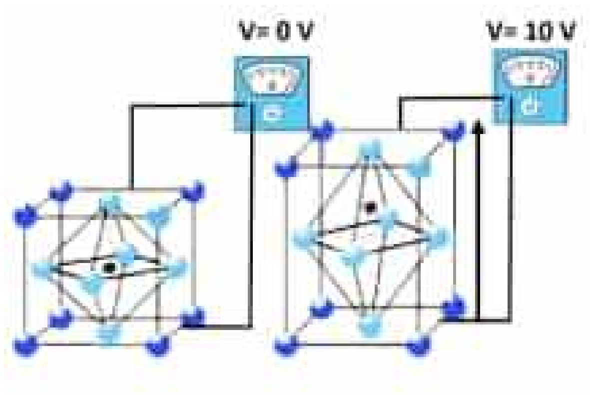
Unit 21 Physics of Solids

Teaching Periods 11 **Weightage %** 07



The Piezoelectric effect is the ability of certain materials to generate an electric charge in response to mechanical stress, such as pressure, vibration, or stretching, causing the material's internal electric dipoles to align and produce a voltage across the material, with the magnitude of the charge being directly proportional to the applied stress, allowing the material to convert mechanical energy into electrical energy.

In this unit student should be able to:

- Distinguish between the structure of crystalline, glassy, amorphous and polymeric solids.
- Describe that deformation in solids is caused by a force and that in one dimension; the deformation can be tensile or compressive
- Define and use the terms Young's modulus, bulk modulus and shear modulus.
- Demonstrate the force-extension graphs for typical ductile, brittle and polymeric materials.
- Become familiar ultimate tensile stress, elastic deformation and plastic deformation of a material.
- Describe the idea about energy bands in solids.
- Classify insulators, conductors, and semiconductors on the basis of energy bands.
- Become familiar with the behavior of superconductors and their potential uses.
- Describe the applications of superconductors in magnetic resonance imaging (MRI), magnetic levitation trains, powerful but small electric motors and faster computer chips.
- Distinguish between dia, para and Ferro magnetic materials.
- Describe the concepts of magnetic domains in a material.
- Explain the Curie point. Classify hard and soft ferromagnetic substances.
- Describe hysteresis loss.
- Synthesis from hysteresis loop how magnetic field strength varies with magnetizing current.
- Identify the importance of hysteresis loop to select materials for their use to make them temporary magnets or permanent magnets.

Introduction:

The Physics of solids is a branch of physics that deals with the study of the physical properties of solid materials, including their electronic, magnetic, optical, thermal and mechanical properties. It aims to understand the behavior of solid materials under different conditions, such as temperature, pressure and electromagnetic fields, using principles of quantum mechanics.It also helps to explain phenomenon like crystal structures, phase transitions, defects in material, and the interactions between electrons, ions and atoms in solids.

For example, a key hurdle to enhance solar power which is an affordable energy source. It is increasing the efficiency of photovoltaic cells that convert solar radiation to electricity, making solid materials in solar cells as conductive as possible

DO YOU KNOW?

John B, who credited for the identification and initial development of the first lithium-ion (Li-ion) batteries. He realized how a battery with lithium anode could provide high charge density and thus give us the pre-requisite technology for electric cars, and smart phones.

21.1 Classification of Solids:

Solids are usually crystalline substances their molecules are arranged in a definite pattern and in fixed positions.The way in which a solid behaves depends on its internal structure and there are three types of solid.

(i) Crystalline solids (ii) Amorphous solids (iii) Polymeric solids

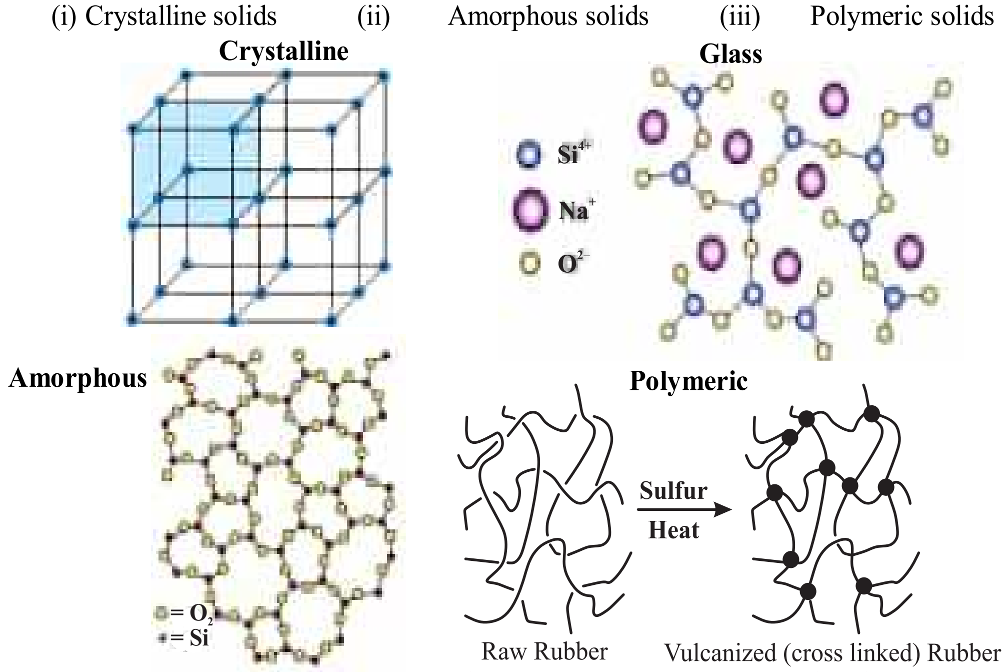


Figure 21.1 structures of crystalline, glassy, amorphous and polymeric solids

21.1.1 Distinguish between structure of crystalline, glassy, amorphous and polymeric solids:

Property	Crystalline Solids	Glassy Solids	Amorphous Solids	Polymeric Solids
Atomic Arrangement	Regular, Repeating pattern.	Random, short-range order.	Random, no long-range order.	Long chains or networks of repeating units.
Melting Point	Sharp, Specific temperature.	Gradual, over a range of temperature.	Gradual, over a range of temperatures.	Varies, typically lower than crystalline solids.
Rigidity	Very rigid and well-defined structure.	Rigid, but less than crystalline solids.	Not as rigid as crystalline solids.	Can be flexible or rigid.
Transparency	Can be transparent or translucent.	Transparent or opaque depending on composition.	Opaque.	Depending on structures, can be transparent or opaque.
Examples	Diamond, salt crystals, silicon.	Window glass, certain plastics, amorphous metals.	Rubber, some plastics, glass.	Polyethylene, PVC, nylon.

21.1.1 Deformation:

In material science, deformations refer to modifications of the shape or size of an objectdue to applied forces or a change in temperature. Deformation is usually caused by forces such as tensile (pulling) or Compressive (pushing) as shown in figure 21.2. As deformations occurs, internal inter-molecular forces arise that oppose the applied force.Different types of deformations may result from variations in type of material, size and the forces applied.

Deformation in one dimension (1D):

Stress:

It is usually defined as force applied to a material per unit area.Stress is a quantity which defines the magnitude of force that cause deformation.

