Unit – 5: Superconductivity

Superconductivity: *The phenomenon of disappearance of electrical resistance of a material on cooling below certain temperature, is called Superconductivity.*

Superconductors: *It is defined as a substance that offers no resistance to the electric current when it becomes colder than a critical temperature.*

This phenomenon was first discovered by **K. Onnes** in 1911 when he was studying the electrical conductivity of metals at low temperatures.

He observed that electrical resistivity of **Mercury (Hg)** suddenly drops to zero at **4.16K**.

Temperature Dependence of Resistivity in Superconductors

Specific Resistance/ Resistivity: It is the characteristic property of a material which qualifies how strongly it resists or conducts electric current. It is given as under

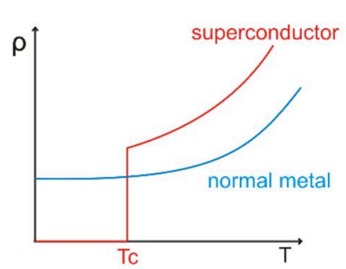
$$\boxed{\textbf{Resistivity}, \rho = R\left(\frac{A}{l}\right)}$$

- Its SI unit is *Ohm × m*
- Its dimensional formula is $[ML^3T^{-3}A^{-2}]$.
- It depends on temperature and nature of the material.
- It is independent of dimensions of the conductor, i.e., length, area of cross-section etc.
- Resistivity of metals increases with increase in temperature as $\rho_t = \rho_o(1 + \alpha t)$, where ρ_o and ρ_t are resistivities of metals at O°C and t°C. α is the temperature coefficient of resistivity of the material.
- For metals α is positive, for some alloys like nichrome, manganin and constantan, α is positive but very low.
- For semiconductors and insulators, α is negative.
- Resistivity is low for metals, more for semiconductors and very high for alloys like nichrome, constantan etc.

The electrical resistivity of all metals and alloys decreases when they are cooled. But in some metals and alloys it was found that when they are cooled then at a particular temperature the resistivity suddenly drops to almost zero i.e. conductivity becomes infinite.

Critical / Transient Temperature (T_c):

The temperature at which the transition from normal state to superconducting state takes place on cooling in the absence of external magnetic field is called Critical temperature or Transition temperature.



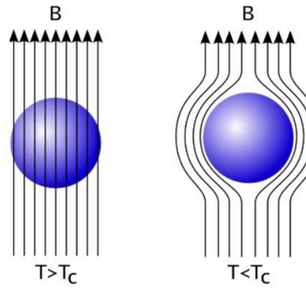
Critical temperatures given in Kelvins

Material	Element or Alloy	Critical temperature(K)
Aluminum	Element	1.20
Cadmium	Element	0.56
Lead	Element	7.2
Mercury	Element	4.16
Niobium	Element	8.70
Thorium	Element	1.37
Tin	Element	3.72
Titanium	Element	0.39
Uranium	ELement	1.0
Zinc	Element	0.91
Niobium/Tin	Alloy	18.1
Cupric sulphide	Compound	1.6

When Temperature is lowered at constant Magnetic Field

In 1933 German physicists Walther Meissner and Robert Ochsenfeld discovered that when superconducting tin and lead samples were cooled below their critical or transition temperatures in the presence of an applied magnetic field, all the magnetic field inside was pushed out (B=0). They detected that; because the magnetic flux is conserved by a superconductor, when the interior field decreased the exterior field increased. The phenomenon was named Meissner effect.

Meissner effect: *It is the expulsion of a magnetic field from a superconductor during its transition to the superconducting state on cooling below its critical temperature.*



Under normal state the magnetic induction inside the specimen is

$$B = \mu_o(H + M)$$

Where H is the external applied magnetic field and M is the magnetization produced inside the specimen.

When the specimen enters its superconducting state on cooling; B = 0 inside it.

∴ $$0 = \mu_o(H + M)$$

Hence, $M = -H$

Magnetic susceptibility of the superconductor becomes

$$\boxed{\chi = \frac{M}{H} = -1}$$

Thus, the material starts acting as **perfectly diamagnetic**.

** When temperature is increased above critical temperature the magnetic flux enters the specimen suddenly and substance comes back to its normal state. This shows that* ***Meissner effect is reversible****.*

Explanation of Magnetic Flux Expulsion

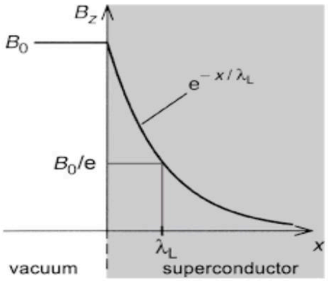
- In a weak applied field, a superconductor "expels" nearly all magnetic flux by setting up electric currents near its surface.
- The magnetic field of these surface currents cancels the applied magnetic field within the bulk of the superconductor.
- As the field expulsion does not change with time, the currents producing this effect do not decay with time.
- So, *the surface currents which flow in a superconductor without any loss in its value for long time, producing a magnetic field which cancels the applied magnetic field within the bulk of the superconductor are called* ***Persistent Currents****.*
- Near the surface, within a short distance range, the magnetic field is not completely cancelled. This distance is called the London penetration depth.

