



CHAPTER 14

Nanotechnology

14.1 Basic principle of nanoscience and nanotechnology

Nanotechnology is the extension of existing science into the nanoscale. It pushed towards microminiaturization. The word 'nano' means 'one-billionth', (10^{-9}). Feynman, a noble laureate in physics, brought this nanotechnology into daylight by delivering lectures in 1959. Nanoscience is the study of the fundamental principles of molecules and structures having sizes in between 1 and 100 nm. These are known as nanostructures. The 20th century scientists called this as top-down science. The physical, chemical, biological properties associated with the nanostructures constituted from atoms and molecules is known as bottom-up process. The top-down process refers to machining and etching techniques and the bottom-up process refers to building organic and inorganic structures atom-by-atom or molecule-by-molecule.

Nanotechnology deals with the design, manufacturing and applications of nanostructures in useful nanoscale devices such as electronic circuits and mechanical devices at the molecular level. These are the smallest solid things possible to make. In nanotechnology, the fundamental properties of materials and machines depend on their size. For example, a nanoscale wire or circuit component does not necessarily obey Ohm's law.

The principle of the nanoscale science and engineering refers to the fundamental understanding and technological advances from the exploitation of new physical, chemical, electrical and biological properties of systems having size in between molecules [or atoms] and bulk materials. Nanotechnology refers to the field of applied science and technology that deals with the fabrication of devices or materials which lie in the sizes of 1 to 100 nm.

Through nanotechnology, we can understand many new things. For example, if we properly arrange carbon atoms in coal then it may become diamond. By rearranging atoms in sand, silicon chip can be made. Single atom manipulation has been known in late 1980s using the scanning tunneling microscope (STM). The probe of the STM is as sharp as an atom at the tip. The distance between the tip and the flat surface of the specimen is nearly 1 nm and kept constant by monitoring the tunneling

current. By applying a voltage pulse in this condition, a single atom can be extracted from the surface of the specimen and then placed at a desired position. The STM is also useful for manipulating single molecules, observing molecular shapes, microfabrication technology for semiconductor devices and bio-chemical technology. Nanotechnology produces materials that are built up atom-by-atom. With carbon atoms tubular molecules are made and they are called carbon nanotubes. Spherical molecules with 60 carbon atoms having a diameter slighting less than 1 nm can also be made and these are called bucky balls or fullerenes. The factors that differentiate nanomaterials from bulk materials is the increase in surface area to volume ratio and quantum confinement effects. These are explained below.

(a) Surface area to volume ratio: This value is very large for nanomaterials. To understand this concept, consider a spherical material of radius ' r ' then:

$$\frac{\text{Surface area of the sphere}}{\text{Volume of the sphere}} = \frac{4\pi r^2}{\left(\frac{4}{3}\right)\pi r^3} = \frac{3}{r}$$

As the size of the sphere decreases, the above ratio increases. Alternatively, if the material is cubic, as it is divided into small cubes, then also the surface area to volume ratio increases. Hence, the nanomaterials possess large value of surface area to volume ratio as compared to the bulk material.

(b) Quantum confinement effects: According to band theory, solid materials have energy bands and isolated atoms possess discrete energy levels. Nanomaterials are intermediate to the above two cases. For nanomaterials, if the dimensions of potential wells or potential boxes are of the order of the de Broglie wavelength of electrons or mean free path of electrons, then the energy levels of electrons change, and the electron will remain confined to a small region of the material. This is called quantum confinement.

Nanomaterials are very strong, hard, wear resistant, corrosion resistant, erosion resistant and chemically active.

The electrons in bulk solid material possess alternatively discrete allowed and forbidden bands of energies. As the material changes from bulk to nanoparticle size, the energies of electrons change. A graph plotted between the density of electron states versus the energies of electrons for a bulk material is a parabola, whereas this is not the case for nanoparticle materials. The quantum effects are dominant in nanoparticle materials. So, we come across quantum dots, quantum wires and quantum wells (or quantum films) in nanoscience. They are zero, one and two dimensional nanoparticles. The concept of the above materials and their electron density states are illustrated below.

When a bulk nanoparticle material is reduced in one, two and three dimensions to nanometers then it results in the formation of quantum film, quantum wire and quantum dot as shown in Fig. 14.1.

The energies of electrons in quantum dots appear as clusters. The density of electron states vary from cluster to cluster as shown in Fig. 14.2a.

In the case of quantum wires, the density peaks are high at energy values $E_1, E_2, E_3 \dots$ and decrease rapidly for ranges in between as shown in Fig. 14.2b. The density of states

$$\Omega(E)dE = \frac{\sqrt{2m}}{\pi\hbar} \sum \left[\frac{n_i H(E - E_i)}{\sqrt{E - E_i}} \right] dE$$

Where n_i is degeneracy factor and $H(E - E_i)$ is the Heaviside function. The density of states is of the order of $10^9/m$ eV.

Figure 14.1

Representation of quantum film, quantum wire and quantum dot in a bulk nanoparticle material