Strain:

Strain is a measure of how much a material deforms (stretches or compresses) when a force is applied to it. It is calculated by dividing the change in length by the original length of the material:

When pulling force on an object is applied which causes elongation, like the stretching of an elastic band, we call such stress a tensile stress. When forces cause a compression of an object, we call it a compressive stress. As illustraded in Figure 21.2.

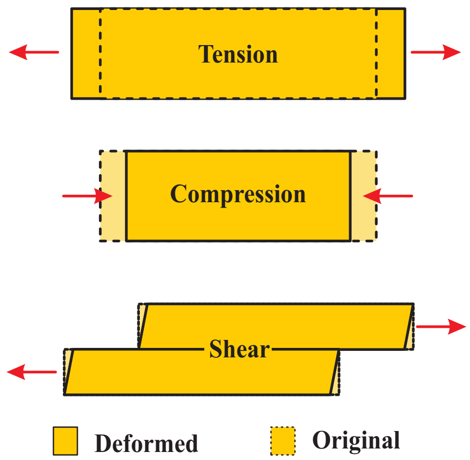


Figure 21.2 Deformation in one dimension

The greater the stress, the greater the strain; however, the relation between strain and stress does not need to be linear. When stress is sufficiently low, deformation is causesd in direct proportion to the stress value. The proportionality constant in this relation is calledthe **elastic modulus**. In the linear limit of low stress values, the general relation between stress and strain is known as Hooke's law is given as under

Stress =(elastic modulus)$\times$Strain

We can also see from above equation that when an object is characterized by a large value of elastic modulus, the effect of stress is small. On the other hand, a small elastic modulus means that stress produces large strain and noticeable deformation happens. For example, a stress on a rubber band produces larger strain (deformation) than the same stress on a steel band of the same dimensions because the elastic modulus for rubber is two orders of magnitude smaller than the elastic modulus for steel.

DO YOU KNOW?

The zircons, the oldest known terrestrial materials, have helped portray how the Earth's crust formed during the first geologic eon of the planet. "This may also help us understand how other habitable planets would form.

21.2 Mechanical Properties of Solids

Mechanical properties of solids refer to the characteristics that describe how a solid material responds to applied forces or deformation; some important mechanical properties of solid are Elasticity, Ductility, Brittleness, and Hardness etc.

21.2.1 Young's Modulus (modulus of elasticity)

It is a mechanical property of solids that measures the stiffness or elasticity of a solid material and it computes how much a material will deform (stretch or compress) under a given force.

It is denoted by the symbol Y and has units of $Y = \frac{\text{Force}}{\text{Area}}$ or (Pascal, Pa or N/m^2).

It is a measure of a material's resistance to elastic deformation when subjected to an external force. The higher the Young's Modulus, the stiffer the material.

For example, steel has a higher Young's Modulus than rubber, which makes steel more resistant to deformation than rubber when subjected to a force.

The amount of extension of an object depends upon

i) Applied force
ii) Material
iii) Dimension

If we compare rods made of the same material having different lengths and cross-sectional areas, it is found that the longer the object, the more it elongates for a given stress; and the thicker it is, the less it elongates because strain is proportional to the original length and inversely proportional to the cross-sectional area.

Then Hooke's law can be written for Young's Modulus is defined as the ratio of stress to strain.

$$Y = \frac{Stress}{Strain}$$

$$Y = \frac{\frac{F}{A}}{\frac{\Delta L}{L}}$$

$$Y = \frac{F \times L}{\Delta L \times A} \quad \ldots\ldots\ldots (21.1)$$

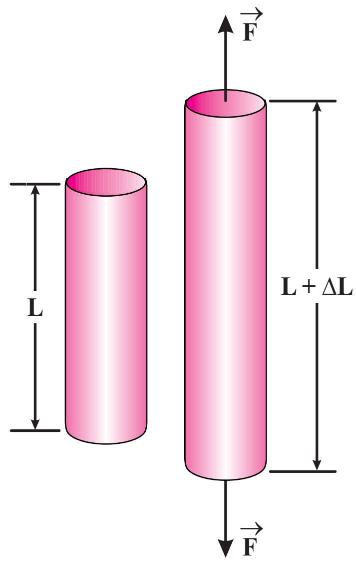


Figure 21.3 longitudinal stress

Worked Example 21.1

Calculate the change in length of the upper leg bone (the femur) when a 70.0 kg man supports 62.0 kg of his mass on it, assuming the bone to be equivalent to a uniform rod that is 40.0 cm long and2.0 cm in radius. Young's modulus for bones is 19×10^9 N/m^2.

Solution:

Step 1: data

Mass of man = 70.0 kg
Mass supported by leg = 62.0 kg
Length of leg, L = 40.0 cm = 0.4 m
Radius of bone = 2.0 cm = 0.02 m
Young's modulus, Y = 19×10^9 N/m^2.
Change in length, ΔL = ?

Step 2:

F= W = mg = 62.0 × 9.8 = 607.6 N

Step 3: Calculate the cross-sectional area:

$A = \pi r^2 = (3.14)(0.02)^2 = 12.56 \times 10^{-4} m^2$

Now calculate the change in length

$$Y = \frac{F \times L}{\Delta L \times A}$$

$$\Delta L = \frac{F \ x \ L}{A \ x \ Y}$$

$$= \frac{607.6 \times 0.40}{19 \times 10^9 \quad \times \quad 1.256 \times 10^{-4}}$$

$$\Delta L = 1.01 \times 10^{-5}\ m$$

Result: $\Delta L = 1.01 \times 10^{-5}\ m$

Self-Assessment Questions:

1. Calculate the amount of stretch in steel cable. Suspension cables are used to carry gondolas at Murree Hills. Consider a suspension cable that contains an unsupported span of 1.5 km with diameter of 3.0 cm, with maximum tension it can withstand is 3.0×106N.

21.2.2 Shear Modulus:

Shear modulus, also known as the modulus of rigidity is a mechanical property that describes a material's resistance to shear deformation when a force is applied perpendicular to the material's surface. It is denoted by the symbol G or S and has units of force per unit area, typically expressed in Pascal (Pa) or Giga Pascal (GPa).

Shear modulus is the measure of the rigidity of the body which is the ratio of shear stress to shear strain.
Consider a rigid body as shown in figure 21.4. When acted upon by tangential force to twist it.

The shear stress is F/A and shear strain is ΔX/L. Therefore, the shear modulus becomes

$$G = \frac{\frac{F}{A} \times L}{\Delta x}$$

Table: No 21.1

Material	G(10^9 Nm^2 or GPa)
Aluminum	25
Brass	36
Copper	42
Glass	23
Iron	70
Lead	5.6
Nickel	77
Steel	84
Tungsten	150
Wood	10
Diamond	450
Rubber	0.1

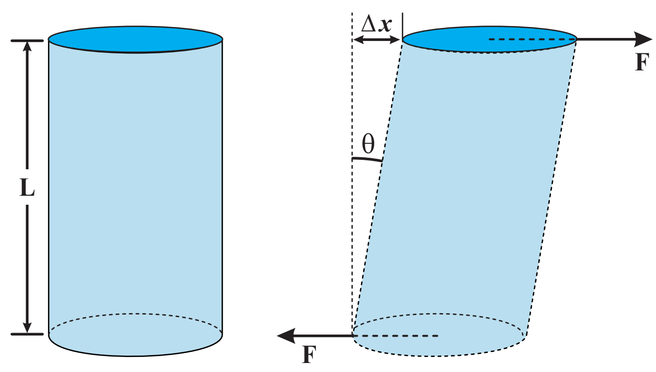


Figure 21.4: shear modulus

$$ShearingStrain = \Delta X = \frac{\tan\theta}{l} \quad \ldots\ldots\ldots (21.2)$$

Worked Example 21.

