GE8073 Fundamentals of Nanoscience
Unit-I
Introduction

UNIT I INTRODUCTION **8 periods**

Nanoscale Science and Technology- Implications for Physics, Chemistry, Biology and Engineering-Classifications of nanostructured materials- nano particles- quantum dots, nanowires-ultra-thinfilms-multilayered materials. Length Scales involved and effect on properties: Mechanical, Electronic, Optical, Magnetic and Thermal properties. Introduction to properties and motivation for study (qualitative only).

Nanoscale Science and Technology

Nanotechnology is the art and science of manipulating matter at the nanoscale (down to 1/100,000 the width of a human hair) to cr new and unique materials and products with enormous potential to change society.

1 nanometer (nm) = 1 billionth of a Meter = 10^{-9} ***m***

Nanotechnology

Definition

Nanotechnology is the ability to measure, design, and manipulate at the atomic, molecular and supramolecular levels on a scale of about 1 to 100 nm. It is possible to understand, create, and use material structures, devices, and systems with fundamentally new properties and functions.

Introduction

In 1959, Physics Nobel Laureate Richard Feynman gave a talk at Caltech on the occasion of the American Physical Society meeting. The talk was entitled, “There’s Plenty of Room at the Bottom.” This lecture was to become a central point in the field of *nanotechnology*, long before anything related with the word *nano* had emerged. The term *nanotechnology* was first used in 1974 by Norio Taniguchi to refer to the precise and accurate tolerances required for machining and finishing materials. In 1981, K. E. Drexler, now at the Foresight Nanotech Institute for Molecular Manufacturing, described a new “bottom-up” approach, instead of the top-down approach discussed earlier by Feynman and Taniguchi. The bottom-up approach involved molecular manipulation and molecular engineering to build molecular machines and molecular devices with atomic precision. In 1986, Drexler published a book, *Engines of Creation*, which finally popularized the term *nanotechnology*.

The term *nano* derives from the Greek word for *dwarf*. It is used as a prefix for any unit such as a second or a meter, and it means a billionth of that unit. Hence, a nanometer (nm) is a billionth of a meter, or 10^{-9} meters. Photosynthesis is in fact an excellent example of the role of nanostructures in the world's daily life. Leaves contain millions of chloroplasts, which make a green plant green. Inside each chloroplast, hundreds of thylakoids contain light-sensitive pigments. These pigments are molecules with nanoscale dimensions that capture light (photons) and direct them to the photo reaction centers. The fundamental properties such as physical, chemical, electrical, magnetic, mechanical etc., change drastically at this scale. The laws of classical physics do not apply but quantum mechanics to the nanoworld. Scientists and engineers identified the importance of nanoscale technology in the development of materials and related products with new properties which is applicable to almost all industries such as medicine, telecommunications, electronics, chemical and computers. The operation of computer chips in present-day computers can be explained by the laws of classical electron flow; but when electrons are confined to nanoscale dimensions, they behave according to the laws of quantum mechanics. Consequently, future chips made with nanoscale dimensions (called q-bits) will process information differently and lead to computers with new logic and functionality. The semiconductor industry utilizes electron and optical lithography techniques to fabricate integrated circuits with billions of nanometer-size features on 8-inch silicon wafers (so-called "top-down" technology). Now scientists have learned to manipulate individual molecules or fabricate nanowires and connect them for information processing (so-called "bottom-up" technology). In fact, most of the technologies what we discuss have already gone into market place.

Timeline of Nanotechnology

4th Century: The Lycurgus Cup (Rome) is an example of dichroic glass; colloidal gold and silver in the glass. It looks ***opaque green*** when light from outside but ***translucent red*** when light shines through the inside.

6th-15th Centuries: Vibrant ***stained glass windows*** in European cathedrals owed their rich colours to nanoparticles of AuCl3 and other metal oxides and chlorides.

9th-17th Centuries: Glowing, ***"luster" ceramic glazes*** used in the Islamic world containing Ag or Cu or other metallic NPs.
13th-18th Centuries: ***"Damascus" saber blades*** contained CNT and cementite nanowires.
1857: Michael Faraday discovered ***colloidal "ruby" gold***, in that nanostructured gold under certain lighting conditions produces different-colored solutions.
1936: Erwin Muller invented the **field emission microscope**, allowing near-atomic-resolution images of materials.
1947: Discovery of the **semiconductor transistor** – a laying foundation for electronic devices and the Information Age.
1958: Jack Kilby originated the concept of, and built the first **integrated circuit**, for which he received the Nobel Prize in 2000.
1959: The ideas & concepts behind ***Nanoscience and Nanotechnology*** started with a talk entitled **"There's Plenty of Room at the Bottom"** by physicist **Richard Feynman** at an American Physical Society meeting on December 29, **1959.**
1965: Gordon Moore given the "**Moore's Law**," described the density of transistors on an integrated chip (IC) doubling every 2 years.
1974: Norio Taniguchi coined **the term nanotechnology** to describe the machining of materials within atomic-scale dimensions.
1981: Invention of the **scanning tunneling microscope** to "see" individual atoms for the first time.
1985: Richard Smalley discovered the **Buckminsterfullerene** (C60), more commonly known as the **buckyball**, which is a molecule resembling a soccer ball in shape and composed entirely of carbon, as are graphite and diamond.
1991: Sumio Iijima credited with discovering the **carbon nanotubes (CNT)**.
1999: Invention of **dip-pen nanolithography** for "writing" of electronic circuits as well as patterning of biomaterials, and other applications.
1999–early 2000's: Consumer products making use of nanotechnology began appearing in the marketplace.
2000 to – till date Rapid developments in nanotechnology and commercialization

Terminologies

Nanomaterials: A class of materials in which at least one of the dimensions is on the nanoscale (<100 nm).