London penetration depth

In 1935 the London brothers described that the magnetic field does not drop to zero at the surface of the superconductor suddenly, but decays exponentially according to the relation

$\boxed{B_{(x)} = B_o\, e^{\left(-\frac{x}{\lambda}\right)}}$; Here B_o is the magnetic field at the surface, $B_{(x)}$ is the magnetic field inside the sample superconductor at a distance x from the surface. λ is called London penetration depth.

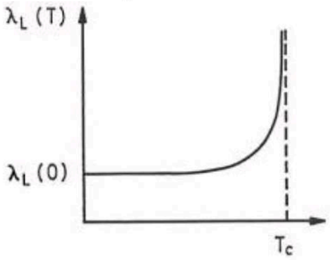
It can be defined as the depth where the persistent current drops to 1/e times of its value at the surface.



- The penetration depth depends on temperature and it gets significantly increased as T approaches T_c.

$$\boxed{\lambda_L(T) = \lambda_0 \left[1 - \left(\frac{T}{T_c}\right)^4\right]^{-1/2}}$$

where $\lambda_L(T)$ and λ_0 are the London penetration depths at temperature T kelvin and 0 kelvin respectively.



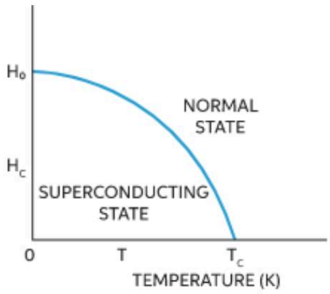
- Each superconducting material has its own characteristic penetration depth.

Effects of Magnetic Field on Superconductors

When strength of the applied magnetic field upon a material sample in its superconducting state at constant temperature is increased, the magnetic flux enters back inside the material sample at a particular value of magnetic field and it comes back in its normal state.

Critical Magnetic Field:

The value of the magnetic field beyond which the superconductors return to conducting state, is known as the critical magnetic field.



It is given by

$$\boxed{H_c(T) = H_c(0)\left[1 - \frac{T^2}{{T_c}^2}\right]}$$

where $H_c(T)$ is the critical magnetic field at temperature T and $H_c(0)$ is its value at 0 K.

** The value of the critical magnetic field is inversely proportional to the temperature.*

Critical Current

The magnetic field which destroys the superconductivity is not necessarily an external applied field. When the current is supplied through a superconductor it produces a magnetic field. Increasing current would increase the magnetic field as well. If the magnetic field reaches the critical value the material returns to its normal state, destroying its superconducting state.

So, *the maximum value of current flowing through the superconductor at which superconductivity is destroyed is called critical current*.

If a superconducting wire of radius r carries current I, then from Ampere's law we have

$$\oint \vec{H}.\vec{dl} = I \qquad \Rightarrow \qquad \oint H\, dl = I$$

Magnetic field loop length around the wire = $2\pi r$

$$\therefore \qquad \oint H\, dl = H\, 2\pi r = I$$

If $H = H_c$ then the value of current is $I = I_c$

i.e. $\boxed{I_c = 2\pi r\, H_c}$

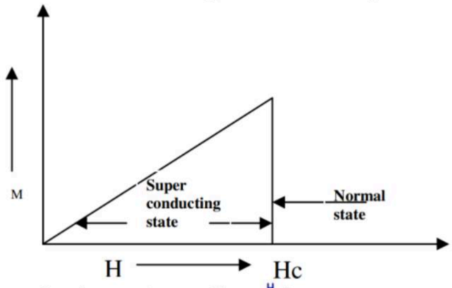
here H_c is the critical field and I_c is the critical current.

Classification of Superconductors

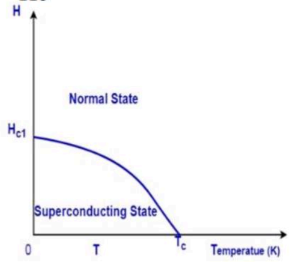
Depending upon their behaviour in an external magnetic field, superconductors are divided into two types:

a) Type - I or Soft superconductors:

- These are those superconductors that lose their superconductivity abruptly at the critical field value (H_c), when placed in an increasing external magnetic field.



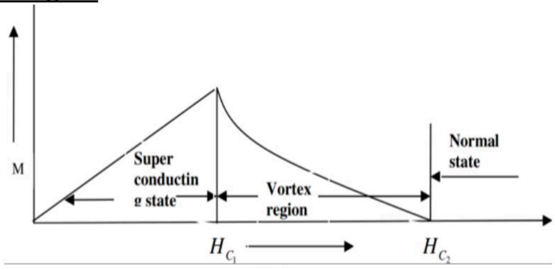
- They have a single and small value of H_c.
- These don't have a mixed or vortex state.
- These exhibit complete Meissner's effect.
- Usually pure substances form Type-I superconductors.