The area of the upper face of a rectangular block is 0.25 m^2 and the lower face is fixed. The height of the block is 1.5 cm, a shearing force applied to the top face which produces a displacement of 0.0152 mm. Find the strain, stress and the shearing force. Modulus of rigidity is 4.5×10^{10} N/m^2.

Solution:

Step 1:data

$Area\ under\ shear\ =\ 0.25\ m^2$

$Height\ of\ block\ =\ 1.5\ cm\ =\ 1.5\ \times 10^{-2}\ m$

$Displacement\ of\ top\ face\ =\ 0.0152\ mm\ =\ 0.0152\ \times 10^{-3}\ m$

$Modulus\ of\ rigidity\ = G\ =\ 4.5\ \times 10^{10}\ N/m^2.$

$Shear\ Strain\ =?$

$Shear\ Stress\ =?$

Shearing Force =?

Step 2: Formula:

$Shearing\ Strain\ =\ \Delta X/L$

Step 3: Calculations: Shearing Strain

$$Shearing\ Strain = \frac{0.0152\times10^{-3}}{1.5\times10^{-2}}$$

Shearing Strain = 1.01×10^{-3}

Shear Stress = G × Shearing Strain

Shear stress= $4.5\times10^{10}\times 1.01\times10^{-3}$

Shearing Stress = 4.56×10^{7} N/m^2

Shear Stress = F /A

F = Shear Stress × A

F = $4.56\times 10^{7}\times 0.25$

F = 1.14×10^{7} N

Result: F = 1.14×10^{7} N

21.2.3 Bulk Modulus:

Bulk modulus, also known as the modulus of compressibility, is a mechanical property that describes the resistance of a material to compression under uniform external pressure. It is denoted by the symbol K and has units of pressure (usually expressed in Pascal, Pa or Giga Pascal (GPa).

Bulk modulus is defined as the ratio of the change in pressure applied to a material to the resulting fractional change in volume that occurs in the material. Mathematically, it is expressed as:

$$\frac{\Delta V}{V} = -\frac{\Delta P}{B}$$

DO YOU KNOW?

Compressibility

The reciprocal of bulk modulus of elasticity is called as compressibility

$Compressibility = 1/B$

Its SI unit is m2 /N or Pa.

Material	Bulk modulus
Air	100KPa
Water	2.2 GPa
Steel	150GPa
Diamond	443 GPa

$$B = -\frac{\Delta P}{\frac{\Delta V}{L}} \ldots\ldots\ldots\ldots (21.3)$$

where B is the bulk modulus, ΔP is the change in pressure applied to the material, ΔV is the resulting change in volume, and V is the original volume of the material.

21.2.4 Force– Extension Graph:

In material science, the force versus extension graph for a material gives the relationship between stress and strain. This is obtained by gradually applying a load to a test component and measuring its deformation according to tensile standards. These curves reveal many of properties of materials, such as the young's modulus, the yield strength, the ultimate tensile strength and so on. For different types of materials as shown in figure 21.5,

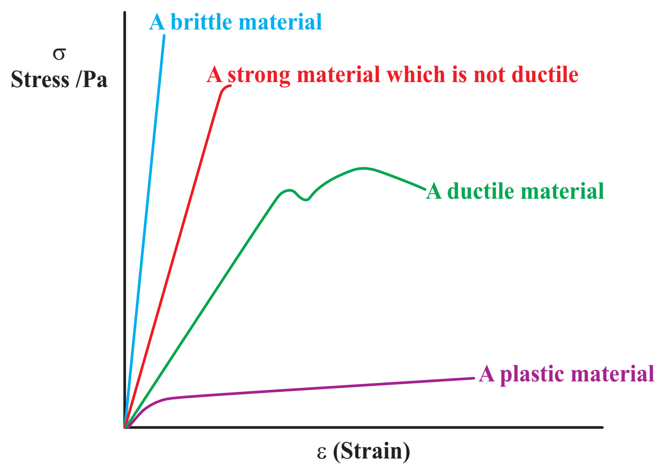


Figure 21.5 force extension graph reveals the properties of different materials

The blue line (brittle) represents the behavior of a typical elastic material, which follows Hooke's Law. As the material is stretched, the force applied to it increases linearly with the extension, up to a point called the yield point. The material eventually reaches a maximum point of extension, is called the ultimate extension or fracture point, beyond which it breaks or fractures.

The green line (ductile) represents the behavior of a typical viscoelastic material, which exhibits time-dependent deformation under a constant force. In this case, the material initially undergoes elastic deformation, similar to the elastic material, but then continues to deform slowly over time under a constant force, eventually reaching a maximum extension or creep limit.

DO YOU KNOW?

Viscoelastic materials combine the properties of rubber and slush, deforming and flowing when stressed. They absorb and dissipate energy over time, making them ideal for shock absorbers, vibration reduction, and noise dampening. Examples include rubber, plastics, oil, and molten glass, which are valuable in engineering for designing durable products like gaskets and automotive parts that withstand repeated stress and deformation.

DO YOU KNOW?

Silk is a natural polymer that is widely used worldwide in textiles. Silk threads are extremely light, but are very strong relative to their weight. It is extremely ductile, so it can bend and stretch without breaking.

The purple line (Plastic) represents the behavior of a typical plastic material, which exhibits permanent deformation when subjected to a force. In this case, the material undergoes plastic deformation immediately, with no linear region or yield point, and continues to deform permanently as the force is increased, until it ultimately fractures or breaks.

The Red line is showing strong material which is not ductile, like steel wires stretch very little and breaks suddenly.

Polymeric Materials:

Polymer curves are produced by stretching a sample at a constant rate through the application of a tensile force. By using a constant rate of testing the strain-rate dependency of polymer behavior is not allowed to dominate. However, it should be appreciated that polymers have a marked inherent time - dependence in their response to deformation, which sets their behavior apart from other classes' materials.

21.2.5 Graph of Ultimate tensile stress, elastic deformation and plastic deformation:

Figure 21.6, represents the graph of applied force versus elongation up to a point is called the proportional limit. Hooke's law is the best approximation for many common materials, and the curve is a straight line. Beyond this point, the graph deviates from a straight line, and no simple relationship exists between F and Δl. Nonetheless, up to a point farther along the curve called the elastic limit, the object will return to its original length if the applied force is removed. The region from the origin to the elastic limit is called elastic region. If the object is stretched beyond the elastic limit, it enters the plastic region: it does not return to the original length upon removal of the external force, but remains permanently deformed (such as bent paper clip shown in figure 21.7) such is elastic deformation. The maximum force that can be applied without breaking is called ultimate tensile strength of the material. If the stretching of bonds happens but the atoms do not slip past each other, when the stress is sufficient to permanently deform the metal i.e., soft metal like silver, gold, it is called plastic deformation.