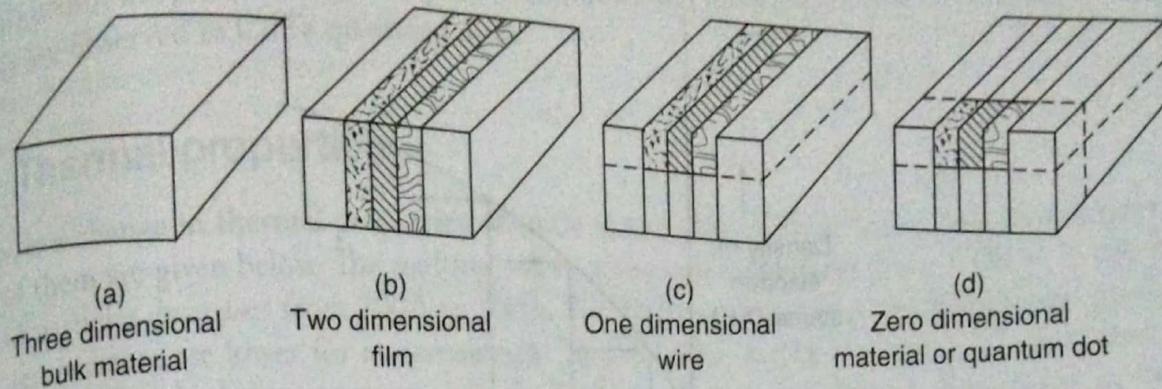


Figure 14.2a

Density of electron states versus energy of electrons for quantum dots

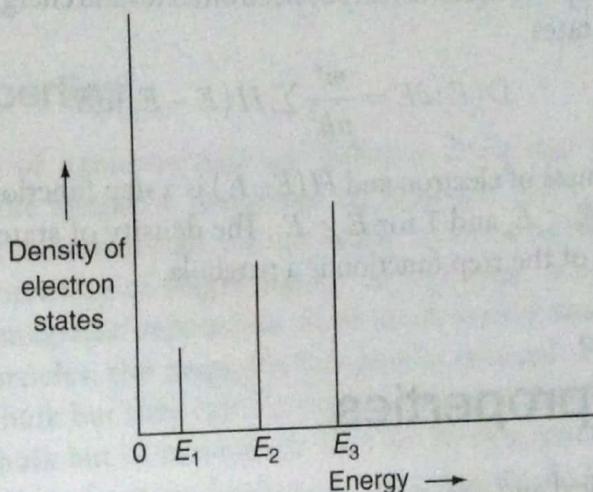


Figure 14.2b

Density of states versus energy of electrons for quantum wire

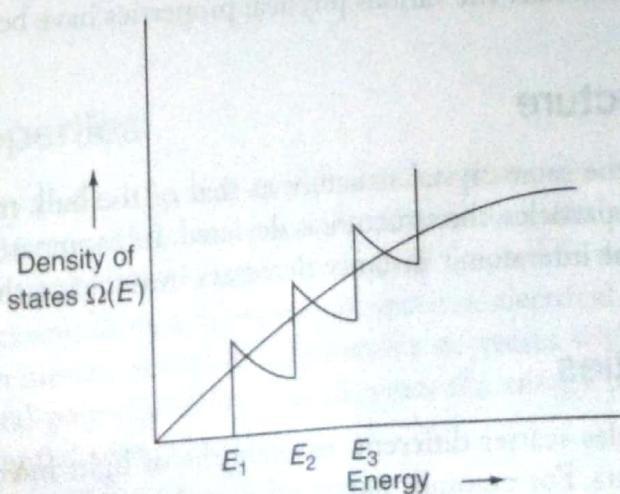
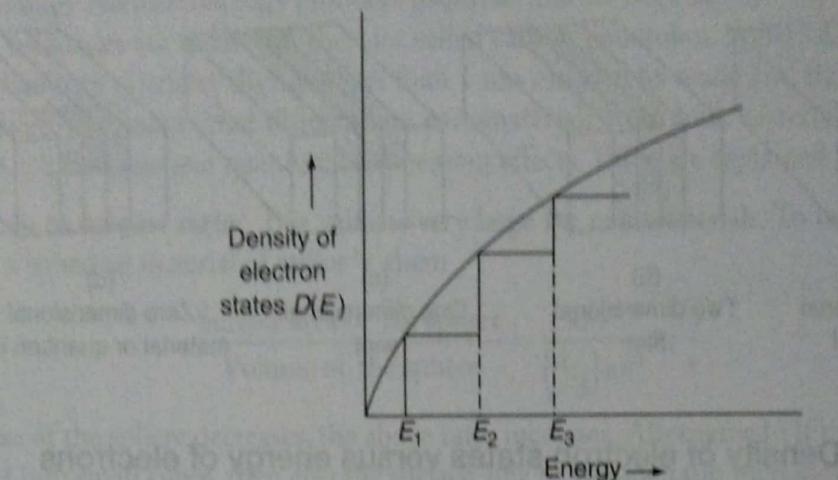


Figure 14.2c

Density of electron states versus energy of electrons for quantum film



In quantum wells, the graph between density of electron states and energy is a step function as shown in Fig. 14.2c. The density of states

$$D(E)dE = \frac{m^*}{\pi\hbar^2} \sum H(E - E_i) dE$$

Where m^* = effective mass of electron and $H(E - E_i)$ is a step function called the Heaviside function. This value is zero for $E < E_i$ and 1 for $E \geq E_i$. The density of states is of the order of $10^{18}/\text{m}^2 \text{ eV}$. The locus of all corners of the step function is a parabola.

14.2 Physical properties

At the macro scale, the physical and chemical properties are not dependent on the size of the material, but at the nanoscale every thing will change including colour, melting point and chemical properties. This is due to the difference in the nature of interactions between atoms in nanostructures and in bulk materials. Materials reduced to the nanoscale can suddenly show very different properties compared to what they exhibit on a macroscale. The various physical properties have been explained below:

(i) Geometric structure

Large nanoparticles have the same crystal structure as that of the bulk material but different lattice parameters. In cluster nanoparticles, the structure is deviated. In nanomaterials, the surface to volume ratio increases. Similarly, the interatomic distance decreases by reducing the size of nanoparticles.