Nanotechnology is study of manipulating matter/devices on an atomic and molecular scale; generally deals with structures sized between 1 - 100 nm in at least one dimension.

Nanoscience &Nanotechnology are the study & application of *extremely small things* and can be used in all science fields, such as chemistry, biology, physics, materials science, and engineering

<u>Implications for Physics, Chemistry, Biology and Engineering</u>

Negative implications

1. Creation of biological weapons eg. Anthrax

    very small quantities is enough-detection is difficult in the range

2. Gene editing facilitates creation of new organism

    Nanomaterial can be a carrier for lethal organisms such as new viruses

    - without any signature of protein which is detected by immunity

3. Do it yourself 'DNA nanotechnology lab' available online for less than USD 500 which is sometimes dangerous to the society
4. Environmental and health effects need to be understood clearly
5. Drug delivery systems having nanoelectronic sensors may malfunction inside the body
6. Invasion of human body through implantation of communicative devices.
7. Toxicity of inorganic nanomaterials will be increased

    Arsenic poisoning will be manifold compared to bulk metal

8. Spread of dangerous chemicals can't be avoided
9. Nanotechnology leads to new drug development - which are both positive and negative
10. Replacement of human intelligence by machines and AI
11. Terrorism/Threats will increase
12. Rise in number of Patent disputes – single wall carbon nanotube IBM
13. Many of the technologies have yet to be regulated
14. Toxicity of the nanofertilizers/nanopesticides to plants has to be investigated
15. Cost of the new products
16. Waste management and pollution requires development of new techniques

Positive implications

1. The use of nanotechnology in electrical and electronics devices will exhibit different properties compared to their bulk counterparts.
2. Surface area/Volume ratio will increase with the decrease in size. Using this concept, more number of transistors can be fabricated within a small chip. Nanotechnology helps to produce smaller, faster, and better transistors.
3. Because of the quantum confinement effect, the bandgap value of the semiconductors increases with decrease in size of the nanomaterials. It exhibits size dependent electrical and optical properties.
4. MRAM (magnetic random access memory) is enabled by nanoscale magnetic tunnel junctions and effectively save data during a system shutdown. Computers will be able to boot almost instantly.
5. Ultra-high definition displays and televisions are now being sold that use quantum dots. They produce more vibrant colors while being more energy efficient.
6. Flexible, bendable, foldable, rollable, and stretchable electronics are being integrated into a variety of products, including wearables, medical applications, aerospace applications, and the Internet of Things. Example: Graphene is being used in flexible electronics
7. Nanoparticle copper suspensions have been developed as a safer, cheaper, and more reliable alternative to lead-based solder.
8. Other computing and electronic products include Flash memory chips for smart phones and thumb drives; ultra-responsive hearing aids; antimicrobial/antibacterial coatings on keyboards and cell phone casings; conductive inks for printed electronics for RFID/smart cards/smart packaging; and flexible displays for e-book readers.
9. Nanotechnology can be incorporated into solar panels to convert sunlight to electricity more efficiently, promising inexpensive solar power in the future.
10. Nanotechnology is already being used to develop many new kinds of batteries that are quicker-charging, more efficient, lighter weight, have a higher power density, and hold electrical charge longer.
11. An epoxy containing carbon nanotubes is being used to make windmill blades that are longer, stronger, and light-weight.
12. Nanoscale sensors and devices may provide cost-effective continuous monitoring of the structural integrity and performance of bridges, tunnels, rails, parking structures and pavements over time.

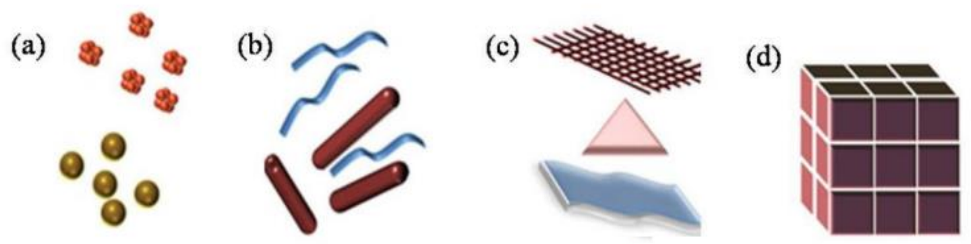
Classifications of nanostructured materials- nano particles- quantum dots, nanowires-ultra-thinfilms-multilayered materials

The dimensionality plays a major role in determining the characteristic of nanomaterials including physical, chemical and biological characteristics. Nanomaterials can be classified in 0D, 1D, 2D and 3D nanomaterials.