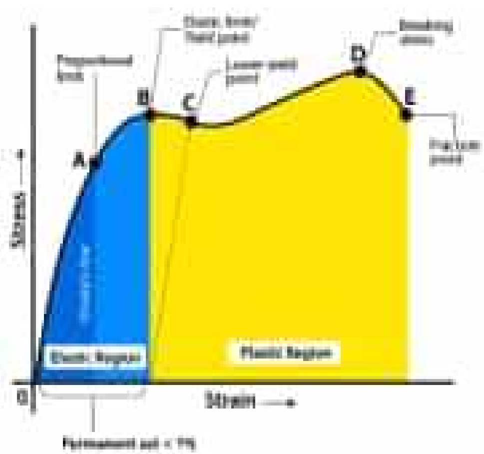


Figure 21.6 Applied force vs elongation


Figure 21.7 elastic deformation

21.3 Electrical Properties of Solids:

The electrical property of a good conductor depends on its ability to transmit energy without boiling, melting, or changing its composition in any way.

- **Resistivity:** The resistance per unit length and cross-sectional area is called resistivity. It varies from material to material. Its SI unit is Ohm-meter (Ω - m).
- **Conductivity:** It is a measure of a material's ability to conduct electric current, which is influenced by the availability and mobility of charge carriers within the solid.
- **Temperature Coefficient of resistivity:** The temperature coefficient of resistance is defined as the change in electrical resistance of a substance with respect to per degree rise in temperature. When the temperature increases, the process of electron collision becomes rapid and faster. As a result, the resistance will increase with the rise in temperature of the conductor.
- **The quantity of charge carriers' n,** the number of chare carriers per unit volume, can be found from measurement of the Hall Effect. Its SI unit is m^{-3}.

21.3.1 Energy Bands in Solids:

When isolated atoms comes together to form a solid, interactions between neighboring atoms cause the electron energy levels to split and overlap, creating continuous energy bands.

Valence Band:

The valence band is the range of energy levels occupied by electrons that are bound to atoms and participate in chemical bonding. It is the highest energy band that contains electrons under normal conditions.

Forbidden Band (Energy Gap):

The forbidden band, or energy gap, is the range of energy levels between the valence band and the conduction band where no electron states exist. This gap influences the material's electrical properties; a larger gap typically means the material is less conductive.

Conduction Band:

The conduction band is the range of energy levels where electrons are free to move throughout the material, allowing electrical conduction. Electrons in the conduction band are not bound to any particular atom and can carry electric current through the solid.

In the case of a diamond crystal, carbon atoms with the electronic structure $1s^2\ 2s^2\ 2p^2$ form two main energy bands as shown in figure, 21.8. The valence band and the conduction band are separated by an energy gap known as the "forbidden band." The valence band contains the lower

DO YOU KNOW?

The Pauli Exclusion principle states that "No two electrons in a given interacting system may have the same quantum state". Thus there must be a splitting of the discrete energy levels of the isolated atoms into new level belonging to the pair, other than to individual atoms

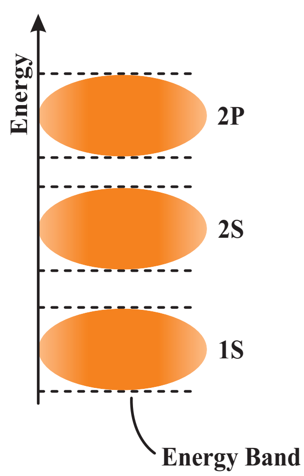


Figure 21.8 energy Bands

energy states, while the conduction band contains higher energy states. This energy gap prevents electrons in the valence band from easily moving to the conduction band, significantly influencing the electrical properties of the solid, such as its ability to conduct electricity.

21.3.2 Classification of Solids:

Depending on the electrical conductivity solids are classified into three main categories: conductors, semiconductors and insulators, as shown in figure 21.9.

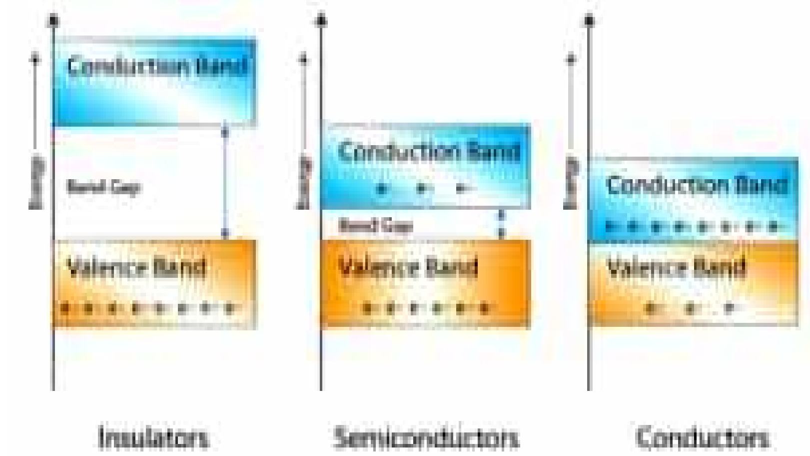


Figure 21.9 Classifications of Solids in three main categories: Insulators, Semiconductors and conductors

Insulators:

These materials do not conduct electricity. The band gap between the valence band and conduction band is very large. Even if a large amount of energy is provided to these solids, they do not conduct electricity. such as wood, plastics etc.

Conductor:

There is no gap between the conduction band and the valence band. Thus, electrons can easily flow from the valence band to the conduction band under the influence of an electric field, making them good conductors of electricity.

Semiconductors:

The gap between the conduction band and the valence band is very less; therefore, whenever sufficient energy is provided to the electrons in a semiconductor, electrons jump from the valence band to the conduction band. The conductivity of the semiconductors increases with an increase in temperature, for semiconductors, it lies in between 10^{-6} to 10^{-4} $(\Omega\ m)^{-1}$. There are two types of semiconductors:

a) Intrinsic semiconductor:

When energy is provided to intrinsic semiconductors like silicon and germanium, electrons leave their positions,

DO YOU KNOW?

Measurements show that the resistivity of super conductors is less than 4×10^{-25} Ω m, which is over 1016 times smaller than copper, and is considered to be zero in practice.

creating positive holes. Under an electric field, electrons and holes move in opposite directions, enabling electrical conductivity. Group IV elements are considered as an interinsic semiconductors

b) Extrinsic semiconductor:

Silicon and germanium have low conductivity at room temperature. Adding small amounts of group III or group V impurities, a process called doping, increases their conductivity, resulting in extrinsic semiconductors.

Intrinsic and extrinsic semiconductor are shown in Figure 21.10

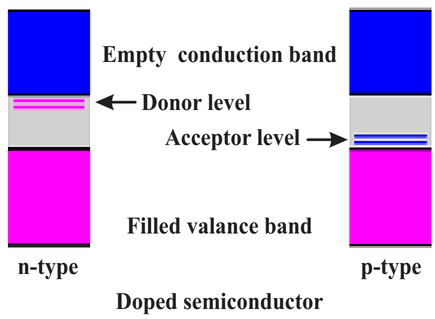


Figure 21.10
Intrinsic and extrinsic semi-conductor

21.3.3 Superconductor:

In 1911, Dutch physicist Heike Kamerlingh Onnes discovered that mercury's resistivity disappears below about 4 Kelvin.