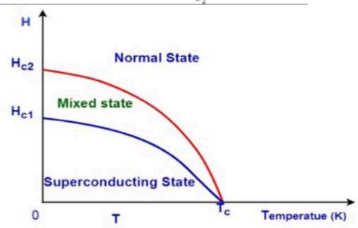
- These are called Soft Superconductors.
- These can't be used for strong electromagnets. Their practical applications are limited.
- Examples are Aluminium, Tin, Lead, Mercury etc.

b) Type - II or Hard superconductors:

- These are those superconductors that lose their superconductivity gradually when placed in an increasing external magnetic field.
- In type II superconductors, the specimen is in pure superconducting state up to the field H_{c1} (lower critical field) when the field is increased beyond H_{c2} (upper critical state) the magnetic flux lines start penetrating.
- The specimen is in mixed state between $H_{c1}$and H_{c2}. AboveH_{c2}, the specimen is in normal state.
- This means that the Meissner effect is incomplete in the region between H_{c1} and H_{c2}. This region is known as vortex region.



- They two values of H_c.
- These have a mixed or vortex state.
- Usually impure substances form Type-II superconductors.



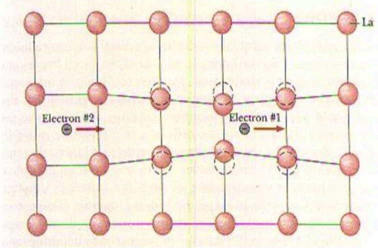
- These are called Hard Superconductors.
- These are used for strong electromagnets.
- Examples are NbTi, Nb_3Sn, etc.

BCS Theory of Superconductivity

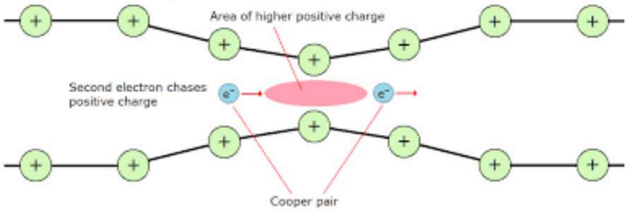
Bardeen, Cooper and Schrieffer explained the phenomenon of superconductivity in the year 1957.

The main points of the BCS theory are as follows:

- We know that resistance of the conductor is due to the scattering of electrons from the lattice ions.
- When current is supplied through a superconductor, an electron interacts with a positive lattice ion due to Coulomb attraction.

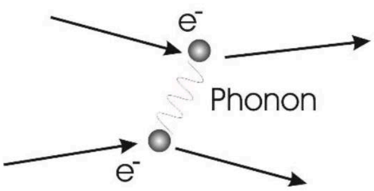


  This causes the ion core to get distorted from its mean position. This is called **lattice-distortion**.
- Now another electron of opposite spin starts interacting with this lattice ion which results in exchange of mechanical vibrational energy quanta (called ***phonon***) between the electrons through the lattice. This interaction is called **electron-lattice-electron interaction** via phonon field.



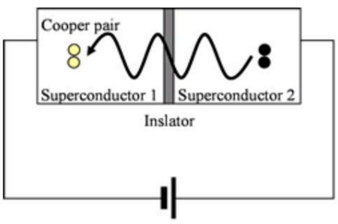
- It was shown by Cooper that below the critical temperature this exchange in energy between the two electrons, causes a bonding between the two electrons overcoming the coulombs repulsive force between them and form bound pair of electrons called **Cooper pairs.**
- At temperatures below the critical temperature large number of electron lattice electron interaction takes place and all electrons form a cloud of Cooper pairs.
- These Cooper pairs move collectively through the crystal, which results in an ordered state of the conduction electrons without any scattering on the lattice ions. This results in a state of zero resistance in the material.

<u>Cooper pair</u>: It is a bound pair of two electron with opposite spins, mediated by a phonon interaction.



Josephson Effect

If two superconductors are separated by a thin film of insulating material, which forms a low resistance junction, it is found that the Cooper pairs of electrons, can tunnel from one side of junction to the other side. This is called **Josephson Effect**.



The current, due to flow of such cooper pairs, is called **Josephson Current**.

Isotope Effect

It was discovered in 1950 that the critical temperature T_c of the superconductors varies with their isotopic mass m as under

$$T_c\sqrt{m} = constant$$

- *The choice of isotope ordinarily has little effect on the electrical properties of a material, but does affect the frequency of lattice vibrations.*
- *This effect suggests that superconductivity is related to vibrations of the lattice.*

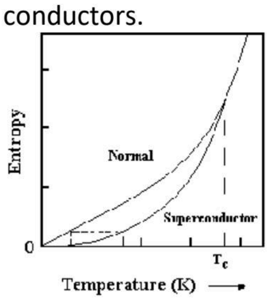
High Temperature Superconductors

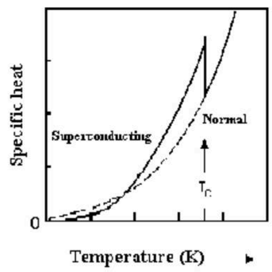
- Superconducting materials, which exhibit superconducting property at higher temperatures, are called high temperature superconductors.
- Thus, *those superconductors which possess higher value of critical temperature as compared to conventional superconductors are called **high temperature superconductors**.*
- Most of the high temperature superconductors are found to be non-metals and inter metallics compounds, but are oxides, that fall into the category of **ceramics**.
- All high temperature superconductors are oxides of copper, and bear a particular type of crystal structure called **Perovskite crystal structure**.
- *Crystal structures having large number of copper-oxygen layers are called **Perovskite crystal structure**.*
- It was found that addition of <u>extra copper-oxygen layer raises the critical temperature Tc</u> to higher values.
- The super currents are strong in the copper-oxygen layer and weak in the direction perpendicular to the planes.

