Unit-IV

Nanotechnology

Basic definitions:-

Nano :-

Nano comes from the Greek word "nanos," meaning "dwarf", but nano is infinitely smaller than a dwarf. Nano means 10^{-9}. Nanometer is one billionth of a meter (i.e. 1nm= 10^{-9} m).

Nano Scale:-

Nanometer is the scale used to measure objects in the nanoworld. The scale ranges from **1nm to 100nm** is known as **Nanoscale**.

Nanoscience :-

Nanoscience deals with the study of materials, particles, structures and their unique properties at the nanoscale.

Nanotechnology :-

Nanotechnology can be defined as the design, characterization, production and application of structures, devices and systems by controlling size and shape at the nanometre scale (1–100 nm). Nanotechnology is the art of science which manipulates matter at nanoscale to create novel materials and devices with enhanced potential.

Nanomaterial :-

The material which has at least one dimension in the nano range (1nm to 100nm) is called **nanomaterial**. Properties of the material at the nano scale (Nanomaterial) are highly different from the properties of the same material at the larger scale (Bulk material).

Surface area to volume ratio :-

One of the most fundamental differences between nanomaterials and bulk materials is that nano scale materials have very large value of surface to volume ratio. The larger surface area of nanomaterials plays a major role in dictating these material's important properties. The surface area to volume ratio and its effect on the properties of the nanomaterials is the key feature of nanoscience and nanotechnology.
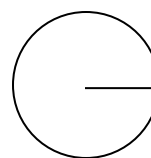
To understand this concept, consider a spherical material of radius 'r'

The surface area of the sphere (S) $= 4\pi r^2$

The volume of the sphere (V) $= 4/3\pi r^3$

Surface area to Volume ratio(S/V) $= \dfrac{4\pi r2}{4/3\pi r3}$

∴   **Surface area to Volume ratio $\dfrac{S}{V} = \dfrac{3}{r}$**

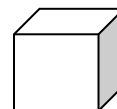It means that the surface area to volume ratio increases as the radius of the sphere decreases and vice versa.

Let us now consider the material consist cubic shape, the side of the cube is 'L'

in this case, Surface area (S) $= 6L^2$

Volume (V) $= L^3$

Surface area to Volume ratio(S/V) $= \dfrac{6L2}{L3}$

∴   **Surface area to Volume ratio $\dfrac{S}{V} = \dfrac{6}{L}$**

In this case also, the surface area to volume ratio is inversely proportional to the size of the material.

## Effect of Surface area to volume ratio :-

As the particle size decreases, a greater proportion of the atoms are found at the surface of the material. For example, a particle of size 3 nm has 50% of its atoms on the surface; at 10 nm, 20% of its atoms are on the surface; and at 30 nm, 5% of its atoms are on the surface. Therefore, materials made of nanoparticles have a much greater surface area per unit volume

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ratio compared with the materials made up of bigger particles. This leads to nanoparticles being more chemically reactive. As chemical reactions occur between particles that are on the surface, a given mass of nanomaterial will be much more reactive than the same mass of material made up of large particles. This means that materials that are inert in their bulk form are reactive when produced in their nanoparticle form. Therefore, the properties of nanomaterials are drastically different from those of bulk materials because of their small dimensions, nanomaterials have a vast surface area to volume ratio (S/V), which causes the large fraction of atoms of the material be on the surface, resulting in more surface dependent material properties.

Quantum confinement effect :-

Quantum confinement is a phenomenon observed in nanomaterials when the size of the material becomes comparable to or smaller than the Bohr exciton radius ($\leq$ 10nm). At this small scale, the movement of charge carriers (i.e., electrons and holes) is restricted or confined in one or more spatial dimensions. This confinement leads to the quantization of energy levels. This effect is called quantum confinement.

In bulk materials, electrons can move freely, and the energy levels form continuous bands. However, in nanomaterials, due to the reduced size, electrons and holes are trapped in a very small region, resulting in discrete energy levels. As a result of quantum confinement, the band gap of the material increases as the particle size decreases. This means more energy is needed for electrons to jump from the valence band to the conduction band. Because of this, nanomaterials show different optical and electrical properties compared to their bulk form.

Line spectrum of atoms   Nanomaterials   Band spectrum of Bulk materials
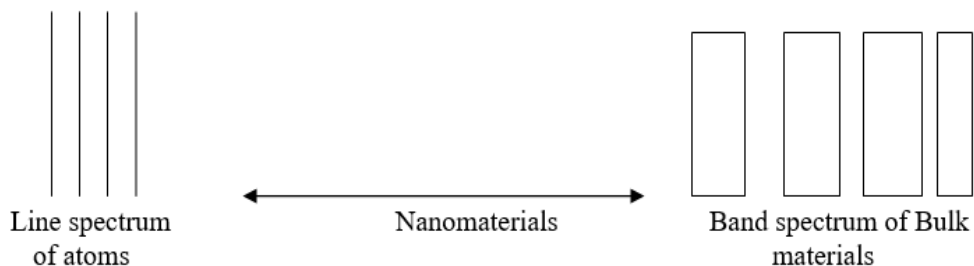
For example, quantum dots made of the same material can emit different colors depending on their size — smaller particles emit light of shorter wavelength (blue), while larger

ones emit longer wavelength light (red). This Quantum confinement effect is useful in many modern technologies, including LEDs, solar cells, QLED TVs, and biomedical imaging.

In summary, quantum confinement is the restriction of electrons in nanoscale materials. It results in discrete energy levels and size-dependent properties, which are significantly different from those of bulk materials. This makes nanomaterials highly useful in science and technology.

Synthesis routes:-

There are two types of approaches for synthesis of nano materials and fabrication of nano structures.