A superconductor is a material that can conduct electricity without resistance when it is cooled below a certain critical temperature, typically near absolute zero. As shown in figure 21.11

This allows charge to flow without energy loss to thermal effects. Superconductors exhibit this behavior below a critical temperature, usually near absolute zero, with resistivity less than $4\times10^{-25}\Omega$-m. They also exhibit perfect diamagnetism, expelling magnetic fields in the superconducting state, known as the Meissner effect, and enabling phenomena like magnetic levitation.

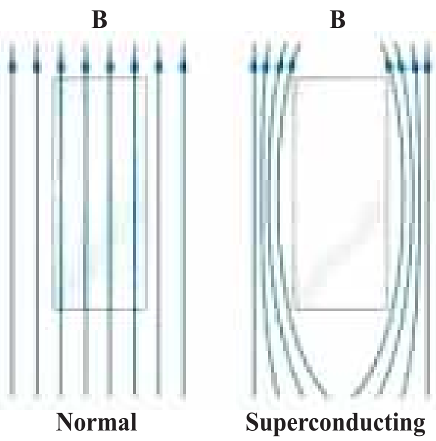


Figure 21.11 supper conductor graph

21.3.4 Super conductor Applications:

Superconductors are used in particle accelerators, generators, transportation, computing, electric motors, medical applications, and power transmission, among other fields.

1. Magnetic Resonance Imaging (MRI):

MRI scanners provide high resolution picture of the tissues inside the body. Superconducting coils produce a strong magnetic field (up to 60,000 times as strong as the intensity of Earth's magnetic field) that is used to align the protons of hydrogen atoms in the body of the

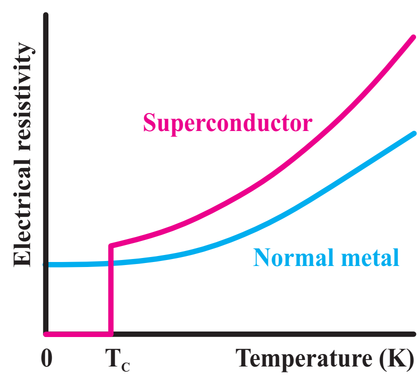


Figure 21.12 Meissner effect super conductors

patient, as shown in figure 21.13. Like electrons, protons have a 'spin' property, so they align with a magnetic field the proton's axis vibrates about the applied magnetic field. Vibrating protons are crashed with a burst of radio waves tuned to push the Protons' spin axes are sideways, perpendicular to the applied magnetic field. When radio waves pass and the protons quickly return to their vibrating pattern, they emit a faint electromagnetic signal whose frequencies depend slightly on the chemical environment in which the proton resides. These signals, detected by sensors, are then analyzed by a computer to reveal varying densities of hydrogen atoms in the body and their interaction s with surrounding tissue. The resulting images clearly distinguish between fluid and bone. MRI was formerly called NMRI (Nuclear Magnetic Resonance Imaging) because hydrogen nuclei resonate with the applied fields.

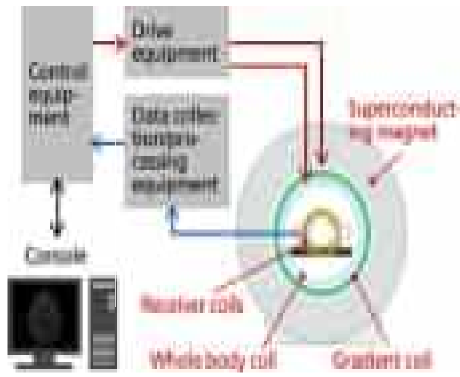


Figure 21.13 working principle of MRI

2. Maglev Train Systems:

Maglev train systems use powerful electromagnets to float the trains over a guide-way, instead of the old steel wheel and track system as shown in figure 21.14. A system called electromagnetic suspension suspends, guides, and propels the trains. A large number of magnets provide controlled tension for lift and propulsion along a track. Maglev (derived from magnetic levitation) is aim of train transportation that uses two sets of magnets: one set to repel and push the train up off the track and another set to move the elevated train ahead, taking advantage of the lack of friction.

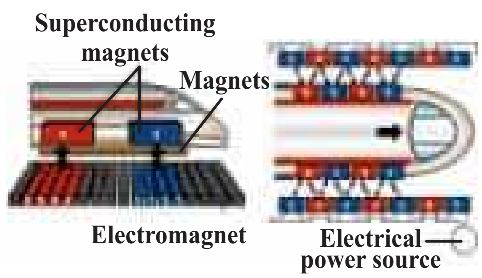


Figure 21.14 Magnetic Levitation

3. Small Electric Motor:

Precision Instruments:

Superconducting motors can be used in precision instruments where high efficiency and low noise are critical.

Medical Devices:

Compact, efficient motors for medical devices such as MRI machines, which already use superconducting magnets.

Aerospace:

High-efficiency, lightweight motors for aerospace applications, where every gram of weight saved is crucial.

Robotics:

Small, powerful motors for advanced robotic applications requiring precise control and high power output.

4. Super Conductivity and Super Computers:

Super conducting components can improve the performance of super computers in several ways as:

Super conducting qubits:

These are the basic building blocks of quantum computers, which are able to perform calculations at speeds that are exponentially faster than classical computers. Superconducting qubits can maintain their quantum states for long periods of time, allowing for complex computations to be performed.

Faster processing speeds:

Super conducting components can process information at much faster speeds than traditional electronic components, resulting in faster computing times and the ability to handle larger datasets.

Lower power consumption:

Super conducting circuits require less power to operate than traditional electronic circuits, reducing energy costs and making them more environmentally friendly.

Improved reliability:

Super conducting components are less prone to errors and can operate for longer periods of time without failure, resulting in more reliable and efficient supercomputers.

However, the use of superconducting components in super computers is still in the experimental stage and faces several challenges.

21.4.1 Magnetic Properties of Solids:

The magnetic properties of solids depend on how their electrons behave in response to an external magnetic field. There are three main types of magnetic materials: ferromagnetic, paramagnetic, and diamagnetic.

Material	Behavior	Examples
Ferromagnetic	Have magnetic moments (tiny magnetic domains) that tend to align parallel to each other. When exposed to an external magnetic field, these materials can become strongly magnetized.	Iron, Cobalt, Nickel.
Paramagnetic	Have individual magnetic moments that are randomly oriented, and they become weakly magnetized when exposed to an external magnetic field	Aluminum Platinum, Titanium
Diamagnetic	Have no intrinsic magnetic moment. When exposed to an external magnetic field, they develop a weak, negative magnetization that opposes the applied field.	Copper, Bismuth.

21.4.2 Magnetic Domain:

The magnetic domain theory was proposed by Weiss in 1907. According to this theory, ferromagnetic material contains a large number of tiny regions, and each region (magnetic domain) consists of atomic magnetic moments that are aligned in a specific direction. Initially, these magnetic domains are randomly oriented, resulting in a weak magnetization where the magnetic moments cancel each other out in the absence of an external magnetic field.