(ii) Optical properties

Different-sized nanoparticles scatter different wavelengths of light incident on it and hence they appear with different colours. For example, nanogold doesn't act like bulk gold. The nanoscale gold

particles can be orange, purple, red or greenish in colour depending on their grain size. The bulk copper is opaque whereas nanoparticle copper is transparent. Porous silicon exhibits red photoluminescence, but bulk silicon will not show this effect. In nanoparticle semiconductor elements (such as Ge, Si), a shift in optical absorption spectra (towards blue) have been observed. The electroabsorption effects are observed in CdTe quantum dots.

(iii) Thermal properties

There is a change in thermal properties of some materials as they go from bulk to nanoparticles. A few of them are given below. The melting point of nanogold decreases from 1200 K to 800 K as the size of particles decreases from 300\AA to 200\AA . The Debye temperature and ferroelectric phase transition temperature are lower for nanomaterials. The diffusion coefficient and solid state phase transition pressure are high for nanomaterials. At higher temperatures, there is breakdown in symmetry of nanoparticles due to high thermal vibrations of surface atoms in nanostructures. Superplasticity of nanomaterial occurs at lower temperatures by reducing the grain size. Stable aluminium becomes combustible in nanophase. Solid gold changes into liquid as it goes from bulk to nanomaterial at room temperature.

(iv) Magnetic properties

The magnetic properties of nanomaterials are different from that of bulk materials. In small ferromagnetic particles, the magnetic properties are different from that of bulk material. They are saturated magnets. In nanomaterials, we use single domains unlike large number of domains in bulk materials. The coercivity of single domain is very large. Small clusters [containing less than 80 atoms] of non-magnetic substances show spontaneous magnetic moment whereas in case of magnetic nanoparticles, the magnetic moment is reduced. For example, Fe, Co, Ni and Gd are ferromagnetic in bulk but they exhibit super paramagnetism in the nanophase. Na, K and Rh are paramagnetic in bulk but in nanophase, they are ferromagnetic. Cr is anti-ferromagnetic in bulk, in nanophase it shows frustrated paramagnetic property. At higher temperatures, clusters show less magnetic moment called super paramagnetism because thermal vibrations change the alignment of magnetic moment. Clusters of non-magnetic element supported on metal substrates also show magnetism. This shows that small particles possess more magnetism than the bulk material.

(v) Electronic properties

The electrical conductivity and energy bandwidth of some materials change when they pass from bulk phase to nanoparticle phase. For example, bulk silicon is an insulator; it becomes a conductor in the nanophase. Nanomaterial semiconductors such as Ge and Si do not show semiconducting property. In nanoceramics and in nanomagnetic composites, electrical conductivity increases with reducing particle size. In metals, electrical conductivity decreases with reducing particle size. By reducing the size of metal particles from bulk to nano, the energy bands become narrower and hence the ionization potential energy increases.

(vi) Mechanical properties

The mechanical behaviour of nanostructures is dominated by the nature of interfaces in them. Mechanical properties such as hardness, toughness, elastic modulus, scratch resistance, fatigue strength, crack initiation and propagation are significantly different for nanostructures than bulk materials. In metals and alloys, the hardness and toughness are increased by reducing the size of nanoparticles. In ceramics, ductility and superplasticity are increased on reducing particle size. Nanostructured composites offer an increased density of inhibitors to slip crack migration so that the strength of the material increases. Hardness increases 4 to 6 times as one goes from coarse grain Cu to nanocrystalline Cu and it is 7 to 8 for Ni.

It is observed that the materials with smaller grain size are stronger, because crack propagation can be delayed or reduced in nanostructures than bulk materials. Fe and Ni continue to harden with decreasing grain size. By decreasing the size of nanocrystalline metals from $1\text{ }\mu\text{m}$ to 10 nm , the hardness increases 2 to 7 times. As the grain size is reduced below 10 nm , the hardness reduces in some nanomaterials. The transition from bulk to nanophase reduces elastic strength and increases plastic behaviour. Brittle materials [ceramics, intermetallics] can become ductile by reducing their grain size. At higher temperatures, nanozirconia material possesses superplastic property. When the material is superplastic, it can undergo large tensile deformation without necking and fracture. Creep involves atomic transport along grain boundaries, and materials having large number of grains have large creep rates. This leads to superplasticity. The creep rates can be increased by 6 to 8 times by reducing the grain size from microns to nanometers. The reduction of the size of nanoparticles in steel leads a reduction in ductile-to-brittle transition temperature.

14.3 Chemical properties

Nanocrystalline materials are strong, hard, wear resistant, erosion and corrosion resistant. They are chemically active and have the following chemical properties.

(a) The nanostructures in chemistry are colloids and these are formed in a condensed phase having sizes in the range from 1 to 100 nm . Nanoscale catalysts have a high degree of dispersion, and this maximizes the contact area of a catalyst with the reactant.

(b) The effect of nanoscale materials on chemical reactivity: Changes in chemical reactivity of nanoscale materials have been expected. Chemical reactions are governed by electrons, electron affinities [or ionizational potential] and electron orbital densities. Coupling exists between chemical reactivity and the electronic character of the reactants and any catalyst. It was known that the ionizational potential increases as the cluster size drops below the bulk limit and it has limited applicability.

The electronic properties of a catalyst is host-dependent and possibly even reaction-dependent. Clusters of platinum, iridium or osmium reduced to a size of 1 nm and supported on alumina or silica exhibited electronic properties similar to those found for large crystallites of the metal. The electronic structure of metal nanocrystallites depends on supported non-conducting oxides. The reactivity of a cluster depends on the cluster size. This is useful in the preparation of catalytic agents. Some chemically inert bulk materials become good chemical catalysts in the nanophase, for example: platinum and gold.