- ➢ *1. Top-Down method*
- ➢ *2. Bottom-up method*

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          ┌─────────────────┐
          │  Synthesis of   │
          │  Nanomaterials  │
          └────────┬────────┘
                   │
      ┌────────────┴────────────┐
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│ Top-Down method │    │ Bottom-Up method │
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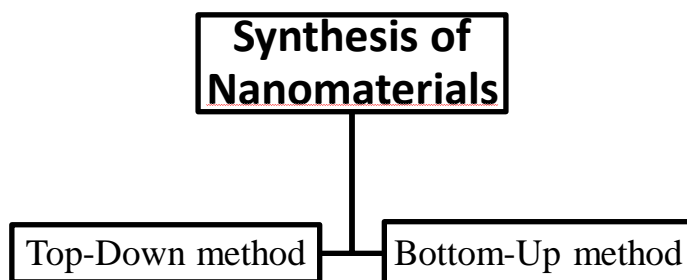
<u>Top-Down method</u> :-

This approach for the synthesis of nanomaterials is the one in which the bulk material is broken down to smaller dimensions by different means and then restructured. This approach may involve mechanical methods such as cutting, carving and moulding.

<u>Bottom-Up method</u> :-

The formation of a material via atom-by-atom, molecules-by-molecules and cluster-by-cluster deposition is called a bottom up approach. Bottom-up approaches are generally based on chemical growth process techniques.
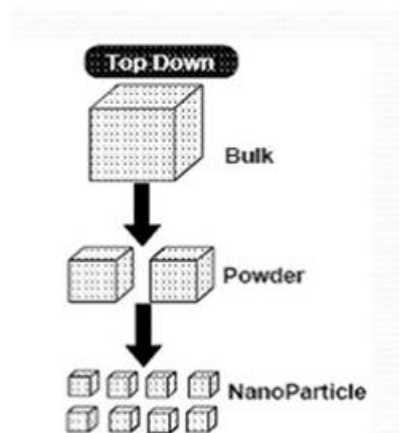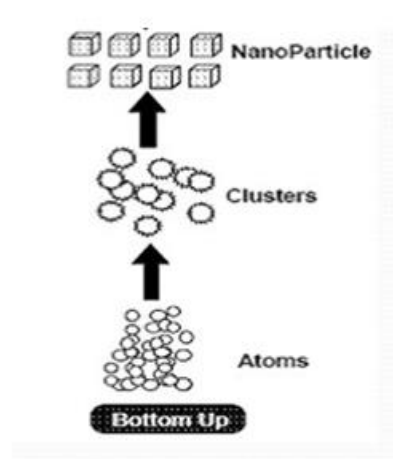
Fig: Top - Down approach   Fig:Bottom-Up approach

Table:- Difference between Top- Down and Bottom- Up methods

Top-Down method	Bottom- Up method
Advantages	Advantages
➢ Large scale production , deposition over a large surface area is possible ➢ Chemical purification is not required	➢ Ultra- fine nano particles, thin films, nanowires, nanotubes can be prepared ➢ Narrow size distribution is possible ➢ Simple and Cheaper technique ➢ Minimum imperfections and uniform chemical composition. ➢ Short execution time
Disadvantages	Disadvantages
➢ Broad particle size distribution ➢ Varied particle size and shapes ➢ stress, defects and contaminations (impurities) during the preparation of the nanostructures ➢ Expensive technique	➢ Large scale production is difficult ➢ Chemical purification is required

Bottom–Up Methods:-

Sol-gel method:-

Sol-gel process involves the formation of colloidal suspension (Sol) and gelation of the sol to form nano particles in a continuous liquid phase.

Sol:- A sol is a dispersion of the solid particles(approximately 20 to 100nm) in a liquid where only the Brownian motions suspend the particles.

Gel:- The gel is a state where both liquid and solid are dispersed in each other, which presents solid networking containing liquid components.

Synthesis procedure:-

Various stages of the synthesis of the nano particles by sol-gel method are given below

Sol-formation (Hydrolysis):-

The precursors have taken in required stoichiometric ratios and completely dissolved in minimum quantity of de-ionized water. Ammonia solution (AR grade) was drop wise added to achieve pH =7 by stirring the solution simultaneously using a magnetic stirrer. The desired colloidal particles are dispersed in a liquid to form a sol.

Typically, the starting materials can be metal alkoxides or metal nitrates used to form solvated metal precursor (sol). The precursors are hydrolyzed with water (or alcohol) to produce hydroxide as shown in the following Eq. (1). Apart from water and alcohol, an acid or base can also help to hydrolyze the precursor.

$$M(OR)_n + xH_2O \leftrightarrow M(OR)_{n-x}(OH)_x + xROH \text{ ------------------(1)}$$
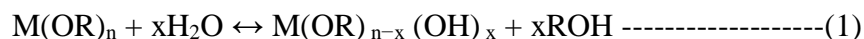
Gel formation (Condensation) :-

The stirring process is continued for one hour. The solution was evaporated by intensive stirring and heating for 1 hour at 100 °C and kept at this temperature until the sol turned into a gel. The hydroxide molecules later form oxide bridged polymer network (the gel) through condensation reactions (condensation reaction is shown in Eq. 2). At this stage, gelation occurs and a dense gel consisting of three-dimensional skeleton with interconnected pores is obtained.

The properties of the final products are largely influenced by the rates of hydrolysis and condensation. Slower and more controlled hydrolysis will yield smaller particles.

$$M-OR + M\text{-}OH \rightarrow M-O-M + ROH \qquad \text{-------------------(2)}$$

Drying :-

Now stirring is stopped but heating is continued until the entire gel was burned out to form a powder sample.

Dehydration :-

During this process, the surface bound M-OH groups are removed. This is normally achieved by sintering the compound at temperatures up to 800°C. Sintering process can also decrease lattice defects and strains.

Densification :-

The resulting powder is crushed in an agate mortar for removing pores from the sample and to obtain fine powder (nano particles). In this way one can prepare nano particles by using Sol-gel method.