In the presence of a strong external magnetic field, these magnetic domains align in the direction of the field, resulting in strong magnetization. This alignment occurs because the magnetic moments within each domain are parallel due to the influence of the external magnetic field. Paramagnetic, Ferromagnetic and Anti ferromagnetic as shown in Figure 21.15.

(a) Paramagnetic (Randomly oriented order,)

(b) Ferromagnetic (Perfect order)

(c) Anti ferromagnetic (Perfect anti order)

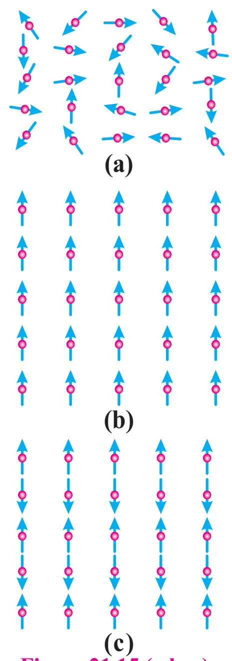


Figure 21.15 (a,b,c) magnetic domain

In ferromagnetic materials, once all the magnetic domains are aligned in one direction and the external field is removed, the domain boundaries do not change their orientation. This property prevents demagnetization, making ferromagnetic materials useful for making permanent magnets. Ferromagnetic materials are strongly attracted to external magnetic fields due to their aligned magnetic domains.

21.4.3 Curie Point:

Curie point is also known as Curie temperature. Some magnetic materials lose their magnetic properties as the temperature rises above the Curie temperature. The Curie temperature weakens the magnetic properties of the material. Pierre Curie, a French physicist, discovered it in 1895 and proposed certain laws related to the magnetic properties of materials as temperature changes.

DO YOU KNOW?

Alloys of iron differ; soft iron is easier to magnetize than steel. It helps to tap the material to nudge any stubborn domains into alignment. Another way is to stroke the material with a magnet. The stroking motion aligns domains. If a permanent magnet is dropped or heated outside the strong magnetic field from which it is made, some of the domains are jostled out of alignment and the magnet becomes weaker.

Curie's Law:

The Curie law states that in a paramagnetic material, the material's ***"magnetization is directly proportional to an applied magnetic field". M ∝ H***

$M = \chi H$ ……. (H is the applied magnetic field strength)

But when it is heated, the relation is reversed, i.e., the magnetization becomes inversely proportional to temperature.

Mathematically, it is written as:

$$M = \frac{C X H}{T} \text{……………….(21.4)}$$

Where:
M is the magnetization; H is the applied magnetic field, T is the absolute temperature, and C is the Curie constant specific to the material.
The various experiments by Pierre Curie showed that for many substances, the susceptibility χ (chi) is inversely proportional to the absolute temperature T. $\chi = \frac{C}{T}$ …………(21.5)

Consider an example of iron atoms with a temperature of 770°C (1043 K). Each iron atom acts like a tiny magnet at this temperature spontaneously. Each of them will align themselves as some kind of magnetic material.

For pure iron, as shown in Figure 21.16, the atomic magnets are distributed within each microscopic domain. Pure iron is a kind of ferromagnetic material. The directions of the magnetic fields are the same so that their magnetic fields strengthen each other.

Anti-ferromagnetic materials possess atomic magnets that have alternate properties of magnetic fields. They act in opposite directions so that their magnetic fields cancel each other.

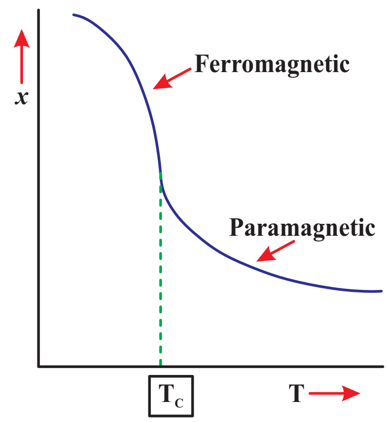


Figure 21.16
critical temperature and curies law

The graph depicts the rise of temperature above the Curie point T_C, which can lead to the production of roughly similar patterns of decreasing magnetic property. This behavior is constant in all three classes of materials.

21.4.4 Hard and Soft Ferromagnetic Substances:

Ferromagnetic materials fall into two main categories: Hard and Soft.

Hard ferromagnetic:

Materials like neodymium, samarium cobalt, and alnico are permanent magnets with high coercivity, suitable for stable magnetic fields in applications like speakers and generators.

Soft ferromagnetic:

Including iron, nickel, and cobalt, these materials have low coercivity, making them easy to magnetize and demagnetize. They are used in devices like transformers and inductors that require rapidly changing magnetic fields. Microstructure influences magnetic properties, with hard substances having a fine-grained structure and soft ones having a coarse-grained structure. The choice between hard and soft ferromagnetic materials depends on the specific application's requirements and operating conditions. For instance, hard ferromagnetic materials are used for permanent magnets in motors, while soft ferromagnetic materials are employed in rotating armatures experiencing rapidly changing magnetic fields.

Table of Curie temperature

TABLE No:21.2 Critical temperature of different elements

Material	Curie T_c(K)
Fe	1043
Co	1388
Ni	627
Gd	293

21.4.5 Hysteresis Loss:

When a material is not magnetized, the axes of different domains point in various directions, resulting in a zero magnetic effect. Upon the application of an external magnetic force, the axes align with the force, creating a strong magnetic field. Repeated cycles of magnetization and demagnetization disturb domain alignment, leading to hysteresis loss. Energy is stored during field establishment and returned during collapse, but hysteresis causes incomplete energy recovery, resulting in heat. This adverse loss, seen in transformers, reduces overall efficiency. To minimize hysteresis loss, soft iron cores are used due to their lower energy loss. Factors affecting hysteresis loss include the area under the hysteresis loop, frequency, and the volume of the material. The loss is directly proportional to these factors, impacting the overall efficiency of devices like transformers.

21.4.6 Synthesis of hysteresis Loop between Magnetic Field Strength and Magnetizing Current.

The hysteresis loop is a graphical representation, as shown in Figure 21.17 that shows the relationship between the magnetic field strength (B) and the magnetization (H) of a material. The loop is particularly useful for understanding how a material responds to changes in an external magnetic field. Here's how you can synthesize the variation of magnetic field strength with magnetizing current from the hysteresis loop.

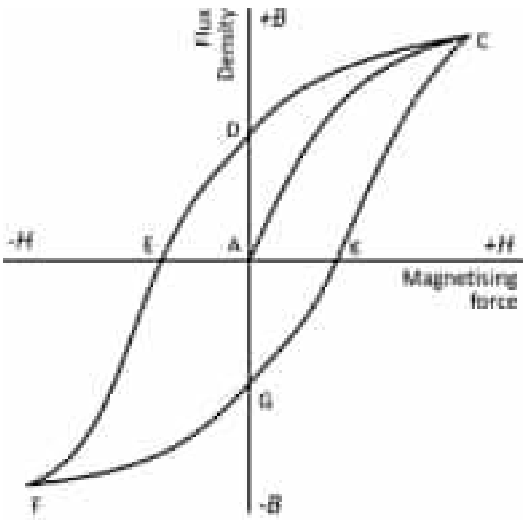


Figure 21.17
hysteresis loop for magnetic material

1. **Hysteresis Loop:**

A hysteresis loop is a closed curve illustrating a material's magnetic behavior under a changing magnetic field, formed by plotting the material's magnetization against the magnetic field strength.