With the decrease in dimensionality, an increase in surface-to-volume ratio is observed. This indicates that smaller dimensional nanomaterials have higher surface area compared to 3D nanomaterials.

Recently, two dimensional (2D) nanomaterials are extensively investigated for electronic, biomedical, drug delivery and biosensor applications.

Classification of Nanomaterials



(a) 0D spheres and clusters; (b) 1D nanofibers, nanowires, and nanorods; (c) 2D nanofilms, nanoplates, and networks; (d) 3D nanomaterials. 3D nanomaterials are also known as nanocomposites.

Bulk Materials: It is a three dimensional system in which the electrons (or holes) can move in all the three directions (x, y & z axis) with **no confinement**.

Quantum Well: It is a two dimensional system in which the electrons (or holes) can move in two directions and are confined to **move in one direction**.

Quantum Wire (Nanowire): It is a one dimensional system in which the electrons (or holes) can move in one direction and are confined to **move in two directions**.

Quantum Dot: It is a zero dimensional system in which the movements of electrons (or holes) are confined to **move in all the three directions**.

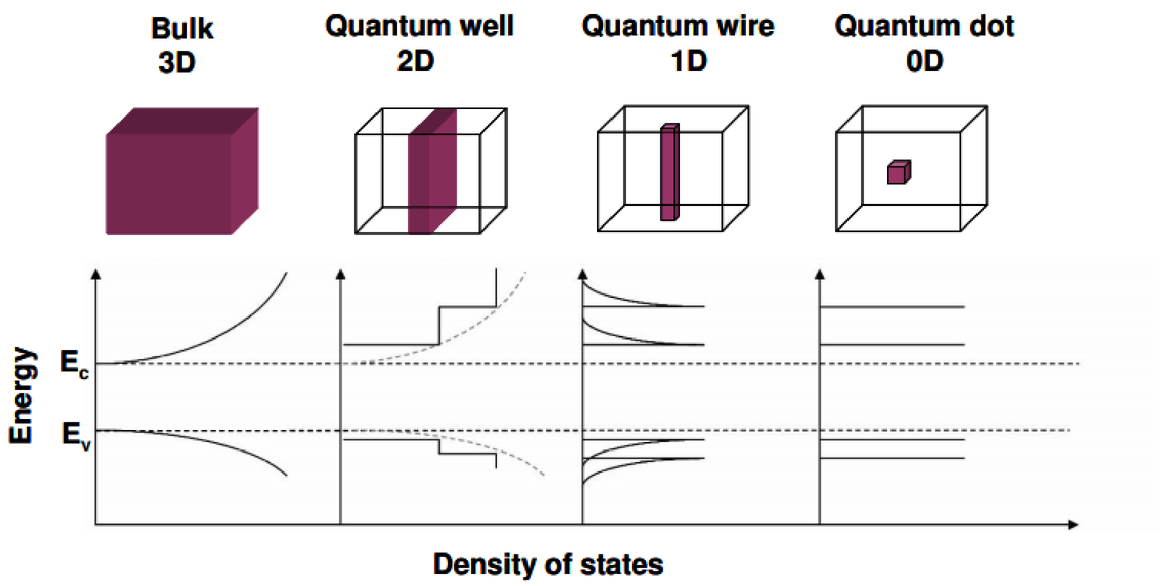
Density of states versus dimensionality

Bulk Material: Here, the density of energy states is not constant at all for any energy. It changes continuously i.e., the density is zero at low energy and it increases till a certain value called Fermi energy level.

Quantum Wells: If the size is reduced to 2D, the density of energy states is constant over a certain energy range and then it suddenly changes i.e., in a step-wise manner.

Quantum Wires (Nanowire): If the size is reduced further, the nature of the density of energy states changes again, there is a variation in the density of states in the lower energy region and then suddenly it jumps to another density of state then again there is a small variation. So this plot is very characteristic of quantum wire.

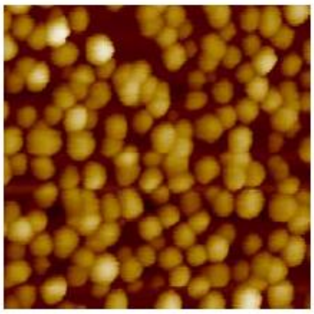
Quantum Dots: If the size is reduced further, the density of energy state cannot change continuously; Energy levels are discrete. There is no variation in density of energy states. When the size of the nanomaterials decreases, the electron energy levels can no longer be treated as continuous and must be treated as discrete (small & finite separation). This phenomenon is called **quantum confinement**. The material will be called as quantum dot



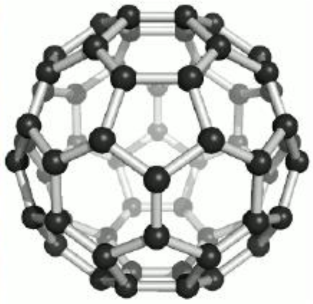
Different types of nanomaterials

Nanoparticles

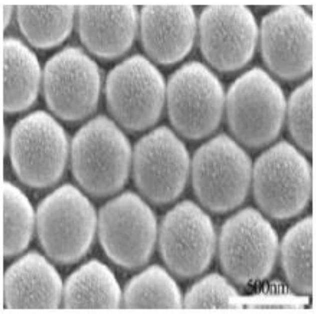
Nanoparticles are particles of size between 1 to 100 nm at least in one dimension. Examples: TiO_2, ZnO, ZnS, CdSe, metal nanoparticles, Fe_2O_3 etc. **Synthesis methods:** Precipitation, Hydrothermal and solvothermal, Laser ablation.