Flow sheet for the preparation of nanoparticles by using sol-gel method is given below
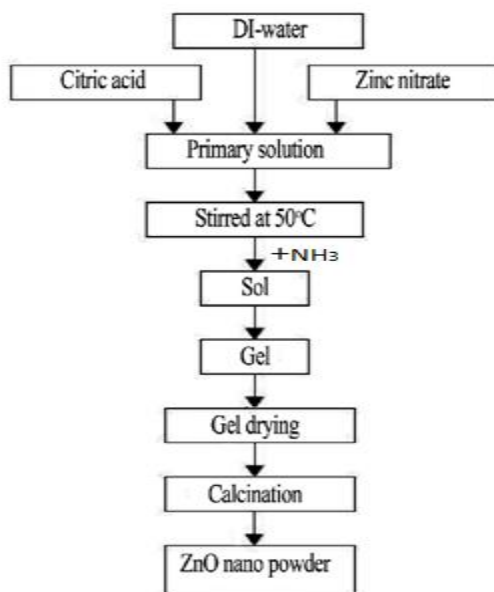

Fig:- Synthesis of nanoparticles by using sol-gel method (Ex:- ZnO)

Combustion technique:-

       Combustion synthesis, also called self-propagating high temperature synthesis (SHS), is an effective low-cost technique for synthesizing highly pure and homogeneous nanocrystalline powders.

       Combustion synthesis (CS) of advanced materials is an energy-saving and efficient approach. CS can be accomplished in two different modes. First is a *self-propagating* mode. In this case, the reactive media are locally preheated by an external source to the ignition temperature, at which point reaction is initiated in this layer. The "hot" reacted layer preheats and ignites the next "cold" layer and thus combustion front self-propagates along the reactive mixture resulting in the formation of the desired solid product. Second is the volume combustion synthesis mode. In this case, the entire reactive media are uniformly heated by some external source to ignition temperature, and reaction starts at each point of the media essentially uniformly, again leading to the production of valuable materials. The maximum synthesis temperature is limited by the thermodynamics of the considered systems, and is in the range of 500K–4000K. It is important that after "ignition" no external heat sources are required. Hence, CS is an energy-efficient method.
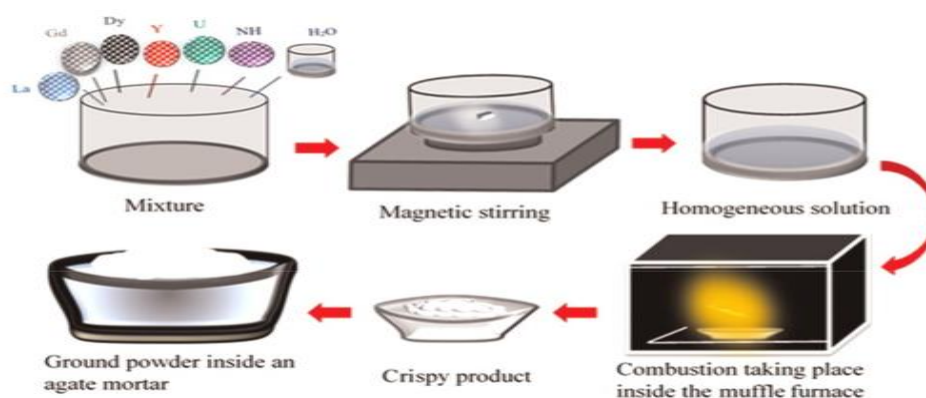

Co-Precipitation Method :-

       The other commonly used solution method for the synthesis of multi component oxide ceramics is co-precipitation method, which produces a "mixed" precipitate comprising two or more insoluble species that are simultaneously removed from solution. The precursors used in this method are mostly inorganic salts (nitrate, chloride, sulfate, etc.) that are dissolved in water or any other suitable medium to form a homogeneous solution with clusters of ions. The solution is then subjected to pH adjustment or evaporation to force those salts to precipitate as hydroxides, hydrous oxides, or oxalates. The crystal growth and their aggregation are influenced by the concentration of salt, temperature, the actual pH and the rate of pH change. After precipitation, the solid mass is collected, washed and gradually dried by heating to the boiling point of the medium. Generally, a calcination step is necessary to transform the hydroxide into crystalline oxides.
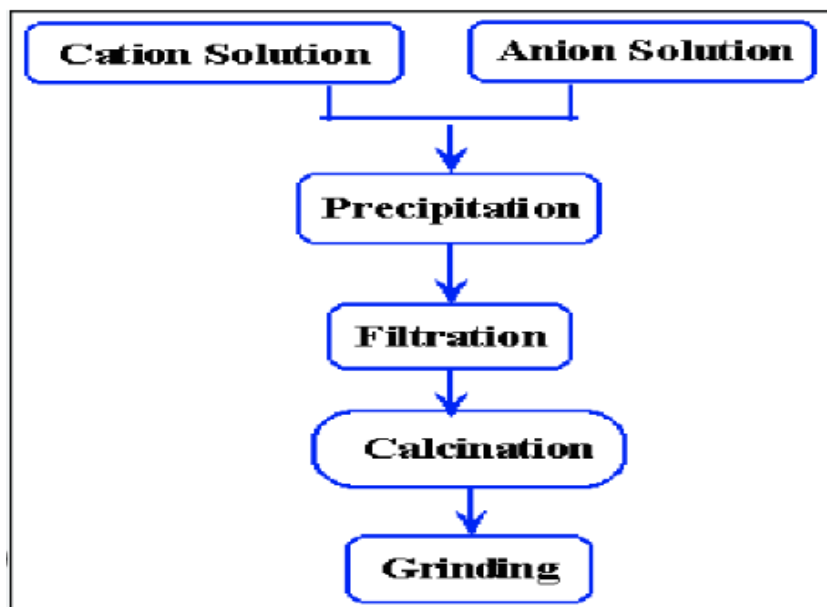
Top–Down Methods:-

Ball milling Method:-

Ball milling is an economic and facile technique to produce nanosized materials. It is a top-down approach of nanoparticle synthesis which includes mechanical breakdown of large substances into smaller one. It is used in producing metallic as well as ceramic nanomaterials.
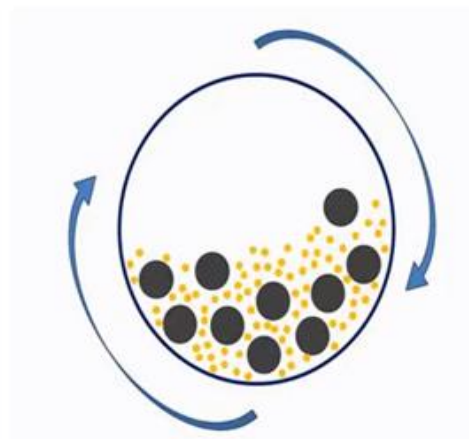
Steps in ball milling method:

1. As the name suggests, the ball milling method consists of balls and a mill chamber. Therefore over all a ball mill contains a stainless steel container and many small iron, hardened steel, silicon carbide, or tungsten carbide balls are made to rotate inside a mill (drum).

