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NANOPHYSICS

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INTRODUCTION

Nano is derived from the Greek word nano which means drawrf. This prefix is used in the metric system to mean 10-9 meter or one billionth of a meter. It is the unit of length that is most appropriate for describing the size of a single molecule. Nanometer objects are too small to be seen with naked eye. To indicate the smallness of any object, we often compare it with the human hair in which the diameter of it is estimated to be about 50,000 - 1,00,000 nanometers, a red blood cell which is approximately 7,000 nm wide and water molecule which is almost 0.3 nm across. The comparative size of a nanometer is the same as the size of a marble to that of the earth. The smallest things that the unaided human eye can resolve are 10,000 nm across. In the nanoscale, common materials are exhibiting unusual properties. Some of these properties include lower melting points, faster chemical reactions and remarkably lower resistance to electricity.

There are two terms related to nano and these are nanoscience and nanotechnology. Nanoscience is an emerging area of science which concerns itself the study of materials that have very small dimensions i.e. in the range of nano scale. The word itself is a combination of nano and science which means dwarf and knowledge. Thus, nanoscience is the study of phenomenon and manipulation of materials at atomic, molecular and macromolecular scales where properties differ significantly from those at a larger scale. It involves an interdisciplinary of sciences such as material science, physics, chemistry, biology, engineering, computer science and more. In contrast, the term nanotechnology is defined as the study and use of structures between 1 - 100 nm in size. Thus, nanotechnology is the design, characterization, production and application of Structures, devices and systems by controlling the shape and size at nanometer scale. Structural features in the range 1 - 100 nm determine important changes as compared to the behaviour of bulk materials. So, while mentioning the word nanoscience and nanotechnology, it is necessary to know the term nanomaterials because nanomaterials are cornerstones of nanoscience and nanotechnology.

Classification

Classification is based on the number of dimensions, which are not confined to the nanoscale range (<100 nm).

- zero-dimensional (0-D)
- one-dimensional (1-D)
- two-dimensional (2-D)
- three-dimensional (3-D).

Zero-dimensional nanomaterials

- Materials wherein all the dimensions are measured within the nanoscale (no dimensions, or 0-D, are larger than 100 nm).
- The most common representation of zero-dimensional nanomaterials are nanoparticles.
- Be amorphous or crystalline
- Be single crystalline or polycrystalline
- Be composed of single or multi-chemical elements
- Exhibit various shapes and forms
- Exist individually or incorporated in a matrix
- Be metallic, ceramic, or polymeric

One-dimensional nanomaterials

- One dimension that is outside the nanoscale.
- This leads to needle like-shaped nanomaterials.
- 1-D materials include nanotubes, nanorods, and nanowires
- Amorphous or crystalline
- Single crystalline or polycrystalline
- Chemically pure or impure
- Standalone materials or embedded in within another medium
- Metallic, ceramic, or polymeric

Two-dimensional nanomaterials

- Two of the dimensions are not confined to the nanoscale.
- 2-D nanomaterials exhibit plate-like shapes.
- Two-dimensional nanomaterials include nanofilms, nanolayers and nanocoatings.

- Amorphous or crystalline
- Made up of various chemical compositions
- Used as a single layer or as multilayer structures
- Deposited on a substrate
- Integrated in a surrounding matrix material
- Metallic, ceramic, or polymeric

Three-dimensional nanomaterials

Bulk nanomaterials are materials that are not confined to the nanoscale in any dimension. These materials are thus characterized by having three arbitrarily dimensions above 100 nm.

- Materials possess a nanocrystalline structure or involve the presence of features at the nanoscale.
- In terms of nanocrystalline structure, bulk nanomaterials can be composed of a multiple arrangement of nanosize crystals, most typically in different orientations.
- With respect to the presence of features at the nanoscale, 3-D nanomaterials can contain dispersions of nanoparticles, bundles of nanowires and nanotubes as well as multinanolayers.

The term nanomaterials cover various types of nanostructured materials which possess at least one dimension in the nanometer range. When dimension of a material is continuously reduced from macroscopic size to nanometers, the physical and chemical properties drastically change. Depending on the dimension of a material, one can classify nanomaterials into three categories namely quantum well, quantum wire and quantum dot.

Quantum well

Quantum wells are those structures where one dimension is reduced to nanometer range i.e. < 100 nm so that the size is comparable to the de-Broglie wavelength of the exciton while the other two dimensions remain large. Example: Thin films, layers and coatings.