Properties of Superconductors

The superconducting material shows some extraordinary properties which make them very important for modern technology. Some are listed below-

- Zero Electric Resistance (Infinite Conductivity)
- Magnetic field does not penetrate inside a superconductor (Meissner Effect).
- Above Critical Temperature they become normal conductors.





- In all superconductors entropy decreases substantially below critical temperature.
- Specific heat of superconductors doesn't vary directly with the temperature but exponentially.
- Critical Magnetic Field
- Presence of Persistent Currents
- Josephson Currents
- Critical Current

Applications of Superconductors

- Superconductors are used in particle accelerators.
- Superconductors are used in generators.
- In the making of Supercomputers.
- Superconductors are used in electric motors.
- Superconductors are used in long-distance, high-power transmission lines.
- Superconductors are primarily employed for creating powerful electromagnets in various applications.
- They are used in memory or storage elements.
- Superconductors are used in Electro-magnetic shielding.
- Magnetic levitation. Magnetically levitating the world's fastest trains.
- SQUIDs (superconducting quantum interference devices) are being used in the production of highly sensitive magnetometers. They are generally used for the detection of land mines.
- Superconductors are also being used for the development of high-intensity Electro Magnetic Impulse (EMP). They are used to paralyze all the electronic equipment within the range, etc.

Short Answer Questions

1. What do you mean by a superconductor?
2. What is critical field?
3. What is Persistent current?
4. What are Cooper pairs?
5. What is Meissner 's effect?
6. What do you understand by transition or critical temperature?
7. What is Josephson effect?
8. What is Isotope effect?

Numerical Questions

1. Critical field for Al is 1.2×10^4 A/m. Determine the critical current and current density which can flow through a long thin superconducting wire of aluminium of diameter 1 mm.
2. A superconducting material has critical temperature of 4.2 K in zero magnetic field and a critical field of 0.0306 tesla at 0 K. Find the critical field at 2.1 K.
3. The critical field of Niobium is 1×10^5 A/m at 8K and 2×10^5 A/m at 0K. Calculate the transition temperature of the element.
4. Calculate the temperature at which critical field is two-third of the value at 0K, for a superconductor having critical temperature 4 K.
5. For a specimen of a superconductor the critical fields are 1.2×10^5 amp/m and 3.6×10^5 amp/m for temperature 12 K and 10 K respectively, calculate the transition temperature and critical field at 0 K and 3.2 K.
6. For a specimen of a superconductor the critical fields are respectively 0.176 tesla and 0.528 tesla for 14K and 13K. Calculate transition temperature and critical fields at 0K and 4.2K.
7. The critical fields at 6K and 8K for a superconductor are 7.616 and 4.284 MA/m respectively. Calculate the transition temperature and critical field at 0K.

Long Answer Questions

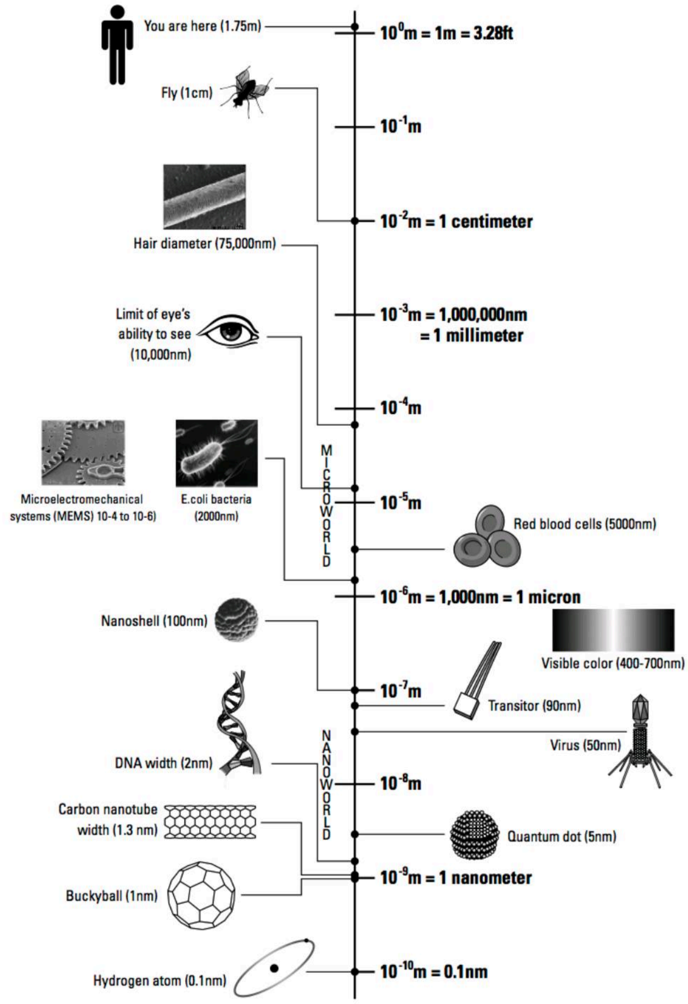
1. Explain superconductivity and transition temperature. Show variation of resistivity with temperature for normal conductor and superconductor.
2. What do you mean by Meissner 's effect? Explain how Meissner's effect proves that a Superconductor is a perfect diamagnetic material.
3. Explain what are type I and type II superconductors.
4. Explain BCS theory of superconductivity.
5. Explain what are high temperature superconductor?
6. What are the applications of superconductor?
7. Discuss the properties of superconductors.