2. The powder of a material is taken inside the steel container. This powder will be made into nanosize using the ball milling technique. A magnet is placed outside the container to provide the pulling force to the material and this magnetic force increases the milling energy when milling container or chamber rotates the metal balls.

3. The ball to material mass ratio is normally maintained at 2 ratio1.

4. These silicon carbide balls provide very large amount of energy to the material powder and the powder then get crushed. This process of ball milling is done approximately 100 to 150 hrs to get uniform fine powder.

Advantages of ball milling process:

1. Nanopowders of 2 to 20 nm in size can be produced. The size of nanopowder also depends upon the speed of the rotation of the balls.

2. It is an inexpensive and easy process.

Disadvantages:

1. As the process is not so sophisticated, therefore the shape of the nanomaterial is irregular.

2. There may be contaminants inserted from ball and milling additives.

3. This method produces crystal defects.

Chemical Vapour Deposition :-

Chemical Vapour Deposition(CVD) is one of the most popular methods to produce one-dimensional nanostructures, as compared with other methods. Chemical vapor deposition (CVD) is a process whereby a solid material is deposited on a heated substrate surface from a vapor by a

chemical reaction. In this technique, gaseous chemicals (called precursors) are passed into a reaction chamber where the surface (substrate) is heated. The heat causes the gases to react and form a solid material, which deposits on the surface. Sometimes, after the chemical reaction, the vapour is passed from a region of high pressure to low pressure onto a **rotating mandrel** (a cylindrical collector) kept at a lower temperature. As the vapour cools down, it forms **particles**, which are then deposited onto the mandrel surface. These particles are collected in a **particle collector**.

The solid material is obtained as a coating, a powder, or as single crystals. By varying the experimental conditions—materials with different structures can be grown in this method.
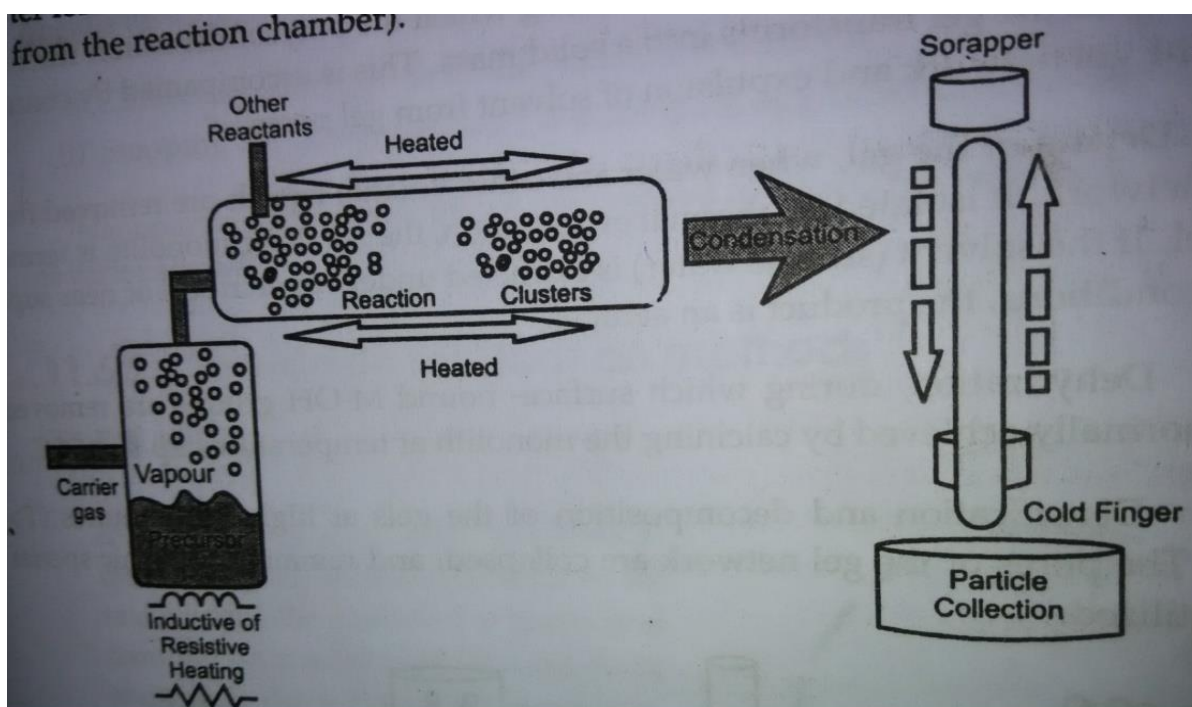

Fig:- CVD Experimental arrangement

CVD setup usually consists of several basic components.

1. Precursors delivery systems

2. Reaction chamber or reactor

3. Energy source

4. Vacuum system

5. Exhaust gas handling system

Precursors Delivery Systems

In CVD, solid, liquid, or gas precursors are used to prepare materials. To deliver them in a controlled way, a **precursor delivery system** is used, which includes a **flow meter or mass flow controller**. The precursor is heated to its boiling point to form vapor, which is then carried by a **carrier gas** into the reaction chamber.

Reaction Chamber or Reactor

A reaction chamber in the reaction tube or reactor is the heart of the CVD setup, in which the CVD reactions take place to form the desired material. The CVD reactor consists of the following parts.