(c) **Electrochemical reactivity:** Nanostructure size effects have been observed in catalysis. In the case of metal nanocrystallites supported on conductors, we see that in nanocrystallites of platinum supported on titanium or glassy carbon, the photocurrent increases whereas the photoemission current for palladium nanocrystallites supported on glassy carbon decreases relative to that of the bulk metal. So, we say that photoemission currents vary as a function of the crystallite size i.e., as compared to the bulk metal, increased reactivity for supported platinum nanocrystallites and decreased reactivity for glassy carbon supported palladium nanocrystallites was observed.

(d) **Effect of nanostructures on mass transport:** In chemical or electrochemical reactions, the rate of increase in mass transport increases as the particle size decreases.

(e) **The effect of chemistry on nanostructures:** The equilibrium vapour pressure, chemical potentials and solubilities of nanoparticles are greater than that for the same bulk material. Exposure to high temperatures or to certain chemicals can increase the size of a nanostructure. The high surface area of atoms or molecules of nanocrystallites supports heterogeneous catalysis.

(f) **Hydrogen storage in metals:** Most of the metals do not adsorb hydrogen, those adsorb have a metal to hydrogen atom ratio of 1. The small positively charged clusters of Ni, Pd and Pt containing atoms in between 2 to 60 can adsorb hydrogen atoms up to 8 per metal atom. This hydrogen adsorption decreases with an increase of cluster size. So, small metallic clusters are used as hydrogen storage devices.

14.4 Fabrication

Fabrication applies to the building of machines, structures or process equipment by cutting, shaping and assembling components made from raw materials. In nanotechnology, the scanning instruments help to a large extent in the development of nanoscience. In these instruments, the tip of the probe slides along a surface. The tip has nanoscale dimensions, usually of single-atom size. During sliding, the instrument measures different properties. To determine these properties, there are different types of scanning probe measurements. They are described in brief below.

(i) **Atomic force microscopy (AFM):** In this, electrons are used to measure the force applied on the probe tip as it moves on the object surface.

(ii) **Scanning tunneling microscopy (STM):** In this, the amount of electrical current flowing between the scanning tip and the object surface is used to measure local electrical conduction and geometry of the object at that place.

(iii) **Magnetic force microscopy [MFM]:** In this, the tip scans the magnetic surface. This locally detects the magnetic structure of the substance.

All other scanning microscopes also work on the principle of STM. The scanning is used to find nanoscale structure by measuring force, current, magnetic drag, chemical identity, etc.

The scanning probe instrument uses the dragging finger analogy. This helps us to see structures and modify a surface with the help of the tip of the scanning probe. The individual atoms or molecules can be moved on the surface by pushing on the surface or by picking them off the surface,

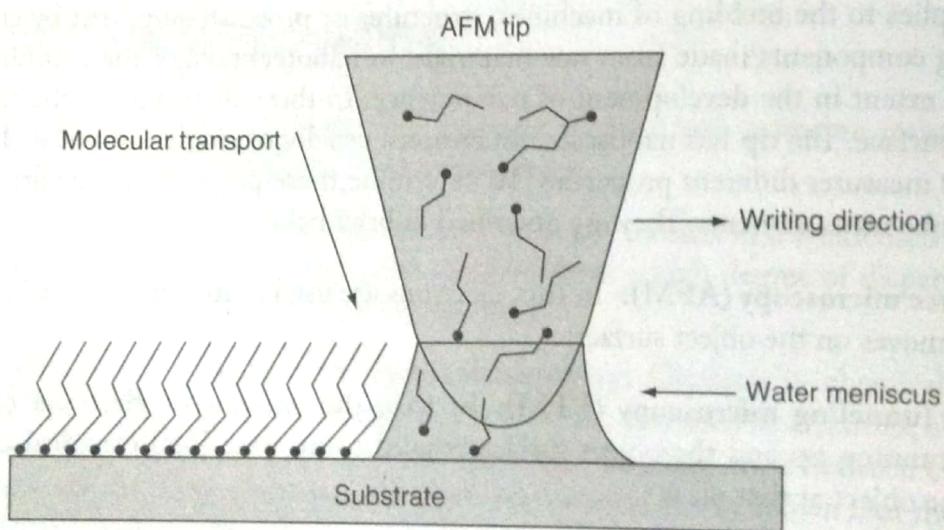
moving and putting them back down. In this process, the scanning tip acts as a sort of earth mover at the nanoscale. Some scanning instruments have hundreds or even thousands of probe tips. The various nanostructure fabrication processes are described below.

(i) **Nanolithography:** Optical or X-ray lithography is used to make the present computer chips. In this, a master mask is made using chemical methods. A lithograph is an image that is produced by carving a pattern on the stone. Lithography is used for making objects from stones. In addition, there is microimprint lithography. This method works in the same way as the rubber stamp.

(ii) **Dip pen nanolithography (DPN):** The DPN is a direct writing technique that is used to create nanostructures on a substrate by delivering molecules through a capillary present at the tip of an atomic force microscope (AFM), as shown in Fig. 14.3. AFM tips are the ideal nanopens to construct arbitrary nanostructures on surfaces. The principle of DPN is similar to that of using the fountain pen. In this method, a reservoir of ink (atoms or molecules) is present at the top of the probe tip and are arranged across the surface.

The ink is alkylthiol molecules; these molecules possess a head group of a thiol and 1–4 nm length hydrocarbon tail group. These molecules are taken as delivery molecules and a gold substrate is used to collect the molecules. The thiol molecules form a single layer on the substance with the thiol group forming a strong bond with gold and the tail group aligning perpendicular to the surface. The DPN device is used to image and write a pattern. Using software, the DPN plotter can write complicated patterns also.