Unit – 5: Nanomaterials

Nano-Scale

The word "nano" is an SI prefix which comes from the Greek word *nanos* meaning dwarf; and used for an extremely small size.

Nano-meter (nm) - A nanometre is one billionth of a meter. i.e. 1nm = 10^{-9} m.



Change in Properties of Materials from Bulk to Nano scales

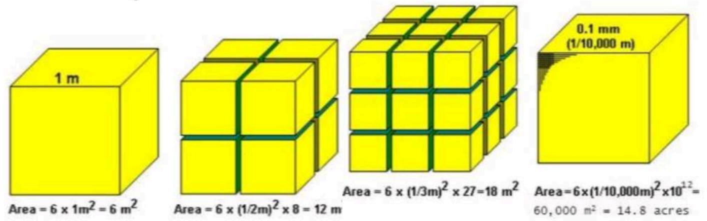
Materials reduced to the nanoscale can suddenly show very different properties compared to what they show on a macroscale. For instance, opaque substances become transparent (Cu); inert materials become catalysts (Pt); stable materials turn combustible (Al); solids turn into liquids at room temperature (Au); insulators become conductors (Si).

Properties	Examples
Catalytic	Better catalytic efficiency through higher surface-to-volume ratio
Electrical	Increased electrical conductivity in ceramics and magnetic nanocomposites, increased electric resistance in metals
Magnetic	Increased magnetic coercivity up to a critical grain size, superparamagnetic behaviour
Mechanical	Improved hardness and toughness of metals and alloys, ductility and superplasticity of ceramic
Optical	Spectral shift of optical absorbtion and fluorescence properties, increased quantum efficiency of semiconductor crystals
Sterical	Increased selectivity, hollow spheres for specific drug transportation and controlled release
Biological	Increased permeability through biological barriers (membranes, blood-brain barrier, etc.), improved biocompatibility

Why do the properties change?

(i) Increase in surface area to volume ratio:

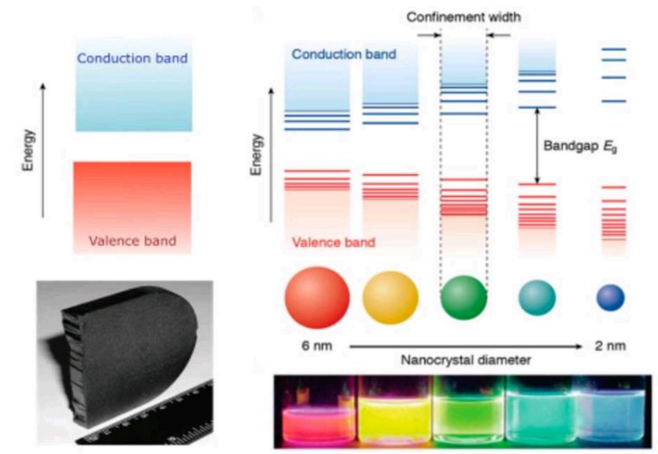
- As the size decreases, the ratio of surface area to volume of the objects increases.



- So, particle size decreases, a greater portion of the atoms are found at the surface compared to those inside.
- A given mass of nanomaterial will be much more reactive than large bulk state, because of greater number of atoms available on the surfaces to react.
- Due to this, nanomaterials have-
  - ➢ Higher chemical reactivity
  - ➢ Better catalytic potentials
  - ➢ Increased strength of materials
  - ➢ Better specific heat
  - ➢ Higher thermal conductivity
  - ➢ Lower melting points
- So, nano materials can serve as very potent catalysts or be applied in thin films to serve as thermal barriers or to improve wear resistance of materials.

(ii) Quantum confinement effect:

- According to band theory, the atoms in solids have energy bands, whereas, isolated atoms possess discrete energy levels.
- When the material size is reduced to nanoscale, comparable to the de Broglie wavelength of electrons, electrons occupy discrete energy levels rather than a continuum of energy levels in a band.
- Because of this, electrons will remain confined to a small region of the material. This is called **quantum confinement** effect.



Bulk of Semiconductor **Nanocrystal of Semiconductor**

(iii) Dominance of Electromagnetic Forces:

- At nanoscales, mass of the particles become insignificant, so gravitational forces loose significance.
- Nano particles are far smaller than nuclear range (10^{-5}nm) hence even short range forces like nuclear forces also become insignificant.
- EM forces, which are not affected by smaller mass & sizes, become dominant in regulating the chemical & physical behaviour of the nano materials.