- ➢ A alumina or quartz tube
- ➢ Couplings to hold the pressure and keeping isolation from the rest of the environment.
- ➢ Inlet & Outlet for the flow of gas into the chamber

Energy Source

CVD reaction tubes can be heated using various energy sources like **resistance, radiant, induction, laser,** and **rapid thermal annealing**. **Uniform temperature control** inside the reactor is crucial for proper material growth in the CVD process.

Vacuum System

A vacuum system is usually used in CVD to provide continuous and uniform pressure throughout the CVD process. Different types of pumps commercially available are used in CVD to maintain pressure and prepare the desired materials.

Exhaust Gas Handling Systems

The gas handling system is used to remove the byproduct gases that are created from reaction process from the reaction chamber and to make clean, non-toxic, hazardless of reacted byproducts of CVD reaction before injecting into the open atmosphere.

Advantages :-

- ➢ CVD films are generally quite conformal, i.e., the ability of a film to uniformly coat a topographically complex substrate.

- ➢ Versatile –any element or compound can be deposited.

- ➢ High purity can be obtained.

- ➢ High density – nearly 100% of theoretical value.

- ➢ CVD films are harder than similar materials produced using conventional ceramic fabrication processes.

- ➢ Economical in production, since many parts can be coated at the same time.

Disadvantages :-

- ➢ Chemical and safety hazards caused by the use of toxic, corrosive, flammable and/or explosive precursor. Therefore extra steps have to be taken in the handling of the precursors and in the treatment of the reactor exhaust.

- ➢ High deposition temperatures (often greater than 600 °C) are often unsuitable for structures already fabricated on substrates.

- ➢ Restrictions on the kind of substrates that can be coated.

- ➢ It leads to stresses in films deposited on materials with different thermal expansion coefficients, which can cause mechanical instabilities in the deposited films.

Physical vapor deposition (PVD) :-

PVD is a **thin film deposition technique** where material is **converted to vapor** and then **condensed** onto a substrate to form a thin layer. Physical vapor deposition (PVD) is an environment friendly vacuum deposition technique.

Main Steps:

- ➢ **Vaporization** of source material.

- ➢ **Transport** of vapor in vacuum.

- ➢ **Condensation** of vapor on the substrate to form a thin film.

Common PVD Methods:

I. **Thermal evaporation**: Material is heated to evaporate.

II. **Sputtering**: High-energy ions knock atoms off the target.

I).Thermal evaporation uses the heating of a material to form a vapour which condenses on a substrate to form the coating. Heating is achieved by various methods including hot filament with high electrical resistance, electron or laser beam etc.

In **resistive heating method**, the current is passed through a filament (high *resistance* material) forming a *heating* element which is used to vapourize the target material. The deposition of the vapour on the thin film is carried out in the vacuum chamber. it is shown in the following figure.
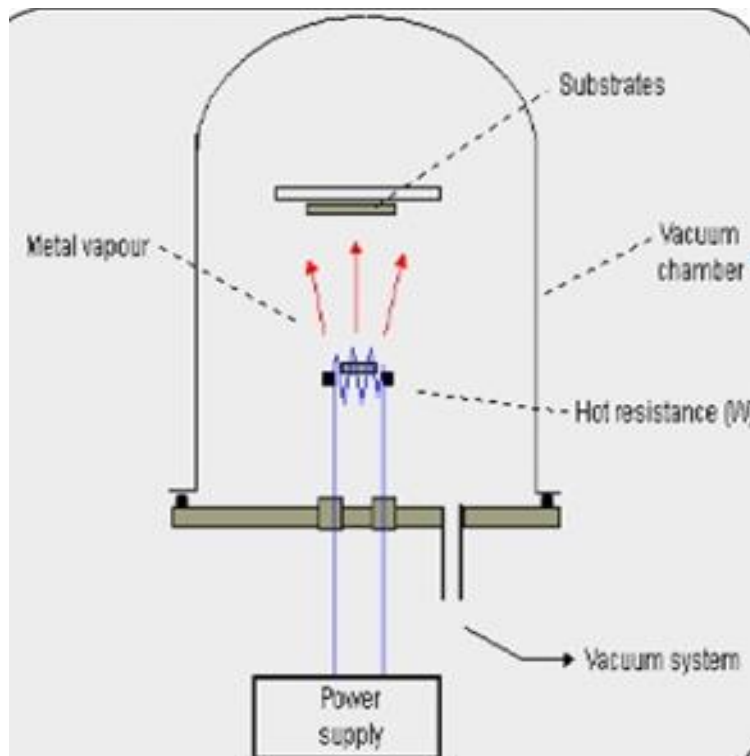

Fig. Resistive heating

In Pulsed laser deposition **(PLD)** a focused pulsed laser strike the highly pure target material to be deposited in vacuum. A laser pulse vaporizes the surface of the target materials and the vaporized materials deposited on the substrate as thin film.
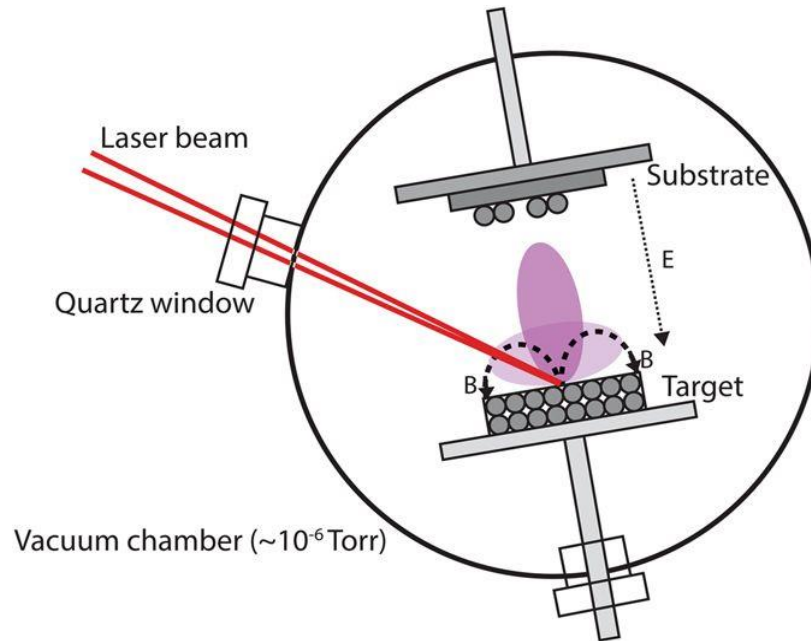