Figure 14.3 Representaion of dip pen lithography

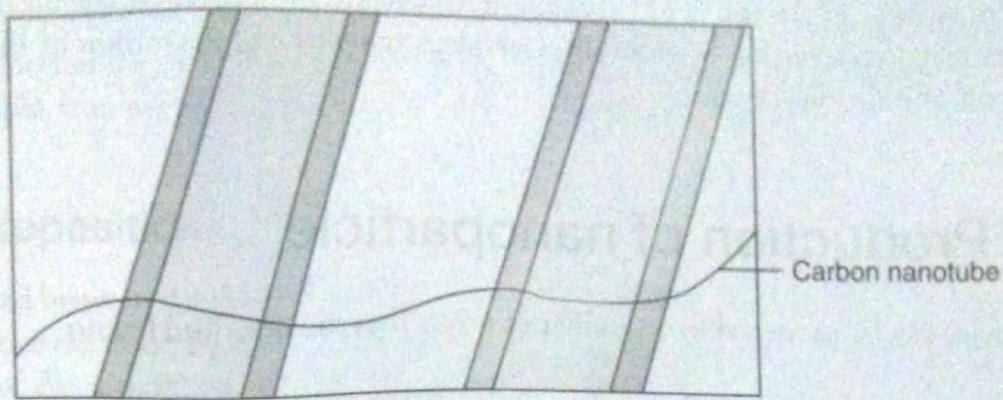


(iii) **Electron beam lithography:** The use of light of small wavelengths generate some problems, so instead of light beam electron beam is to be used in lithography. The structures at nanoscale can be manufactured using e-beam lithography. Figure 14.4 shows the formation of two electrodes using electron beam lithography. The structure lying across is a single molecule carbon nanotube.

In this method, the resolution depends on the granularity of the resist used, the contrast of the resist developer, spatial distribution of deposited energy and the statistical distribution of photons at each pixel. During lithographic process, the whole system is kept under vacuum and a single beam of

Figure 14.4

Two electrodes made using electron beam lithography. The horizontal structure one is the carbon nanotube.

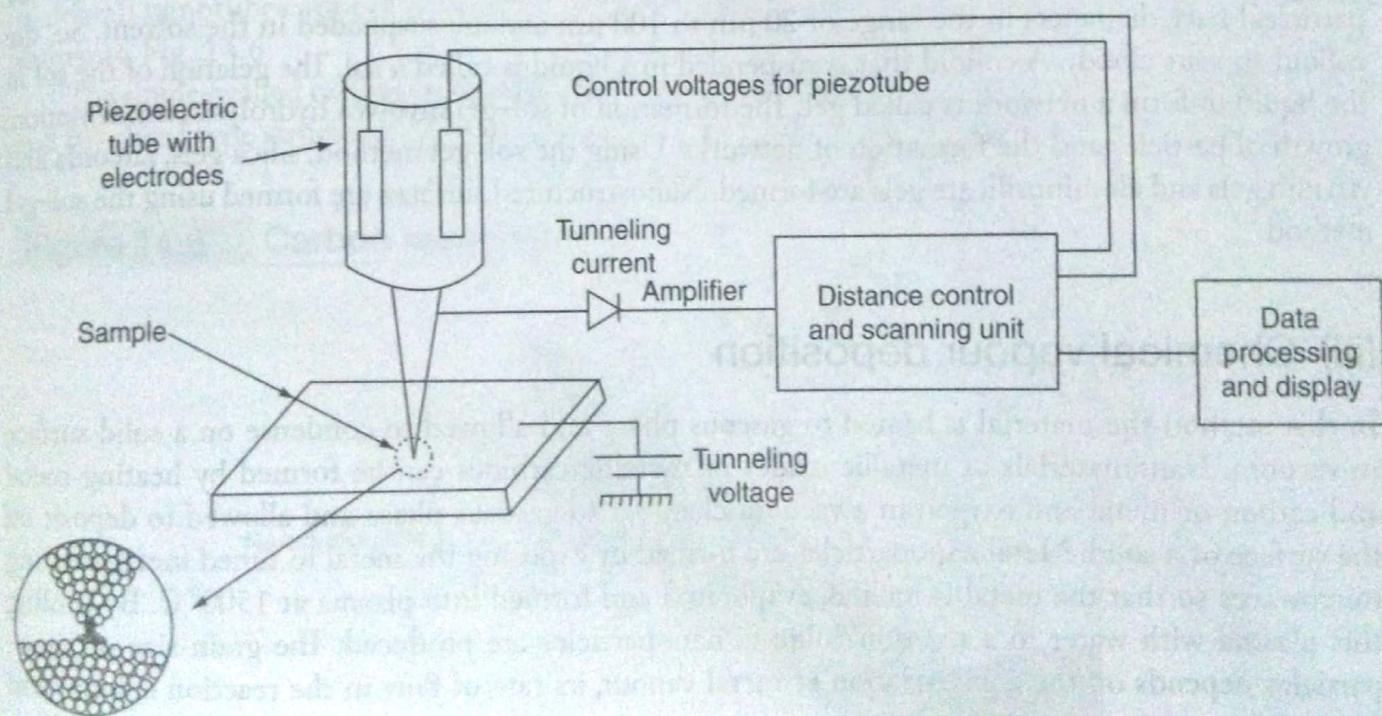


electrons is focused at the surface of the resist-coated semiconductor wafer. Using pattern generator, the electron beam is moved across the surface under computer control.

(iv) **Atomic lithography:** The scanning tunneling microscope [STM] used in this method is capable of imaging individual atoms i.e., directly observe the atoms on the surface of a material. The resolution is of the order of a fraction of atomic diameter. The STM works [Fig. 14.5] by using a very sharp tip that is positioned over the electrically conducting sample.