Quantum wire

Quantum wires are those structures where two dimensions are reduced to nanometer range i.e. < 100 nm and one remain large. Example: Nanotubes, fibres, nanowires.

Quantum dot

Quantum dots are those structures where all the dimensions are reduced to nanometer range i.e. < 100 nm. Example: Nanoparticles, quantum dots, nanoshells, nanorings, microcapsules.

The word quantum is associated with these three types of nanostructure materials because the change in properties arises from quantum mechanical nature of physics in ultra small domain. The physical and chemical properties of materials changes when the bulk becomes nanosize. At this stage, they show a very different properties compared to what they exhibit on a macro scale, enabling unique applications. For instance, copper which is opaque at micro scale becomes transparent; silicon insulators become conductors and gold which is solid, inert and yellow in room temperature at micro scale becomes liquid and red in colour in nano scale at room temperature. This indicates that the optical properties of the gold particles are changed when their size become nanosize.

Synthesis of Nanoparticles

The preparation of nanoscale structures and devices can be accomplished through "bottom-up" or "top-down" methods. In the bottom-up approach, small building blocks are assembled into larger structures; chemical synthesis is a good example of bottom-up approach in the synthesis of nanoparticles. In the top-down approach, large objects are modified to give smaller features, attrition or milling is a good example of top-down approach. Both approaches play very important roles in modern industry and most likely in nanotechnology. There are advantages and disadvantages in both approaches.

Methods to produce nanoparticles from atoms are chemical processes based on transformations in solution e.g. sol-gel processing, chemical vapour deposition (CVD), plasma or flame spraying synthesis, laser pyrolysis, atomic or molecular condensation. These chemical processes rely on the availability of appropriate "metal-organic" molecules as precursors.

Bottom-Up and Top-Down Approaches Obviously there are two approaches to the synthesis of nanomaterials and the fabrication of nanostructures: top-down and bottom-up. Attrition or milling is a typical top-down method in making nanoparticles, whereas the colloidal dispersion is a good example of bottom-up approach in the synthesis of nanoparticles.

Lithography may be considered as a hybrid approach, since the growth of thin films is bottom-up whereas etching is topdown, while nanolithography and nanomanipulation are commonly a bottomup approach. Both approaches play very important roles in modern industry.

Bottom-up approach is often emphasized in nanotechnology literature, though bottom-up is nothing new in materials synthesis. Typical material synthesis is to build atom by atom on a very large scale, and has been in industrial use for over a century. Examples include the production of salt and nitrate in chemical industry, the growth of single crystals and deposition of films in electronic industry. For most materials, there is no difference in physical properties of materials regardless of the synthesis routes, provided that chemical composition, crystallinity, and microstructure of the material in question are identical. Of course, different synthesis and processing approaches often result in appreciable differences in chemical composition, crystallinity, and microstructure of the material due to kinetic reasons. Consequently, the material exhibits different physical properties. In organic chemistry and/or polymer science, we know polymers are synthesized by connecting individual monomers together. In crystal growth, growth species, such as atoms, ions and molecules, after impinging onto the growth surface, assemble into crystal structure one after another.

Sol-Gel processing

Sol-gel processing is a wet chemical route for the synthesis of colloidal dispersions of inorganic and organic-inorganic hybrid materials, particularly oxides and oxide-based hybrids. From such colloidal dispersions, powders, fibers, thin films and monoliths can be readily prepared. Although the fabrication of different forms of final products requires some specific considerations, the fundamentals and general approaches in the synthesis of colloidal dispersions are the same. Sol-gel processing offers many advantages, including low processing temperature and molecular level homogeneity. Sol-gel processing is particularly useful in making complex metal oxides, temperature sensitive organic-inorganic hybrid materials, and thermodynamically unfavorable or metastable materials.

Typical sol-gel processing consists of hydrolysis and condensation of precursors. Precursors can be either metal alkoxides or inorganic and organic salts. Organic or aqueous solvents may be used to dissolve precursors, and catalysts are often added to promote hydrolysis and condensation reactions.

Carbon nanomaterials

- Carbon is a basic element of life
- Carbon is special because of its ability to bond to many elements in many different ways
- It is the sixth most abundant element in the universe
- The most known types of carbon materials: diamond; graphite; fullerenes and carbon nanotubes

Properties of carbon nanomaterials

- Superior stiffness and strength to all other materials
- Extraordinary electric properties
- Reported to be thermally stable in a vacuum up to 2800 degrees Centigrade (and we fret over CPU temps over 50 degrees Centigrade)
- Capacity to carry an electric current 1000 times better than copper wires
- Twice the thermal conductivity of diamonds
- Pressing or stretching nanotubes can change their electrical properties by changing the quantum states of the electrons in the carbon bonds
- They are either conducting or semi-conducting depending on the their structure

What are nanotechnologies good for?