Fig. Pulsed laser deposition **(PLD)**

II).**Sputtering technique:-**

Sputtering is a physical vapor deposition method used to create thin films. Energetic ions, usually from argon plasma, hit a solid target and knock out atoms. These ions are generated by applying DC, AC, or RF power between two electrodes: the cathode (target) and anode (substrate). The ejected atoms then deposit on the substrate to form a thin film or nanowires with the help of catalysts.

The sputtering process consists of the following stages

- ➤ ionization of sputtering gas, usually an inert gas such as argon
- ➤ acceleration of ions towards the target
- ➤ collision between ions and atoms on the surface of target material
- ➤ ejection of atoms from target and
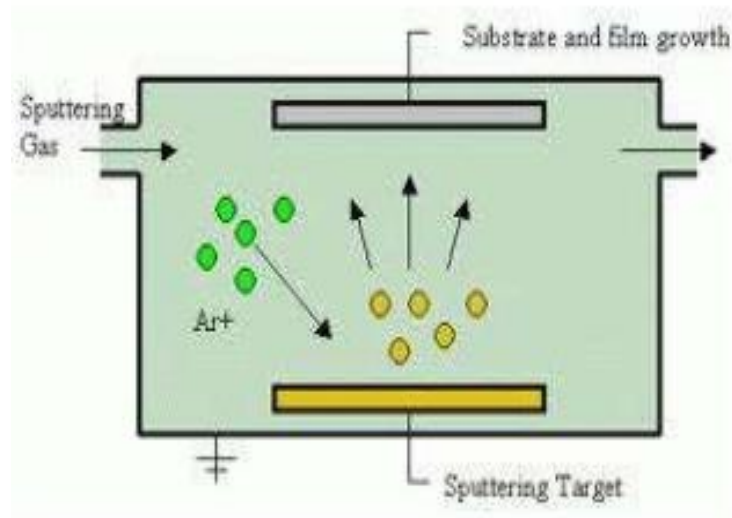- ➤ deposition of sputtered atoms onto the substrate.

Fig:- Sputtering Process

Advantages and disadvantages:-

PVD has several **advantages including:**

> coatings formed by PVD may have improved properties compared to the <u>substrate material</u>;
> all types of inorganic materials and some types of organic materials can be used;
> this process is environmentally friendly compared to many other processes such as electroplating.

However, PVD has also some **disadvantages including:**
> Problems with coating complex shapes;
> High process cost and low output;
> Complexity of the process.

Characterization techniques

X-Ray Diffraction (XRD) :-

X-rays are the electromagnetic radiation with a very short wavelength about 1Å ($\lambda \approx 1$ Å) which is comparable to the atomic size and interplaner spacing in solids. This makes us calculate the variety of crystalline parameters like lattice parameter (a), inter-planner spacing (d), phase purity, X-ray density (ρ_x), and crystallite sizes (D), etc.

X- ray diffraction (XRD) is a versatile, non-destructive characterization method which is used to analyze the structural characteristics of the materials. To determine the structure of a specimen, and thereby to ascertain the positions of its atoms in the lattice, a collimated beam of X-rays are directed toward the sample and is diffracted from the crystalline planes in the specimen. The interaction between the X-rays and the specimen material can be elucidated based on the Bragg's law (Eq. 1). According to Bragg's principle, when X-rays incident on the sample, the lattice planes of the powder sample scatter these X- rays in all the directions. If the total path difference between two diffracted rays is equal to nλ, they interfere constructively and produce the X-ray diffraction pattern.

The Bragg's principle can be expressed as:

$$n\lambda = 2d \sin\theta \qquad \ldots(1)$$

Where, λ is the incident X-rays wavelength, n is an integer, d is inter-planar separation, and θ is Bragg angle or diffraction angle.
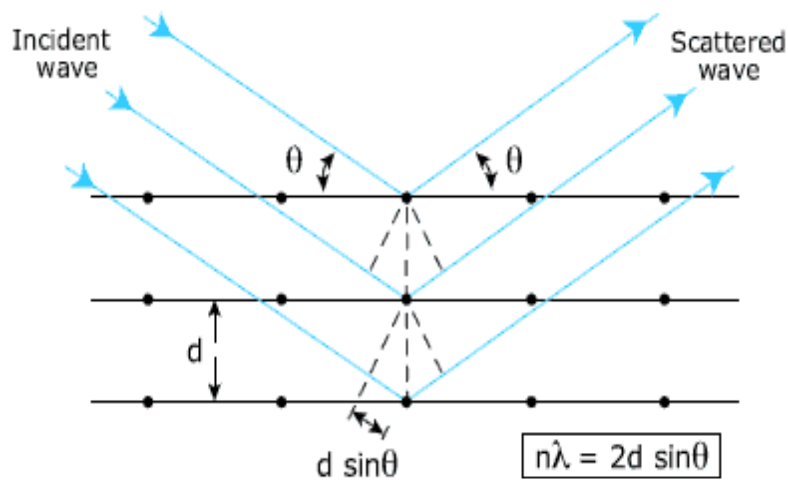

Fig: X-ray diffraction on crystal planes

XRD instrumentation:

A typical powder XRD instrument consist of four main components such as X-ray source, specimen stage, receiving optics and X-ray detector as shown in following figure. The source and detector with its associated optics lie on the circumference of focusing circle and the sample stage at the centre of the circle. The angle between the plane of the specimen and the X-ray source is θ (Bragg's angle) and the angle between the projection of X-ray and the detector is 2θ. For the XRD analysis, fine powder samples can be mounted on the sample holder and the powder was assumed to consist of randomly oriented crystallites. When a beam of X-ray is incident on the sample, X-rays are scattered by each atom in the sample. If the scattered beams are in phase, these interfere constructively and one gets the intensity maximum at that particular angle. The atomic planes from where the X-rays are scattered are referred to as reflecting planes.
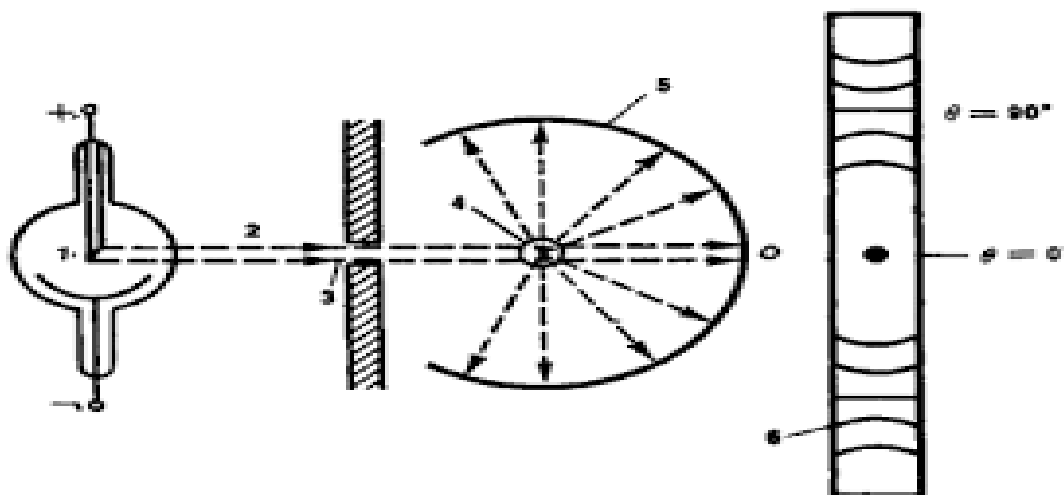

Fig: Schematic of the X-ray diffraction by a crystal

XRD is one of the powerful techniques for the characterization of nanoparticles. This method is widely used to identify the phase formation and crystalline structure of the several materials, which is accomplished by comparing the resultant X-ray diffraction pattern with the standard reference patterns (JCPDS data file of known materials). In addition to this, we can also calculate the other structural parameters like lattice parameter, crystallite size, volume of unit cell, X-ray density and surface area of the material

Scanning Electron Microscope (SEM) :-

SEM is the abbreviation of Scanning Electron Microscope. A SEM is essentially a high resolution electron microscope which uses a collimated beam of electrons instead of light to produce images of the specimen. SEM provides topographical and elemental information of the sample at magnifications of 10 times to 300000 times.

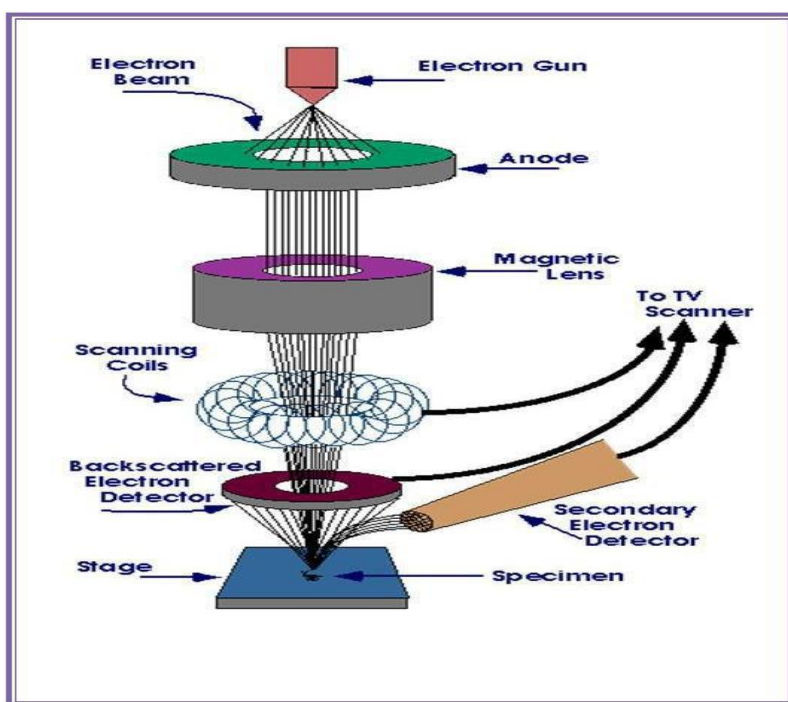The schematic representation of SEM is shown in following figure

Fig: Schematic Block diagram of SEM

Working principle of SEM

SEM produces a highly magnified image using a monochromatic beam of electrons instead of light rays. The specimen does not need special treatment for visualization under the SEM, even air-dried samples can be examined directly. The samples are mounted and coated with thin layer of heavy metal elements (gold) to allow spatial scattering of electric charges on the surface of the specimen allowing better image production, with high clarity. A beam of electrons is produced by a field emission gun is incident on the sample and the scattered

electron signal is used to produce the image of the sample. Detailed working principle is given below:

- ➢ A field emission gun at the top of the microscope produces a stream of electrons.
- ➢ This stream of electrons is condensed by the initial condenser lens.
- ➢ The next electromagnetic lens system produces electrons into a narrow coherent beam.
- ➢ The condenser aperture further eliminates high angle electrons.
- ➢ A collimated electron beam impinges on the thin surface layer of a specimen
- ➢ The beam of electrons interacts with the specimen to produce the backscattered electrons of high energy, secondary electrons of low energy and characteristic X- rays etc.
- ➢ These signals can be detected by suitable detectors and sent to the computer screen.
- ➢ These electrons produce the final image of the sample.
- ➢ The characteristic X-rays generated are used for the identification and estimation of different elements present in the specimen by energy dispersive spectrometer (EDS).
- ➢ In order to avoid the oxidation and contamination of filament (tungsten tip) as well as to reduce the collisions between air molecules and electron, filament and sample have to be placed in a vacuum chamber. Usually, vacuum of the order of 10^{-5} torr or better is necessary for a normal function of SEM.

