm.
- Gas lasers are of different types: they are, Helium (He) – Neon (Ne) lasers, argon ion lasers, carbon dioxide lasers (CO_2 lasers), carbon monoxide lasers (CO lasers), excimer lasers, nitrogen lasers, hydrogen lasers, etc. The type of gas used to construct the laser medium can determine the lasers wavelength or efficiency.