(iv) Random Molecular Motion:

- It is the movement that all molecules in a substance exhibit due to their kinetic energy.
- This motion increases at higher temperatures.
- At the macroscale this motion is very small compared to the sizes of the objects and thus is not very influential in how object behave.
- At the nanoscale however, these motions can be on the same scale as the size of the particles and thus have an important influence on how particles behave.

Quantum size effect

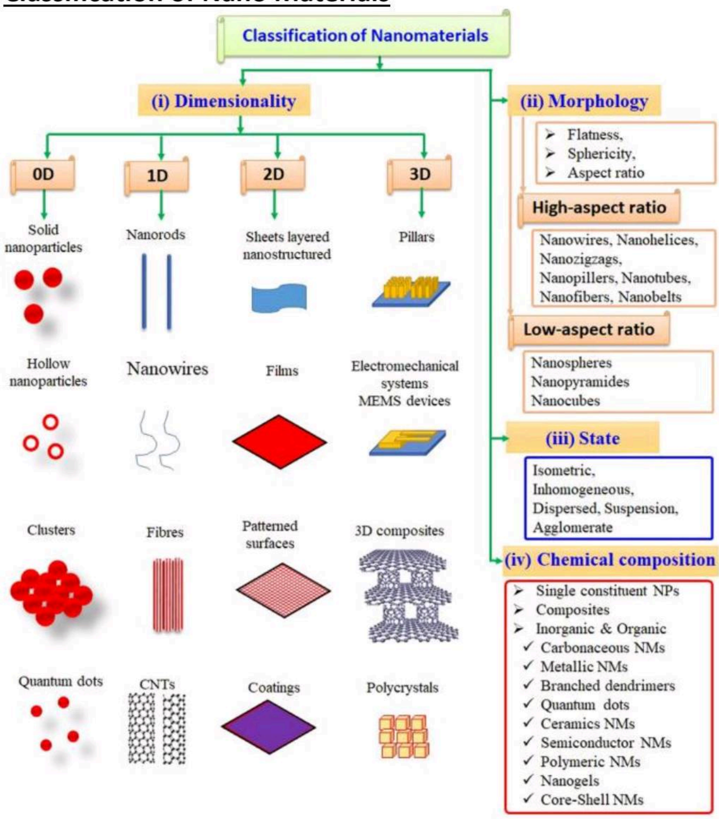
The electronic properties of solids are altered with the reduction in particle size. The physical, chemical, mechanical, electrical, thermal, magnetic & optical properties of solids were changed with the decrease in the particle size. This is called as quantum size effect.

Nanoscience: It is the study of properties of materials at nano scales where properties differ significantly than those at larger scale.

Nanotechnology: It is the design, characterisation, production and application of structures, devices and systems by controlling shape and size at the nanometre scale.

Nanomaterials: Particles in the form of crystals, rods, or spheres having size between 1 nm and 100 nm at least in one dimension.

Classification of Nano Materials



Dimensions of nanomaterials

This nanomaterial classification is based on the number of dimensions of a material, which are outside the nanoscale i.e. <100 nm range.

(i) **Quantum Dots (zero-dimensional - 0D)-**

- When all the dimensions of a nanomaterial fall within the nanoscale i.e. no dimensions is larger than 100 nm, they are called Nano particles or Quantum Dots. Bucky balls, Nano crystals and nano clusters also fall in the same category.
- In this case particle is not free to move in any direction, hence its degree of freedom is zero i.e it is confined in one place.

(ii) **Quantum Wire (one-dimensional nanomaterials - 1D)-**

- When one dimension of the nano material is outside the nanoscale and two dimensions are fall within nano range, it is called nanotube, nanorod, or nanowire. E.g. CNTs.
- In this case the particle is free to move along one direction only and its degree of freedom is 1.

(iii) **Quantum Well (two-dimensional nanomaterials - 2D)-**

- When two dimensions of a nano material are outside the nanoscale and only one dimension falls within nano range, such are called quantum well or quantum layers.
- Examples are graphene, nanofilms, nanolayers, and nano-coatings.
- In this case particle is free to move along two dimensions and its degree of freedom is 2.

(iv) Bulk (Three-dimensional materials - 3D)-

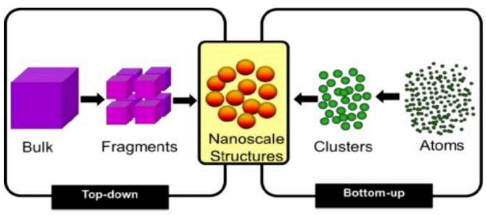
- These are the materials that are not confined to the nanoscale in any dimension. All the dimensions are greater than 100nm.
- This class can contain bulk powders, dispersions of nanoparticles, bundles of nanowires, and nanotubes as well as multi-nanolayers.
- In this case particle can move in any dimension and its degree of freedom is 3.