- Can be used for containers to hold various materials on the nano-scale level
- Due to their exceptional electrical properties, nanotubes have a potential for use in everyday electronics such as televisions and computers to more complex uses like aerospace materials and circuits

Carbon nanotubes (CNTs)

- Carbon nanotubes (CNTs) were discovered in 1991 by Sumio Ijima of the NEC laboratory in Tsukuba, Japan, during high resolution transmission electron microscopy (TEM) observation of soot generated from the electrical discharge between two carbon electrodes.
- The discovery was accidental, although it would not have been possible without Ijima's excellent microscopist skills and expertise.
- Ijima was, in fact, studying were C60 molecules, also known as buckminster fullerenes, previously discovered by Harold Kroto and Richard Smalley during the 1970s.

- Kroto and Smalley found that under the right arc-discharge conditions, carbon atoms would self-assemble spontaneously into molecules of specific shapes, such as the C60 molecule. However, as shown by Ijima's discovery, under different experimental conditions, carbon atoms can instead self-assemble into CNTs.

Types of Carbon nanotubes

Carbon nanotubes (CNTs) are tubes made of carbon with diameters typically measured in nanometers. Carbon nanotubes often refer to **single-wall** carbon nanotubes **(SWCNTs)** with diameters in the range of a nanometer. They were discovered independently by Iijima and Ichihashi and Bethune et al. in carbon arc chambers similar to those used to produce fullerenes. Single-wall carbon nanotubes are one of the allotropes of carbon, intermediate between fullerene cages and flat graphene.

Although not made this way, single-wall carbon nanotubes can be thought of as cutouts from a two-dimensional hexagonal lattice of carbon atoms rolled up along one of the Bravais lattice vectors of the hexagonal lattice to form a hollow cylinder. In this construction, periodic boundary conditions are imposed over the length of this roll up vector to yield a lattice with helical symmetry of seamlessly bonded carbon atoms on the cylinder surface.

Carbon nanotubes also often refer to **multi-wall** carbon nanotubes **(MWCNTs)** consisting of nested single-wall carbon nanotubes. If not identical, these tubes are very similar to Oberlin, Endo and Koyama's long straight and parallel carbon layers cylindrically rolled around a hollow tube. Multi-wall carbon nanotubes are also sometimes used to refer to double and triple-wall carbon nanotubes.

Carbon nanotubes can also refer to tubes with an undetermined carbon-wall structure and diameters less than 100 nanometers. Such tubes were discovered by Radushkevich and Lukyanovich. While nanotubes of other compositions exist, most research has been focused on the carbon ones. Therefore, the "carbon" qualifier is often left implicit in the acronyms, and the names are abbreviated **NT**, **SWNT**, and **MWNT**.

Carbon nanotubes can exhibit remarkable electrical conductivity. They also have exceptional tensile strength and thermal conductivity, because of their nanostructure and strength of the bonds between carbon atoms. In addition, they can be chemically modified. These properties are expected to be valuable in many areas of technology, such as electronics, optics, composite materials (replacing or complementing carbon fibers) nanotechnology and other applications of materials science.

Individual carbon nanotubes naturally align themselves into "ropes" held together by relatively weak van der Waals forces. The length of a carbon nanotube produced by common production methods is often not reported, but is much larger than its diameter. Although rare, nanotubes half a meter long have been created, with a length-to-diameter ratio of more than 100,000,000:1 For many purposes, the length of carbon nanotubes can be assumed to be infinite.

Rolling up a hexagonal lattice along different directions to form different single-wall carbon nanotubes shows that all of these tubes have helical and translational symmetry along the tube axis and many also have nontrivial rotational symmetry about this axis. In addition, most are chiral, meaning the tube and its mirror image cannot be superimposed. This construction also allows single-wall carbon nanotubes to be labeled by a pair of small integers.

A special group of achiral single-wall carbon nanotubes are metallic,[7] but all the rest are either small or moderate band gap semiconductors.[14] These electrical properties, however, do not depend on whether the tube is rolled up above or below the graphene plane and hence are the same for a tube and its mirror image.