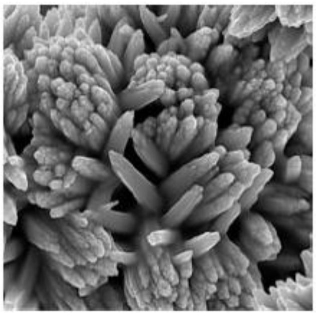
Au nanoparticle



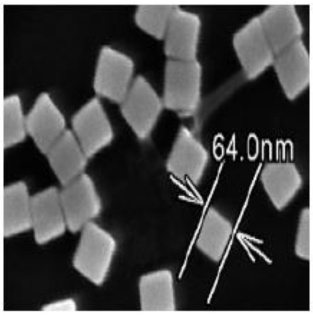
Buckminsterfullerene



FePt nanosphere



Titanium nanoflower

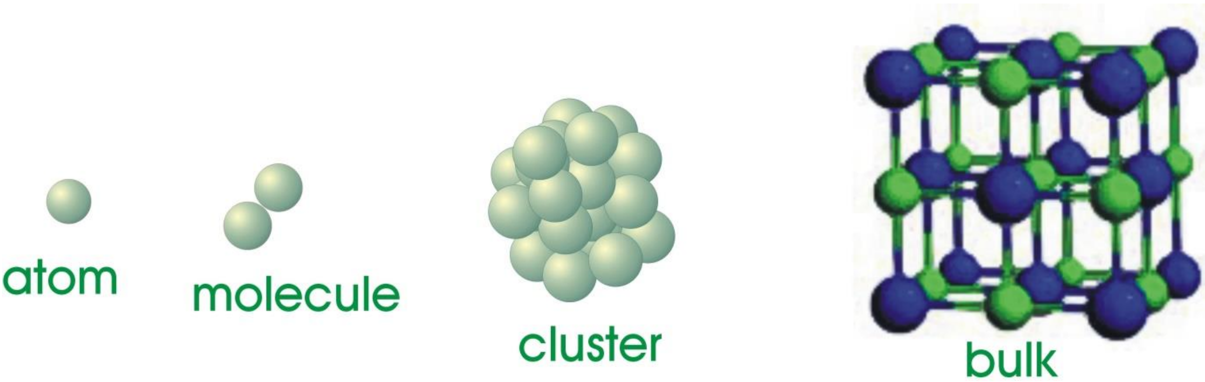


Silver nanocubes

SnO2 nanoflower

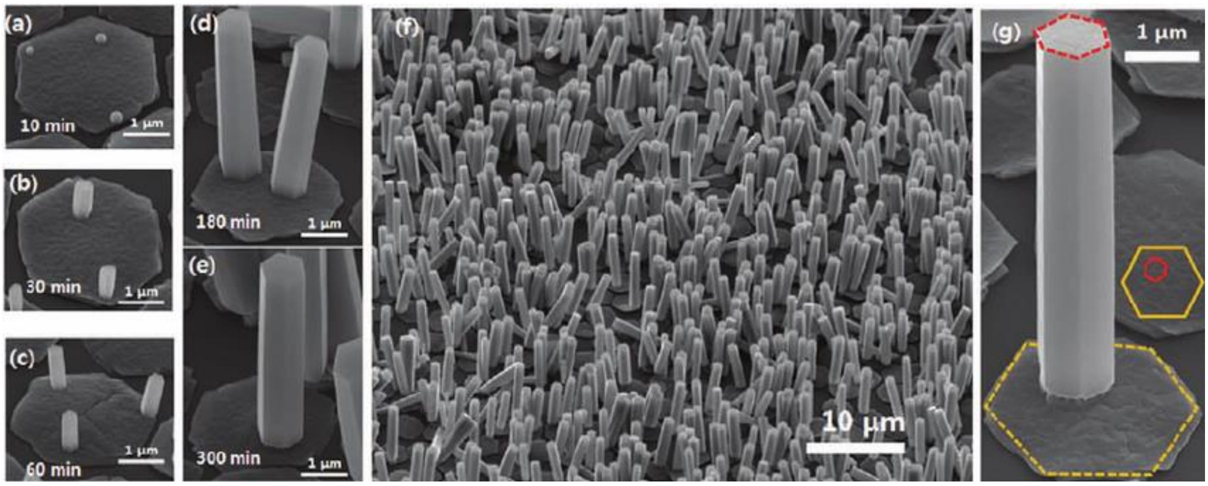
<u>Nanoclusters</u>

Nanoclusters are smaller nanostructures than QDs, composed of a few atoms of a metal or a combination of metals. They provide a bridge between metal atoms and nanoparticles. Examples: Metallic clusters such Ni, Au, and Cu. **Synthesis:** Gas Phase Cluster synthesis, Laser Ablation, Sputtering