The magnitude of tunneling current monitors the separation between the tip and the sample surface. As the tip moves, the tunneling current changes, and this shows the distance between the tip and surface. The change in tunneling current is fed back to an electrical circuit, which controls the up and

Figure 14.5 A schematic diagram of the operation of a STM



down motion of the tip. The decrease in tunneling current is an indication of larger separation, then the feedback circuit lowers the tip. A voltage difference applied between tip and surface causes a small number of electrons to tunnel from the tip to the sample surface. By applying a few volts between the tip and surface, an electric field is produced, this field can break local chemical bonds or initiate a chemical reaction, resulting in atom displacement, removal and deposition of individual atoms or knocking off of individual atoms.

14.5 Production of nanoparticle

Nanoparticles can be produced by a number of ways. They are described below:

(i) Plasma arcing

Plasma is an ionized gas. Plasma can be produced by the discharge of gas between two electrodes, so that the gas dissociates into electrons and positive ions. Using plasma arcing, very thin films of the order of atomic dimensions can be deposited on the surface of an electrode. This deposition is carried in vacuum or in an inert gas. An arc passes from one electrode to the other. The first electrode [anode] vapourizes, so positively charged ions are produced. These ions deposit on the cathode. By using carbon electrodes, carbon nanotubes can be formed on the surface of the cathode. A mixture of conducting and non-conducting materials is also used in electrodes to form thin layers of the materials on the cathode.

(ii) Sol-gel method

In solutions, nano-sized molecules are dispersed randomly. Whereas in colloids, the molecules [or particles] have diameters in the range of $20\text{ }\mu\text{m}$ to $100\text{ }\mu\text{m}$ and are suspended in the solvent. So, the colloid appears cloudy. A colloid that is suspended in a liquid is called a sol. The gelation of the sol in the liquid to form a network is called gel. The formation of sol-gel involves hydrolysis, condensation, growth of particles and the formation of networks. Using the sol-gel method, silica gels, zirconia and yttrium gels and aluminosilicate gels are formed. Nanostructured surfaces are formed using the sol-gel method.

(iii) Chemical vapour deposition

In this method the material is heated to gaseous phase and allowed to condense on a solid surface in vacuum. Nanomaterials of metallic oxides or metallic carbides can be formed by heating metal and carbon or metal and oxygen in a vacuum chamber to gaseous phase and allowed to deposit on the surface of a solid. Metal nanoparticles are formed by exposing the metal to tuned metal-exciting microwaves so that the metal is melted, evaporated and formed into plasma at 1500°C . By cooling this plasma with water in a reaction column, nanoparticles are produced. The grain size of nanoparticles depends on the concentration of metal vapour, its rate of flow in the reaction column and temperature.

(iv) Ball milling

In this method, small balls of the material are made to rotate inside a drum and drop under the influence of gravity on to a solid present in the drum. The balls are broken into nanocrystallites. This is also known as mechanical crushing. This method is used for a large number of elements and metal oxides. For example, iron nanoparticles of sizes 13 to 30 nm can be formed.

(v) Electrodeposition

As current is passed between the electrodes immersed in an electrolyte, some substances will be deposited on the surface of one electrode. By controlling the current, a single layer of atoms can be deposited. Nanostructured films of Au, Cu, Pt, Ni, polymers, oxides and semiconductors can be deposited. These films are robust, flat, uniform and shiny. The deposited plates are used in batteries, solar cells, fuel cells, sensors, photonic devices and field emitters.

14.6 Carbon nanotubes

(a) Introduction

Carbon nanotubes are hollow cylindrical tubes. The length of carbon nanotubes may vary from several micrometers to millimeters and the diameter will vary from 1 to 20 nm. The ends are closed with caps containing pentagonal rings. A tube may contain one cylindrical wall of graphite or a number of concentric cylindrical walls. Under the transmission electron microscope, these cylindrical walls appear as planes. Single wall nanotubes appear with two planes whereas the multiwall nanotubes appear with more than two planes and are seen as a series of parallel lines as shown in Fig. 14.6.

The single-walled carbon nanotubes are of three different types. They are: (i) arm chair, (ii) zig-zag and (iii) chiral type structures. These are shown in Fig. 14.7. In these, a single hexagonal wall is seen.

Figure 14.6 Carbon nanotubes

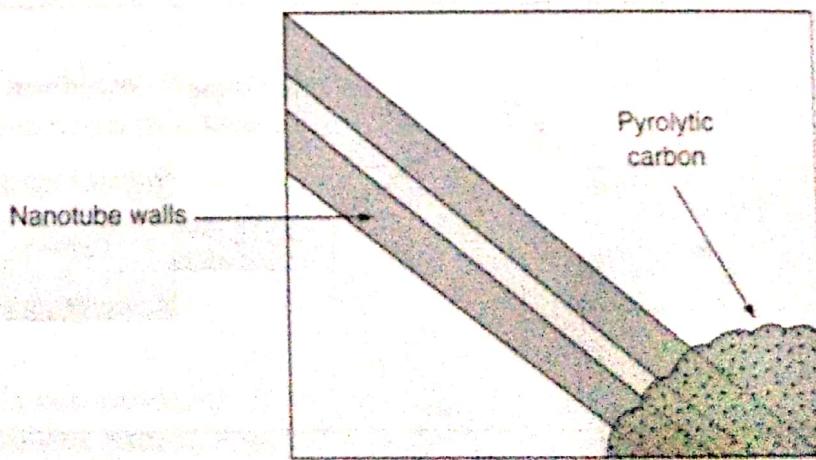
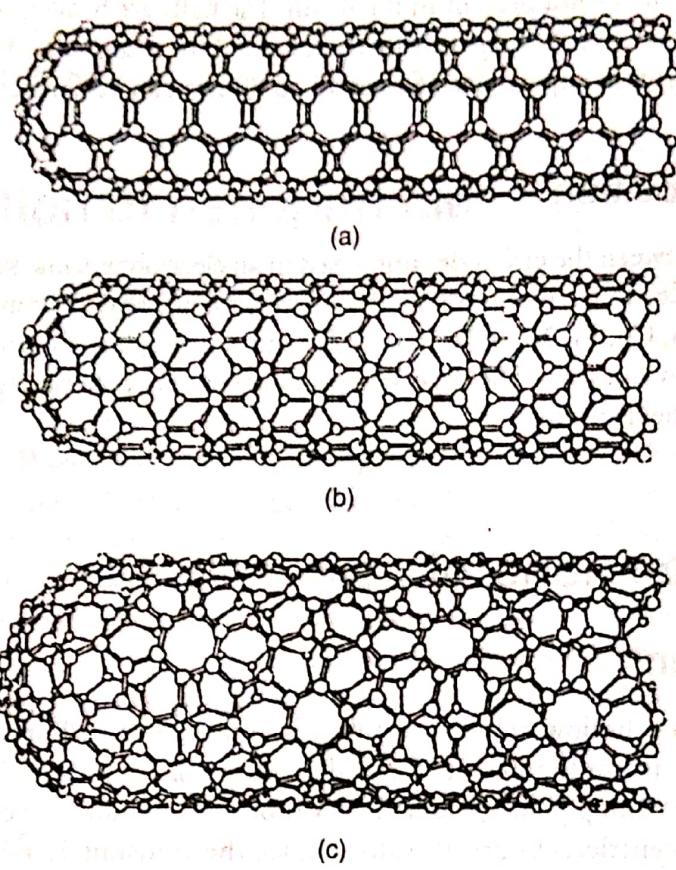