Fabrication of Nano Materials

Nanomaterials can be fabricated by following two approaches –

(i) Top-down approach:

- It was advanced by Richard Feynman in 1959.
- It involves the techniques by very small structures are obtained by breaking down bulk matter into nano sized particles.
- Size and morphology of the particles can't be externally controlled.
- It is relatively expensive and time consuming.
- Not suitable for large scale production.
- Methods involved are-
  1. Ball milling 2. Plasma arching
  3. Laser sputtering 4. Vapour deposition



(ii) Bottom-up approach:

- It was pioneered by Jean-Marie Lehn.
- In this process, nano phase materials are produced
- by building of atom by atom, molecule by molecule or cluster by cluster. This process was used to build larger objects from smaller buildings blocks.
- This approach is more time consuming.

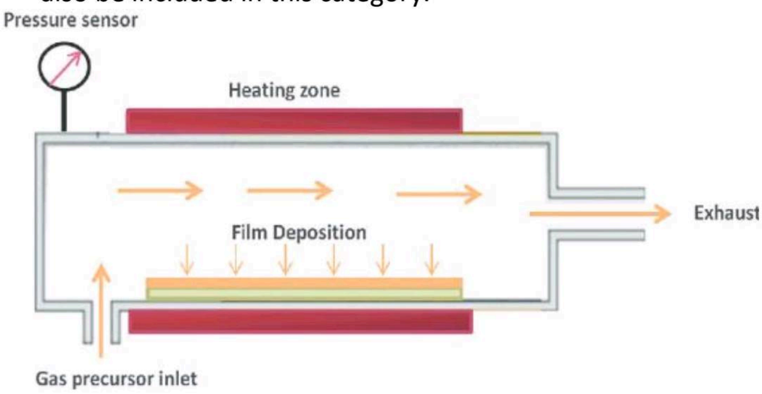
- Size and morphology of the fabricated particles is well controlled.
- Less expensive.
- Suitable for large scale production.
- Methods involved are-
    1. Sol-gel
    2. Colloidal
    3. Electrodeposition
    4. Solution phase reductions

Chemical Vapour Deposition (CVD)

Chemical vapour deposition is a well-known process in which chemically reactive gases are used to deposit a thin film on a solid substrate.

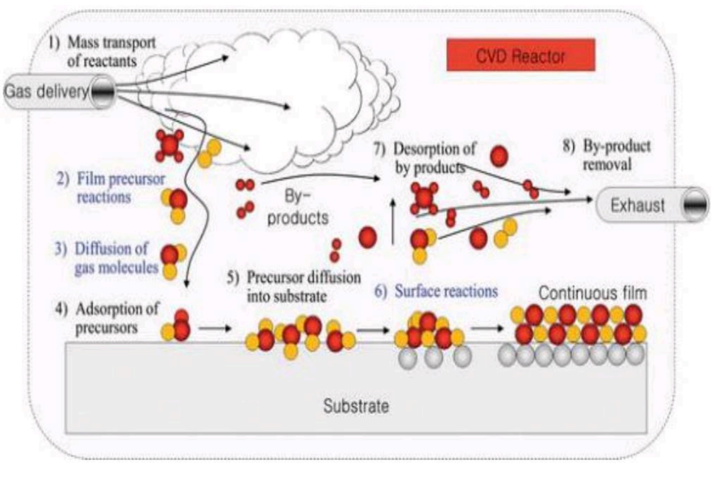
CVD Apparatus: A CVD apparatus will consist of -

- Gas delivery system: For the supply of precursors to the reactor chamber
- Reactor chamber: Chamber within which deposition takes place.
- Substrate loading mechanism: A system for introducing and removing substrates, mandrels etc
- Energy source: Provide the energy/heat that is required to get the precursors to react/decompose.
- Vacuum system: A system for removal of all other gaseous species other than those required for the reaction/deposition.
- Exhaust system: System for removal of volatile by-products from the reaction chamber.
- Process control equipment: Gauges, controls etc to monitor process parameters such as pressure, temperature and time. Alarms and safety devices would also be included in this category.



Process Steps: The basic steps involved in this process are-

- In a chemical vapour deposition process, vapour is formed in a reaction chamber by pyrolysis reduction, oxidation or nitridation, and then deposited on the surface.

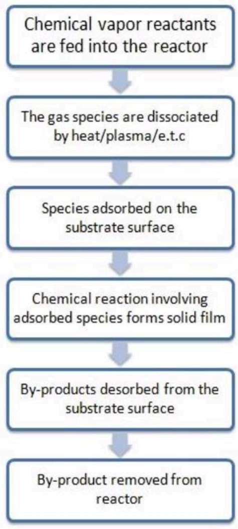


- Areas of growth are controlled by patterning processes like photolithography or photomasking (deposition patterns are etched on to the surface layers of the wafers).

This method is an excellent method which is used to control the particle size, shape and chemical compositions.

This method is used to produce the nano powders of oxides and carbides of metals.

Production of pure metal powders is also possible using this method.