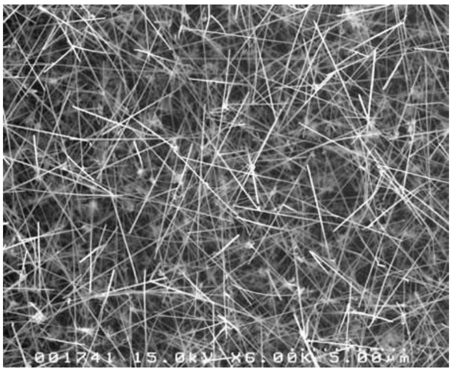


Magic Number of cluster: Certain number of atoms present in a cluster which exhibits stable structure is defined as magic number. Combination of 55 atoms of gold provides a stable cluster and hence 55 is called magic number of Gold cluster.

Nanorods: Nanorods are having the aspect ratio in the range of 1-20. They are one dimensional materials. Examples: ZnO, GaN etc., **Synthesis** Direct Chemical synthesis, Chemical vapour deposition, Electro deposition.



Nanowires: Nanowires are the materials having an aspect ratio greater than 20. They are one dimensional materials. Metals: Au, Ni, Ag; Semiconductors: InP, Si, GaN; Insulators: SiO_2; Molecular nanowires: DNA. **Synthesis:** Spontaneous growth, Template-based synthesis, Electro-spinning, Lithography.



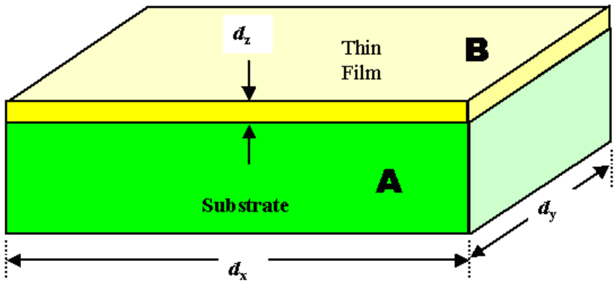
Nanotubes: Nanotubes are defined as the allotropes of carbon with an aspect ratio (length/diameter ratio) greater than 1,000,000. Example: Carbon nanotubes (CNTs). They can be classified into multiwalled carbon nanotube (MWCNT) and single walled carbon nanotube (SWCNT).

<u>Ultra-thinfilms-multilayered materials</u>

<u>Thin films</u>

- A thinfilm is a layer of material ranging from fractions of a nanometer to several micrometers in thickness

- They belong to two dimensional system. Only thickness is considered to be in nanometer scale. Free electrons in conductive systems can propagate only in the *x*–*y* plane.

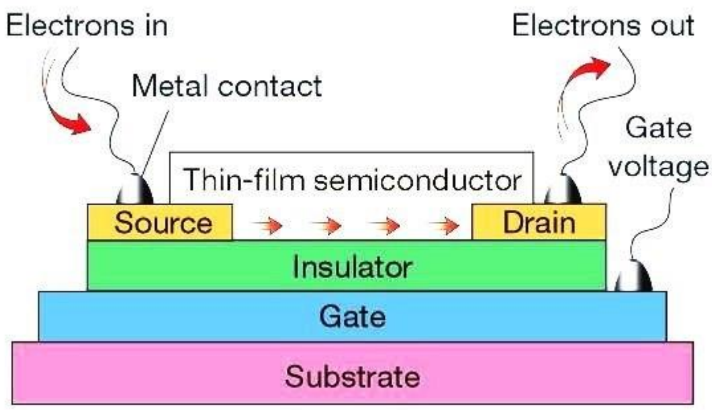


<u>Ultrathin films</u> (thickness <100 nm) represent an important category of modern materials. Constant advances in deposition techniques as well as in micro and nanoscale patterning have significantly contributed in developing the functionality of thin films. Confinement in the z direction may add many specific characteristics, especially in the case of electronic materials. Properly designed ultra-thin films and nanocoatings are sometimes used to reduce stiction and light reflection, for surface modification in extreme conditions, and to enhance dirt release properties.

The applications include Transistors, Solar cells, LEDs, lasers, batteries, fuel cells, catalytic and photocatalytic surfaces, photography, nano filter membranes, electrochromic plates, storage devices etc.,

<u>Multilayered materials</u>

Several thin films are integrated to create a structure or device is defined as multilayered materials. A multilayer structure is fabricated by the combination of several techniques.