2. **Variation of Magnetic Field Strength with Magnetizing Current:**

The horizontal axis of the hysteresis loop represents the magnetizing current or applied magnetic field strength. The vertical axis represents the resulting magnetization of the material.

3. **Magnetizing and Demagnetizing:**

When the magnetizing current increases, the material gets magnetized, and the magnetic field strength goes up, shown on the right side of the hysteresis loop.

When the magnetizing current decreases, the material may not fully demagnetize, and the magnetic field strength remains at a certain level, shown on the descending left side of the loop.

4. Understanding the Loop:

The width of the hysteresis loop indicates energy loss (hysteresis loss) during magnetization and demagnetization cycles.

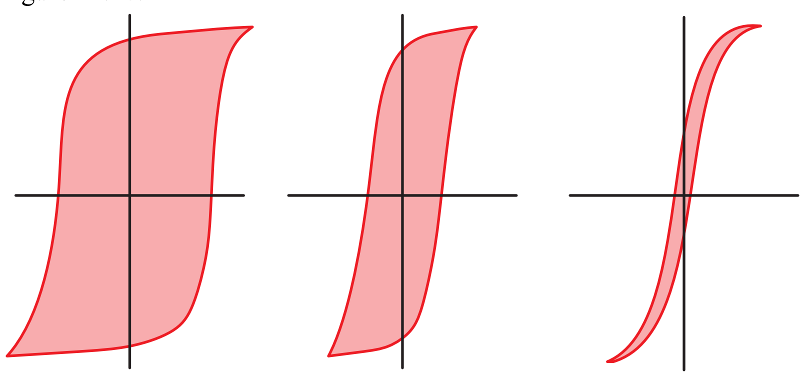
The shape of the loop provides information about the material's magnetic properties, such as coercivity and remanence.

By analyzing the hysteresis loop, the relationship between magnetic field strength and magnetizing current can be observed, aiding in understanding the material's magnetic properties and response to external magnetic field changes.

21.4.7 Hysteresis loop for permanent and temporary magnets:

Hysteresis is especially marked in materials of high residual magnetism, such as hardened steel. In most cases, hysteresis is a necessity as it causes dissipation of heat, waste of energy, and vibration due to change in polarity and rotation of element magnets in the material.

Hysteresis loops for hard steel, wrought iron, cast steel, and for alloyed sheet steel are shown in Figure 21.18.



(a) (b) (c)

Hystersis Loops

Figure 21.18(a, b, c)

hysteresis loops for hard steel, wrought iron and cast steel and low carbon steel respectively

Loop(a) is for hard steel. Due to its high retentivity power and large coercive force, this material is well-suited for permanent magnets. Since the area of the hysteresis loop for hard steel is large, hard steel is not suitable for rapid reversals of magnetization. As shown in Figure 21.18(a)

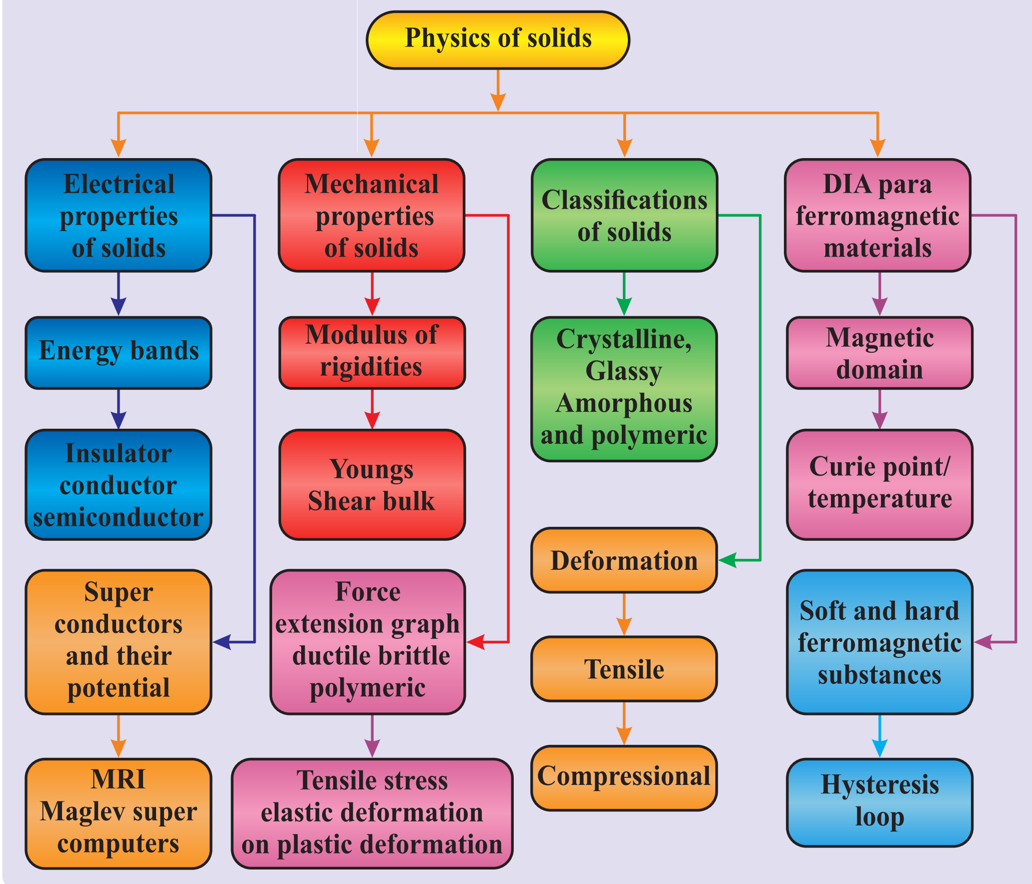
Loop (b) is for wrought iron and cast steel, which rise steeply. Hence, these materials have high magnetic permeability and good retentivity; therefore, these materials are suitable for cores of electromagnets. As illustrated in Figure 21.18(b)

Loop(c) is for iron, low carbon steel, silicon alloys, perm-alloy (alloy of Nickel and Iron), or Mu-metal (Nickel-Iron soft ferromagnetic material) sheets. Since the permeability of these materials is very high and hysteresis losses are very low, these materials are most suitable for transformer cores and armatures, which are subjected to rapid reversals of magnetization. As shown in Figure 21.18(c).