Transmission Electron Microscope (TEM) :-

It is a powerful imaging tool with high resolution to examine nanoparticles that are too small for observation with conventional microscopes and it usually provides more detailed geometrical features than that are obtained from the SEM. The TEM was the first type of electron microscope to be designed, and TEM pattern is exactly similar to the optical microscope except that a collimated beam of electrons is used instead of light rays to "see through" the test sample. TEM studies provide information regarding the crystal structure, crystal quality, and grain size, particle shapes as well as their size and degree of agglomeration. The interior of TEM must be under extremely high vacuum (less than 10^{-7}atm) to inhibit scattering of the electrons by air molecules.

Working principle of TEM

The detailed schematic representation of a TEM is shown in following figure. Each component /part is labeled, and their functions are briefly explained below. All the lenses which are used in this instrument are electrostatic /magnetostatic because the electrons are used to form the image instead of photons.
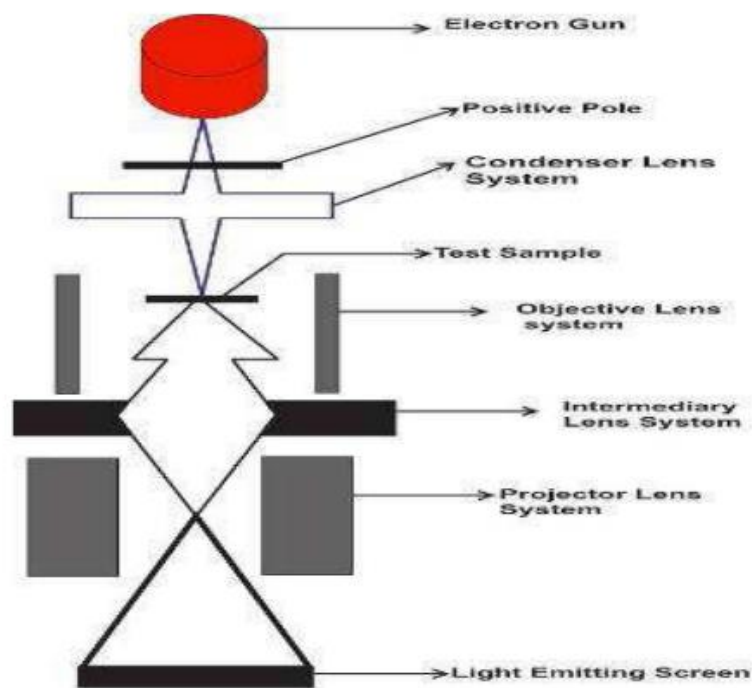

Fig: Block diagram of TEM instrument

➢ A field emission gun at the top of the microscope produces a stream of electrons.

➢ This stream of electrons is condensed by the initial condenser lens.

➢ The next condenser lens produces electrons into a narrow coherent beam.

➢ The condenser aperture further eliminates high angle electrons.

➢ The accelerated electron beam hits the test sample, and some portion of it is transmitted.

➢ The transmitted portion of electron beam is focused by an objective lens arrangement into an image.

➢ The objective aperture improves the contrast by blocking out high angle diffracted electrons.

- Selected area aperture facilitates the observer to examine the diffraction by an ordered arrangement of atoms in the specimen.
- Intermediate and projector lenses magnify the image.
- The beam strikes the phosphor screen to form an image. The brighter areas of the image represent thinner or lesser dense sample areas since these areas transmit more electrons. The darker area of the image represents thicker or denser sample areas since these are transmitted few electrons.

Applications of Nanotechnology:-

1. **Medicine:**

   - **Drug delivery:**
     Nanoparticles carry medicines directly to the affected part of the body.

   - **Cancer treatment:**
     Special nanoparticles are used to kill cancer cells without harming healthy cells.

   - **Diagnosis:**
     Tiny sensors help in early detection of diseases.

   - **Nanosilver for antibacterial use:**
     Nanosilver is added to bandages, masks, and medical tools to kill germs and prevent infection. Nanomaterials help in faster healing of cuts and injuries.

2. **Electronics:**

   - **Smaller and faster devices:**
     Nanotechnology is used to make tiny transistors and circuits for faster computers and phones.
   - **High-density memory chips:**
     Nano-sized materials store more data in smaller space (used in pen drives, SSDs).
   - **Flexible and wearable electronic devices:**
     Nanomaterials help make bendable phones, displays, and wearable devices.
   - **Improved displays:**
     Nanoparticles improve brightness, color, and energy efficiency in TVs and screens.
   - **Better sensors:**
     Nanosensors detect light, sound, motion, or gases with high sensitivity (used in smart devices).

3. **Energy:**

   - High-efficiency solar cells

   - Better batteries and supercapacitors

- Energy-saving coatings and devices

4. **Environment:**

- Water purification (nanofilters)

- Air pollution control

- Waste treatment and sensing

5. **Textiles:**

- Stain-resistant and waterproof fabrics

- Antibacterial clothing

6. **Cosmetics:**

- Sunscreens with better UV protection

- Anti-aging creams with improved absorption

7. **Food Industry:**

- Food packaging with longer shelf life

- Nano-sensors for contamination detection

8. **Automotive and Aerospace:**

- Lightweight and strong materials

- Scratch-resistant coatings

- Fuel-efficient components

9. **Construction:**

- Stronger, self-cleaning, or crack-resistant materials

- Nanopaints with anti-fungal properties

10. **Agriculture:**

- Nano-fertilizers and pesticides for better crop yield

- Soil and crop monitoring using nanosensors