Synthesis techniques: Vapour phase deposition, MOCVD, Sputtering, Evaporation, Molecular Beam Epitaxy, Atomic Layer Epitaxy, MOMBE, Plasma CVD, Spin coating, Dip coating, Electrodeposition, Etc.,

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<u>Length Scales involved and effect of properties</u>

The Prefix of *Nano* derives from the ***Unit of Length*** (**nm**). **1 nm is a billionth of a metre**. It is abbreviated to **1 nm**. These terms refer to the ability to assemble, manipulate, observe & control matter on length scales from one nm up to 100 nm or so. A **medium-size atom** has a size of **a fraction of a nm**, a small molecule is perhaps 1 nm, and a biological macromolecule such as a protein is about 10 nm. A **bacterial** cell about a **few thousand nm** in size. The smallest line width in a modern ICs will be a few hundred nm.

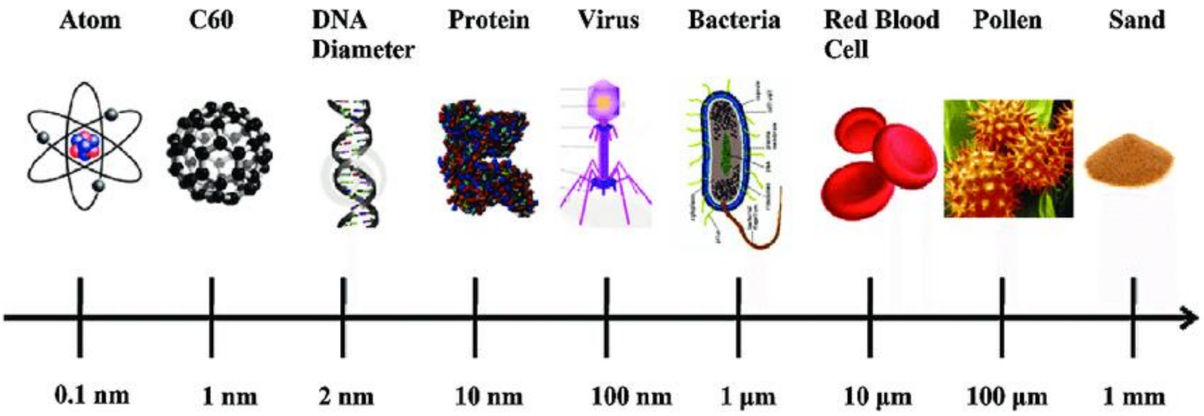
There are three important ways in which Nanoscale materials may differ from macro-scale materials:

1. Gravitational forces become negligible (i.e., a function of mass & distance).

2. Quantum mechanics is the model used to describe motion & energy. (Colors of Nano gold, Probability of where an electron will be found, below a certain length scale systems).

3. Greater surface to volume ratios.

<u>Effect of length scale on properties</u>



The two effects which predominantly control the properties are;

1. Surface area/volume 2. Quantum confinement effect.

<u>Surface to Volume Ratio</u>

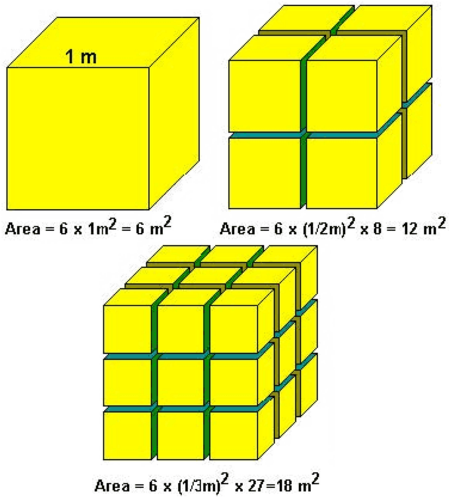
When size decreases, surface area per volume increases. As a consequence, they have

(i) Large fraction of surface atoms;

(ii) High surface energy;

(iii) Spatial confinement;

(iv) Reduced imperfections, which do not exist in the corresponding bulk materials.

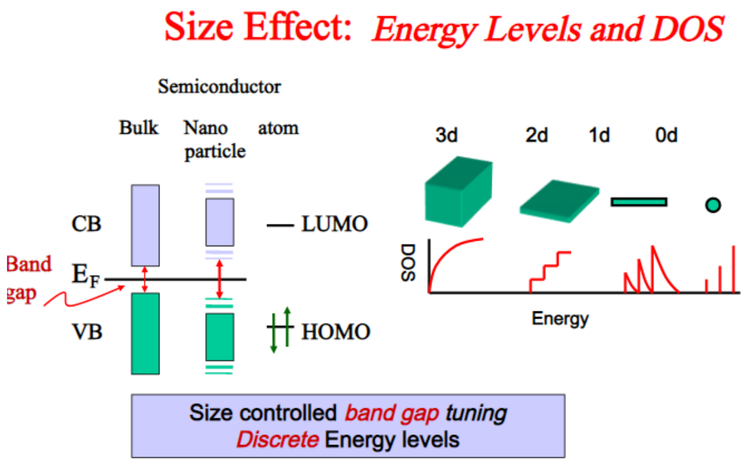


- A greater amount of the substance comes in contact with the surrounding material.
- This results in better reactivity and catalytic effect
- Large surface area makes nanostructured membranes & materials as ideal candidates for water treatment and desalination

Quantum confinement effect

As size decreases, electrons (and holes) are confined. They follow "Particle in a box". In Q-Box, electrons are in Discrete Energy Levels or level of spacing $>k_BT$. These energy levels & variation in the nature of DoS *vs* E plot which cause all the *changes in properties* of the system i.e., energy level diagram is different due to size & shape of particle, hence the property will be different.