SUMMARY

- ✓ A crystalline solid is one where the internal structure is regular in nature, the atoms within it being set in well-defined patterns.
- ✓ Amorphous materials do not possess repeated structures over a long range as in crystalline solids. Rubber is an example of a polymer. It consists of very long chain molecules.
- ✓ Stress is a quantity which defines the magnitude of forces that cause deformation. Stress is usually defined as force per unit area.
- ✓ When forces pull on an object and cause its elongation, like the stretching of an elastic band, we call such stress a tensile stress.
- ✓ Strain is given as a fractional change in either length (under tensile stress) or volume (under bulk stress) or geometry (under shear stress).
- ✓ The tensile strength of a solid is a measure of its resistance to being pulled apart.
- ✓ Ductility is a property of metal that enables it to be drawn through a die to produce a wire.
- ✓ Elasticity is a measure of a deformed object's ability to return to its original size and shape once the outside forces are removed.
- ✓ Young's modulus is defined as the ratio of stress to strain.
- ✓ Bulk Modulus If an object is subjected to inward forces from all sides, its volume will decrease.
- ✓ Energy Band: The electrons in the same orbit exhibit different energy levels. The grouping of these different energy levels is known as an energy band.
- ✓ Superconductivity allows charge to flow through a superconducting conductor without losing its energy to thermal energy.
- ✓ Magnetic Hysteresis / Retentivity: When a magnetic material is placed in an external magnetic field due to which its grains get oriented in its direction and the material is magnetized. If this material is removed from that external magnetic field, even some magnetization remains in that material which is called residual magnetism. This is also called retentivity of the material.
- ✓ A magnetic domain is a region within a magnetic material in which magnetization is in a uniform direction.
- ✓ Curie point or Temperature is defined as when some magnetic materials lose their magnetic property as temperature becomes above the Curie temperature.
- ✓ Hysteresis Loss is the disturbance in the alignment of the various domains causes hysteresis loss.

CONCEPT MAP



EXERCISE

Section (A): Multiple Choice Questions (MCQs)

Choose the correct answer:

1. The property of a body by virtue of which it tends to regain its original size and shape when the applied force is removed is called
   (a) Elasticity (b) Plasticity (c) Rigidity (d) Compressibility
2. Substances which can be stretched to cause large strains are called
   (a) Brittle (b) Ductile (c) Plastic (d) Elastomer

3. If the load is increased beyond the point, the strain increases rapidly for even a small change in the stress.
   (a) Elastic point (b) Yield point (c) Plastic point (d) Fracture point
4. The reciprocal of the bulk modulus is called
   (a) Compressibility (b) Volume stress
   (c) Modulus of rigidity (d) Volume strain
5. Which of the following statements is/are wrong?
   i. Hollow shaft is much stronger than a solid of the same length and same mass.
   ii. Reciprocal of bulk modulus of elasticity is called compressibility.
   iii. It is difficult to twist along rod as compared to small rod.
   (a) III only (b) I only (c) II and III (d) I and II
6. Metals are good conductors of heat and electricity. This property is conferred by
   (a) Covalent (b) Ionic (c) Metallic (d) Hydrogen
7. For a metallic crystal, delocalized electrons occupied band is:
   (a) Conduction band (b) Valence band
   (c) Conduction and valence bands (d) there are no delocalized electrons
8. The semiconductors have resistivity
   (a) Between conductor and insulator (b) More than insulators
   (c) Less than conductors
   (d) Depending upon the semiconductor material property.
9. A ferromagnetic substance becomes a permanent magnet when it is placed in a magnetic field because
   (a) All the domains get oriented in the direction of the magnetic field.
   (b) All the domains get oriented in the direction opposite to the direction of the magnetic field.
   (c) Domains get oriented randomly.
   (d) Domains are not affected by the magnetic field.
10. Identify methods to demagnetize a ferromagnet.
   (a) By cooling, heating, or submerging in water
   (b) By heating, hammering, and spinning it in an external magnetic field
   (c) By hammering, heating, and rubbing with cloth
   (d) By cooling, submerging in water, or rubbing with cloth

Section (B): CRQs (Short Answered Questions):

1. Why are the springs made of steel and not of copper?
2. The breaking force for a wire is F. What will be the breaking force for two parallel wires of the same size?
3. Distinguish between intrinsic and extrinsic semiconductor.
4. A wire is replaced by another wire of same length and material but of twice the diameter. What will be the effect on the:
   (a) Increase in its length under a given load? (b) Maximum load which it can bear?
5. Sand does not possess any definite shape and volume, still it is solid. Give reason.
6. Specify the importance of stress-strain curve.
7. Why liquids don't possess rigidity?

8. Give applications of Curie point.
9. What are amorphous materials and what are their uses?

Section (C): ERQs (Long Answered Questions):

1. Explain Force-Extension graph.
2. Derive relation for Young's Modulus and Shear Modulus.
3. Distinguish between structure of crystalline, glassy, amorphous, and polymeric solids.
4. Describe the energy bands in solids.
5. Describe superconductivity and its applications.
6. Discuss the applications of superconductors for MRI, Maglev's, and supercomputers.
7. Describe hysteresis loss.
8. Synthesize hysteresis loop for relationship between magnetic field strength and magnetizing current.
9. Discuss energy bands and their classification. Explain magnetic properties of soft and hard magnetic materials.

Section (D): Numerical:

1. The 'lead' in pencils is a graphite composition with a Young's modulus of 1.0×10^9 N/m^2. Calculate the change in length of the lead in an automatic pencil if you tap it straight into the pencil with a force of 4.0 N. The lead is 0.50 mm in diameter and 60 mm long. **(1.0mm)**
2. A wire of 2.2 m long and 2.25 mm in diameter, when stretched by a weight of 8.8 kg, its length has been increased by 0.25 mm. Find the stress, strain, and Young's modulus of the material of the wire. Given g = 9.8 m/s^2. **(2.2×10^7 N/m^2, 1.14×10^{-4}, 2×10^{11} N/m^2)**
3. A farmer making juice fills a glass bottle to the brim and caps it tightly. The juice expands more than the glass when it warms up, in such a way that the volume increases by 0.2% (i.e., $\frac{\Delta V}{V_0} = 2 \times 10^{-3}$) relative to the space available. Calculate the normal force exerted by the juice per square centimeter, if its bulk modulus is 1.8×10^9 N/m^2. Assuming that the bottle does not break. **(432 N/cm^2)**
4. The elastic limit of copper is 1.5×10^8 N/m^2. It is to be stretched by a load of 10 kg. Find the diameter of the wire if the elastic limit is not to be exceeded. **(0.912 mm)**
5. What would be the greatest length of a steel wire which is fixed at one end, and can it be hanged freely without breaking? The breaking stress of steel is 7.8×10^8 N/m^2, and the density of steel is 7800 kg/m^3. **(1.02×10^4 m)**
6. A mild steel wire of radius 0.55 mm and length 3.5 m is stretched by a force of 52 N. Calculate: (a) Longitudinal stress, (b) Longitudinal strain, and (c) Elongation produced in the wire if Young's modulus is 2.1×10^{11} N/m^2.
   (5.47×10^7 N/m^2, 2.6×10^{-4}, 0.91 mm)
7. Calculate the change in volume of a lead block of volume 1.3 m^3 subjected to a pressure of 12 atm. Also, calculate the compressibility of lead. Given the bulk modulus as B=80×10^9 N/m^2. **(1.97×10^{-5} m^3, 1.25×10^{-11} N/m^2)**
8. The thickness of a metal plate is 0.35 inches. It's drilled to have a hole of radius 0.08 inches on the plate. If the shear strength is 4×10^4 lbs/in^2, determine the force needed to make that hole. **(0.176 in^2, 7×10^3lbs)**