Scanning Electron Microscope (SEM)

An electron microscope is a special type of a microscope which uses a beam of electrons to create an image of the specimen. It is capable of forming an image with higher magnifications and has a greater resolving power than the light microscope. The electron microscope use electromagnetic and electrostatic lenses to control the path of electrons. The basic design of an electromagnetic lens is a solenoid through which a current can pass through, there by inducing an electromagnetic field. The electron passes through the center of such solenoids on its way down to the column of the electron microscope towards the sample. Electrons are very sensitive to magnetic fields and therefore it can be controlled by changing their current through the lenses.

The faster the electrons travel, the shorter their wavelength. The resolving power of a microscope is directly related to the wavelength of the irradiation used to form an image. Reducing the wavelength will increase their resolution. Therefore, the resolution of the microscope will increase if the accelerating voltage of the electron beam is increased.

SEM images the sample by scanning it with high energy beam of electrons in a raster scan pattern. The electrons interact with the atoms of the sample and produces signals that contain information about the sample's surface topography, composition and other properties such as electrical conductivity. The signals result from interactions of the electron beam with atom at or near the surface of the sample. The SEM can produce very high resolution images of the sample surface, revealing details less than 1 nm in size. Due to the very narrow electron beam, FE-SEM images have a large depth of field yielding a characteristic three-dimensional appearance useful for understanding the surface structure of a sample. The diagram of typical SEM is Fig.

Instrument setup of SEM

Applications of Nanoparticles

Nanoparticles offer radical breakthroughs in areas such as materials and manufacturing, electronics, medicine and health care, environment and energy, chemical and pharmaceutical, biotechnology and agriculture, computation and information technology and national security.

Nano carbon is used to make rubber tyres wear resistant. Nano phosphorous are used for Laser Coupled Devices (LCD's) and Cathode Ray Tubes (CRT's) to display colours. Nano alumina and silica are used for super fine polishing compounds, nano iron oxide is used to create the magnetic material used in disk drives and audio/ video tapes. Nano zinc oxide or nano titania are used in many sunscreens to block harmful UV rays.

Nanocrystalline Materials in Electronics

Nanostructured materials have an increased impact on electronics; smaller dimension in electronics provides higher functionality, increased memory density and higher speed. Quantum effect devices or single electron devices are great potential utility for future electronic circuits. Better resolution of television screens could be achieved by reducing the size of the phosphors. Nanocrystalline zinc sulphide, cadmium sulphide and lead telluride synthesized by sol-gel technique are noteworthy candidates for improving the resolution of monitors. Nanocrystalline phosphor plays a major part in enhancing the resolution of the display devices. Due to enhancement in electrical and magnetic properties of nanomaterials, high brightness and contrast is expected from flat panel displays.

Application of Nanostructured Magnetic Materials

Nano materials are interesting due to their micro structural features and magnetic properties. With the aid if nano magnetic materials, fast, more compact and less power consuming memory systems with greater storage capacity can be designed. Magnet made of nanocrystalline yttrium-samarium-cobalt grains posses very fascinating magnetic properties due to their extremely large surface area. Some typical application includes quieter submarines, automobile alternators, land-based power generators, and motors for ships, ultra sensitive analytical instruments and magnetic resonance imaging in medical diagnostics.

Application of Nanoparticles in Biology and Medicine

Understanding of biological processes in the nanoscale level is a strong driving force behind development of nanotechnology out of the plethora of size dependent physical properties available in the practical side of nanomaterials, optical magnetic effects of the nanoparticles are used for biological application. Hybrid bio-nanomaterials can also be applied to build novel electronic, optoelectronics and memory devices. Some of the application of nanomaterials to biology or medicine is listed below.

- Drug and gene delivery
- Bio detection of pathogens
- Detection of proteins
- Probing of DNA structure
- Tissue Engineering
- Tumor destruction through heating (hyperthermia)
- Separation and purification of biological molecules and cells
- MRI contrast enhancement
- Phagokinetic studies
- Fluorescent biological labels

Application in Thermal Engineering

There is a great need for more efficient heat transfer fluids in many industries, from transportation, energy supply to electronics. The coolant, lubricants, oil and other heat transfer fluids used in today's conventional thermal systems have inherently poor heat transfer properties. The conventional working fluids that contain millimeter or micrometer size particles cannot be used in the newly emerging "miniaturized technology" since they clog in micro channels. these problems can be solved with the help of nanotechnology to thermal angering called nanofluids. The nanofluids have two important factors such as extreme stability and ultra thermal conductivity.