If size decreases, band gap increases, hence wavelength decreases so, colour can be tuned. **Red emission** for the **largest** particles, to **blue emission** for the **smallest** clusters.



<u>Properties of Nanomaterials</u>

In nanoscale, properties like electrical, mechanical, optical, chemical, and biological are ***fundamentally* different from bulk.** These changes in properties of nanomaterials are ***shape and size dependent.***

Types of properties:

Mechanical (e.g. strength)

Electrical/Electronic (e.g. conductivity).

Optical (e.g. light emission).

Magnetic (e.g. super-paramagnetism)

Thermal (eg. thermal conductivity)

Physical (e.g. melting point)

Chemical (e.g. reactivity)

<u>Mechanical Properties of nanomaterials</u>

Mechanical properties of nanomaterials differ from bulk materials i.e., increases with decrease in size, because smaller the size, lesser is the probability of finding imperfections such as *dislocations, vacancies, grain boundaries*.

o As nanomaterials are stronger, harder and more wear resistant and corrosion resistant, they are used in spark plugs.

o Nanocrystalline carbides are much stronger, harder and wear resistant and are used in micro drills.

o Mechanical properties of polymeric materials can be increased by the addition of nano-fillers.

Change in mechanical properties:

As particle size decreases,

• Strength and toughness of materials improves significantly due to perfect defect free surface.

• Hardness, yield strength, elastic modulus and toughness of materials increases as the particle size is decreased.

• Materials become more brittle due to increased grain boundaries density and less dislocation density.

• Brittle-to-ductile transition due to dislocation.

Two possible mechanisms have been proposed to explain the enhanced strength of nanowires or nanorods (in reality with diameters <10 *microns*).

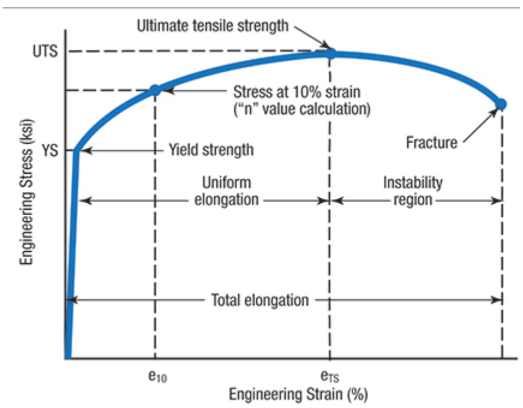
(i). Increased Internal Perfection (ii). Increased Surface Perfection

The smaller the cross-section of the nanowire, the less is the probability of finding any imperfections such as dislocations, micro-twins, impurity precipitates, etc .

Imperfections in bulk materials, such as dislocations are often created to accommodate stresses generated in the synthesis and processing of bulk materials due to temperature gradient and other inhomogeneities. Such stresses cannot be excluded but are generally not as likely to exist in small structures, particularly in nanomaterials.

Smaller structures have less surface defects (when materials are made through a bottom-up approach).

Vapor grown whiskers with diameters of 10 microns or less had no detectable steps on their surfaces by electron microscopy, whereas irregular growth steps were revealed on whiskers with diameters >10 microns. When a whisker is grown at a low super-saturation, there is less growth fluctuation in the growth rate and both the internal & surface structures of the whiskers are more perfect.



AFM and TEM have been applied for measuring the mechanical property of nanowires or nanorods.

<u>Electronic/Electrical Properties of Nanomaterials</u>

The **electrical properties** of nanomaterials **depend upon the diameter** of the nanomaterials. The examples of the change in electrical properties in nanomaterials are:

1. Conductivity of a bulk material does not depend upon dimensions (like diameter or area of cross section etc.,). However, i*n case* of CNTs, conductivity changes with change in area of cross section.

2. It is also observed that conductivity also changes when some shear force (twist) is given to nanotube.

3. Conductivity of a multiwalled CNTs is different than that of SWCNTs of same dimensions.

4. The CNTs can act as conductor or semiconductor in behaviour, but *we all know that* large carbon (graphite) is good conductor of electricity.

5. Electrical conductivity decreases with a reduced dimension due to increased surface scattering.

6. Electrical conductivity increases due to the better ordering and ballistic transport.

Size plays an important role in electrical properties based on 4 mechanisms:

i. Surface Scattering

ii. Change of electronic structure

iii. Quantum Transport

iv. Effect of micro-structure

(i) Surface scattering

In general, reduction in material's dimensions will cause reduced imperfection, thus a *reduction* in resistivity and increase in conductivity. However, in nanowires & thin films, the *surface scattering of electron* results in reduction of electrical conductivity. When the critical dimension is smaller *than the mean free path*, motion of electron will undergo elastic and inelastic scattering.