Figure 14.7

Single-walled carbon nanotubes: (a) Arm chair, (b) Zig-zag, and (c) Chiral type

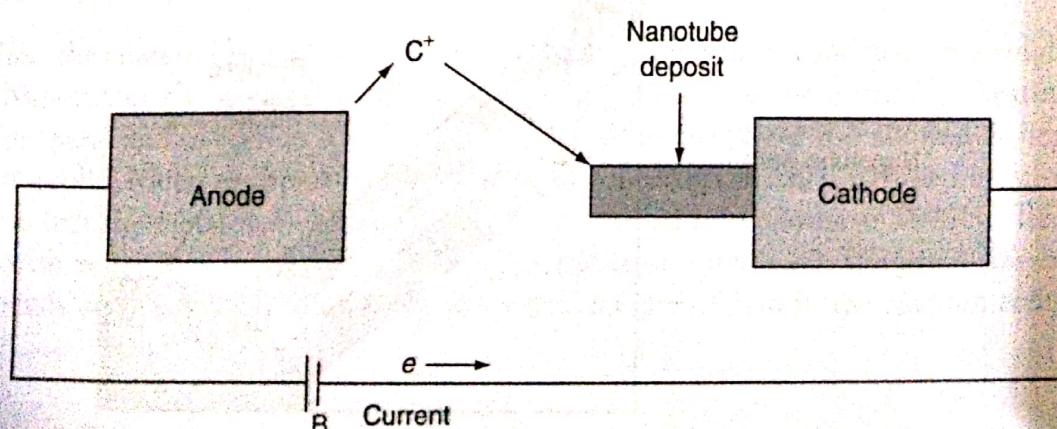


(b) Formation of nanotubes

There are a number of methods of making nanotubes.

(i) Plasma arcing method: Carbon nanotubes are prepared by putting an electric current across two carbonaceous electrodes [graphite] as in a helium or argon atmosphere as shown in Fig.14.8. This method is called the plasma arcing method. In this method, evaporation of one electrode [anode] takes

Figure 14.8 Carbon nanotube formation



place as cations, and the particles are deposited at the other electrode. The deposition on the cathode are nanotubes. Normally, multi-walled nanotubes are formed from plasma arcing. Single-walled nanotubes are formed if the electrodes are bored out and cobalt or other metals are included.

(ii) **Laser method:** Large quantities of single-walled nanotubes can be prepared by dual-pulsed laser vapourization method. In this method, the samples can be prepared by laser vapourization of graphite rods with equal amounts of cobalt and nickel powder at 1200°C in flowing argon. After this, heat treatment is carried out at 1000°C in vacuum to remove C₆₀ and other fullerenes. The first laser vapourization pulse is followed by a second pulse for more uniform vapourization. The product appears as a mat of ropes having a diameter of 10–20 nm and a length of 100 µm or more. The diameter of tubes can be controlled by varying the parameters such as growing temperature and catalyst composition.

The other methods include arcing in the presence of cobalt, chemical vapour deposition method, ball milling, diffusion flame synthesis, electrolysis, solar energy pyrolysis at low temperature, heat treatment of a polymer, etc.

(c) Properties of nanotubes

- (i) The tubes are mechanically robust.
- (ii) Nanotubes are about 6 times lighter, 10 times stiffer and 20 times stronger than steel.
- (iii) The tube behaves as a metal and as a semiconductor. As a metal, its electrical conductivity is 1000 times more than that of copper.
- (iv) The electrical conductivity of nanotubes is a function of diameter, conductivity in multiwalled nanotubes is quite complex.

(d) Applications of nanotubes

(i) **Electronics:** The single-walled nanotube can act as a transistor. Pairs of nanotubes or crossed nanotubes show as logic structures. If a line of hexagons form a helix, then the tube acts as a semiconductor. A single nanotube with a natural junction acts as a rectifying diode. Transistor nanotube circuits are built by drawing a single nanotube over three parallel gold electrodes, adding a polymer between the electrodes and sprinkling potassium atoms on the top. The potassium atoms add electrons to the nanotube. In flat panel displays, a nanotube works due to its field emission property. Nanotubes are used in batteries.

(ii) **Hydrogen storage:** Nanotubes can store hydrogen and also helium, oxides and metals like copper.