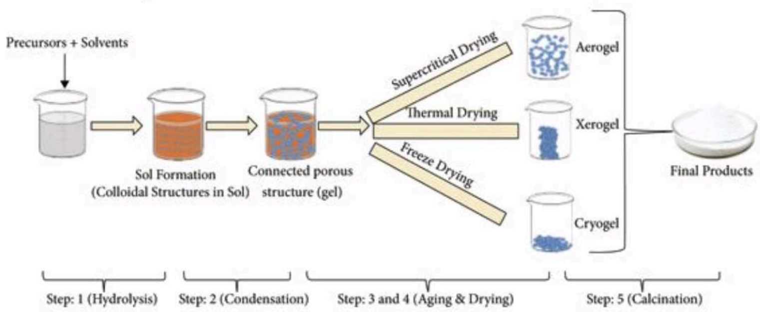
Applications: CVD has applications across a wide range of industries such as:

- Coatings: Coatings for a variety of applications such as wear resistance, corrosion resistance, high temperature protection, erosion protection and combinations thereof.
- Semiconductors and related devices: Integrated circuits, sensors and optoelectronic devices
- Dense structural parts: CVD can be used to produce components that are difficult or uneconomical to produce using conventional fabrication techniques. Dense parts produced via CVD are generally thin walled and maybe deposited onto a mandrel or former.
- Optical Fibers: For telecommunications.
- Composites: CVD techniques to produce ceramic matrix composites such as carbon-carbon, carbon-silicon carbide and silicon carbide-silicon carbide composites.
- Powder production: Production of novel powders and fibres.
- Catalysts
- Nanomachines

SOL-GEL Method

The sol-gel process is a more chemical method (wet chemical method) for the synthesis of various nanostructures, especially metal oxide nanoparticles.

Process Steps-



- In this method, the molecular precursor (usually metal alkoxide) is dissolved in water or alcohol to prepare a stable sol.
- Then precursor solution is converted into a colloidal suspension of increased viscosity, called a gel, by a series of hydrolysis and polymerisation processes.
- This gel is then aged by polycondensation reaction till it becomes like a porous mass and solvent is driven out of the porous gel.

- After that it should be dried using appropriate methods depending on the desired properties and application of the gel.
- After the drying stage, the produced gels are powdered and then calcined.

Advantages-

- Sol-gel method is a cost-effective.
- High purity products are obtained.
- Offers good control over the chemical composition of the products due to the low reaction temperature.

Applications-

- It can be used in the process of making ceramics.
- The materials obtained from the sol-gel method are used in various optical, electronic, energy, surface engineering, biosensors, and pharmaceutical and separation technologies (such as chromatography).
- It can be used to develop filtration membranes.
- The sol-gel method is a conventional and industrial method for the synthesis of nanoparticles with different chemical composition.

<u>General Properties of Nanomaterials</u>

There are three major physical properties of nanoparticles, and all are interrelated:

(i) they are highly mobile in the free state.

(ii) they have enormous specific surface areas i.e. nanoparticles have a very high surface area to volume ratio.

(iii) they may exhibit what are known as quantum effects, where electrons move different for very small sizes of particle.

At nano scale some properties which we can only be seen at the nano scale are -

- reactivity increases which makes them better catalysts (gold).
- increased diffusivity/permeability, especially at elevated temperatures.
- reduction in melting temperature.
- Altered solubility
- suspensions of nanoparticles become possible due to stronger particle-solvent interactions.
- Increased electrical conductivity e.g. insulators become conductors (silicon)
- Altered optical properties, e.g. gold nanoparticles appear deep red to black in solution.
- substances which usually stop light become transparent (copper);
- it becomes possible to burn some materials (aluminium);
- solids turn into liquids at room temperature (gold).
- Nano scale ferro magnetics can switch polarities even at slight intake of energy

<u>Applications Of Nano Materials</u>

(i) Automotive industry:

Lightweight construction
Painting (fillers, base coat, clear coat)
Catalysts
Tires (fillers)
Sensors
Coatings for window screens and car bodies

(ii) Chemical industry:

Fillers for paint systems
Coating systems based on nanocomposites
Impregnation of papers
Switchable adhesives
Magnetic fluids

(iii) Engineering:

Wear protection for tools and machines (anti-blocking coatings, scratch-resistant coatings on plastic parts, etc.)
Lubricant-free bearings

(iv) Electronic industry:

Data memory
Displays
Laser diodes
Glass fibers
Optical switches
Filters (IR-blocking)
Conductive, antistatic coatings

(v) Construction:

Construction materials
Thermal insulation
Flame retardants
Surface – functionalized building materials for wood, floors, stone, facades, tiles, roof tiles, etc.
Facade coatings
Groove mortar

(vi) Medicine:

Drug delivery systems
Contrast medium
Prostheses and implants
Agents in cancer therapy
Active agents
Medical rapid tests
Antimicrobial agents and coatings

(vii) Textile/fabrics/non-woven stuff:

Surface – processed textiles
Smart clothes

(viii) Energy:

Fuel cells, Solar cells, Batteries, Capacitors

(ix) Cosmetics: Sun protection, Lipsticks, Skin creams Toothpaste

(x) Food and drinks:

Package materials
Additives
Storage life sensors
Clarification of fruit juices

(xi) Household:

Ceramic coatings for irons
Odours catalyst
Cleaner for glass, ceramic, floor, windows

(xii) Sports/outdoor:

Ski wax
Antifogging of glasses/goggles
Antifouling coatings for ships/boats
Reinforced tennis rackets and balls.