(iii) **Mechanical machines:** Nanotubes can act as axles in nanomachines. Building gear teeth on nanotube is favoured to translate different rotational motions.

(iv) **Space elevators:** Long filaments of nanotubes are used in fibre-reinforced plastics, these have less weight. So they are used in aeroplanes, space ships and land vehicles. Carbon nanotubes, like graphite, withstand high temperatures, so they are used for thermal protection of spacecraft during re-entry into the atmosphere. Carbon nanotubes have high Young's modules, so they withstand aeronautical strains.

(v) **Hospitals:** Carbon nanotubes are thin, so they can penetrate the skin without pain. Blood can be drawn from diabetic patients through nanostraws to know glucose levels and to inject insulin whenever required.

14.7 Applications of nanotechnology

Nanomaterials are found in both biological systems and man-made structures. Nature has been using nanomaterials for millions of years. The large surface area to volume ratio increases the chemical activity. Nanomaterials have the following applications.

(i) In microelectronics: In microelectronics, the reduction in size of electronic components leads to faster switching times. Nanotechnology includes fabrication of nanowires used in semiconductors. Porous silicon emits visible light, so it finds application in optoelectronics. Quantum dot lasers are nanoscaled objects, they emit good-quality laser beam compared to semiconductor laser diodes. They are cheaper and the emitted wavelength depends on the diameter of the dot.

(ii) Machine tools: Some nanocrystalline materials such as tungsten carbide, tantalum carbide and titanium carbide are harder than conventional materials; they are more wear-resistant and erosion-resistant, so they are used in cutting tools and drill bits. Nanocrystalline silicon nitride and silicon carbide are used in the manufacturing of high-strength springs, ball bearings and valve lifters because of their excellent physical, chemical and mechanical properties. Nanocrystalline ceramics such as zirconia (ZrO_2) are softer than conventional materials, so they can be easily pressed and sintered into various shapes at significantly lower temperatures.

(iii) High-power magnets: The magnetic strength of a material is directly proportional to the surface area per unit volume. The magnetic nanocrystalline yttrium – samarium – cobalt possess very high magnetic properties due to large surface area. The typical applications of high-power rare earth magnets are in submarines, generators, electric motors, automobile alternators, magnetic resonance imaging (MRI) instruments and in ultrasensitive analytical instruments.

(iv) In television or in a monitor: In television or in a monitor, the resolution depends on the size of the pixel made of phosphors. The phosphor glows when a beam of electrons strike them. The resolution of images in these instruments increases as the size of pixels reduces. Materials like nanocrystalline selenide, zinc sulphide, lead telluride and cadmium sulphide synthesized by the sol-gel method improve the resolution. The use of nanophosphors may reduce the making cost of high resolution television. In new generation batteries, the separator plates are made up of nanocrystalline materials prepared by the sol-gel method, and they hold more energy. For example, batteries made of nanocrystalline nickel and metal hydrides are long lasting and requires minimal recharging.

(v) Motor vehicles and air craft: The thermal energy generated in engines is wasted to a large extent. This can be reduced by coating the cylinders with nanocrystalline ceramics such as zirconia and alumina. By retaining more heat energy, combustion of the fuel takes place completely. In air crafts, by decreasing the grain size of the materials the fatigue strength increases. By using nanomaterials, the fatigue life increases as much as 300%. The components made of nanomaterials are stronger and operate at higher temperatures. So air crafts can fly faster using the same amount of aviation fuel.

(vi) Aerogels: Aerogels are nanocrystalline materials. They are porous and hence air is trapped at the interstices. Using these materials for insulation at offices and homes leads to drastic reduction in cooling and heating bills by saving power. These materials are also used as materials for smart windows, so that the materials become darkened when the sun is too bright and lightened when the sun is not shining brightly.

(vii) **Energy efficiency:** For illumination, energy consumption can be greatly reduced by using quantum caged atoms or light emitting diodes (LEDs) instead of ordinary filament bulbs. Nano-structures with a continuum of energy band gaps have an increased solar energy conversion efficiency as compared to ordinary semiconductor solar cells.

In hydrogen fuel cells, nanostructured catalyst material is used on carbon-supported noble metal particles with diameters between 1 and 5 nm. For hydrogen storage, materials with nanosized pores like nanotubes, zeolites, etc. are under investigation.

(viii) **Medical field:** Nanomaterials are used in biology for the development of diagnostic devices, drug delivery vehicles, analytical tools and in physical therapy applications. The genetic sequence of a sample can be detected by tagging gold nanoparticles with short segments of DNA. Magnetic nanoparticles are used to label molecules, structures or micro-organisms of an antibody. Iron nanoparticles are used in cancer treatment. Nanotechnology is used to reproduce or to repair damaged tissue.

(ix) **Textiles:** Clothes made of nanofibres are water and stain repellent and wrinkle-free. They can be washed less frequently at low temperatures.

(x) **Computer:** Quantum computers use fast quantum algorithms and have quantum bit memory space (qubit), so it involves in several computations at the same time.

(xi) **Cosmetics:** Sun screens based on mineral nanoparticles such as titanium dioxide offer several advantages. They have high UV protection compared to the bulk material.

(xii) In addition to the above, we have quantum dots, suntan lotion, nanotubes, protective coatings. Fullerenes [C_{60}] are used as lubricants [molecular ball bearings], diamond seeding, diamond production, xerographic materials, photochromic goggles, etc.

(xiii) There is a scientific evidence that some nanomaterials are toxic to humans or to the environment. Nanomaterials are able to cross biological membranes and access cells, tissues and organs. Normally, this cannot be done by larger sized particles. Some materials penetrate the skin. Nanomaterials have the potential to cause DNA mutation and induce major structural damage to mitochondria, even resulting in cell death.