(ii) Change in electronic structure

Reduction in characteristic dimension below a critical size, i.e., below De-Broglie wavelength results in change of electronic structure, leading to widening of band gap. Such a change results in *reduced electrical conductivity*. Some metal nanowires *undergo transition* to become semiconductor and semiconductors might become insulators when their *diameters* *are* reduced below a critical diameter. If, size is very less, **Metal → Semiconductor → Insulator**

(iii) Quantum Transport

Ballistic Conduction: It occurs when length of conductor is smaller than electron mean free path. Here, there is no elastic scattering and no energy dissipation takes place.

Coulomb Blockade Effect: The charging effect which blocks the injection of a single electron (or) rejection of a single electron from a quantum dot is called coulomb blockade effect

Tunnelling: It involves charge transport through an insulating medium separating between two conductors that are closely spaced. As thickness of layer increases, electrical conductivity decreases.

(iv) Effect of Micro-structure

Electrical conductivity may change due to formation of ordered micro-structure, when size is reduced to nm range. Ex: Polymer fibers shows an increase in electron conductivity.

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Optical Properties

Optical properties of nanomaterials can be significantly different from bulk crystals. The unique optical properties of nanomaterials arise due to their quantum size effect, which is caused by the confinement of electrons for particles with smaller dimensions.

As the size decreases, the specific surface area increases and a quantum effect appears that leads to profound changes in the properties of materials. The colour of nanoparticle depends on both size and shape (due to SPR) of NPs. Ex: Spherical AgNPs gives red colour, flat AgNPs gives blue colour.

Size dependence is due to:

– **Surface Plasma Resonance** (SPR)

– **Quantum Size Effects**.

Surface Plasma Resonance:

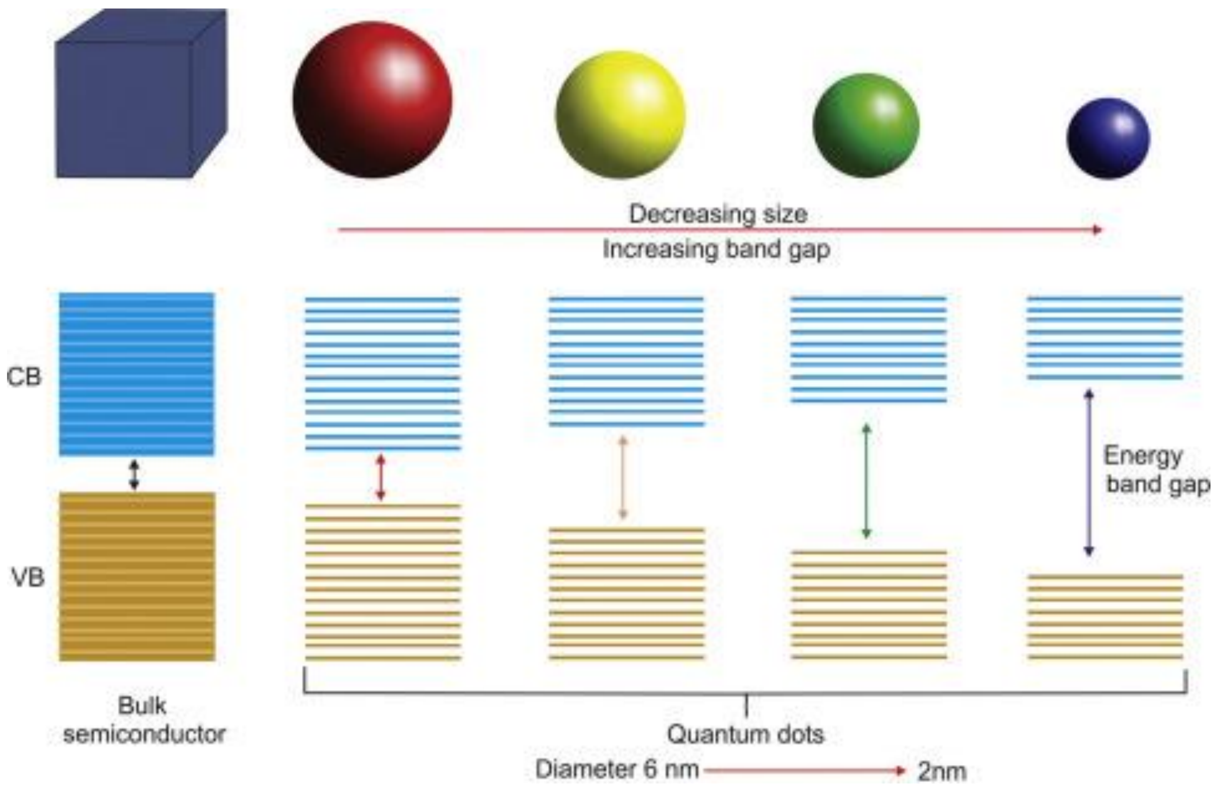
This process takes place when there is coherent oscillation of conduction band electrons upon interaction with an electromagnetic field. It takes place when size of nanoparticle is smaller than wavelength of incident radiations. Electric field of incoming light waves causes polarization of free electrons. It occurs mostly in case of Gold NPs.

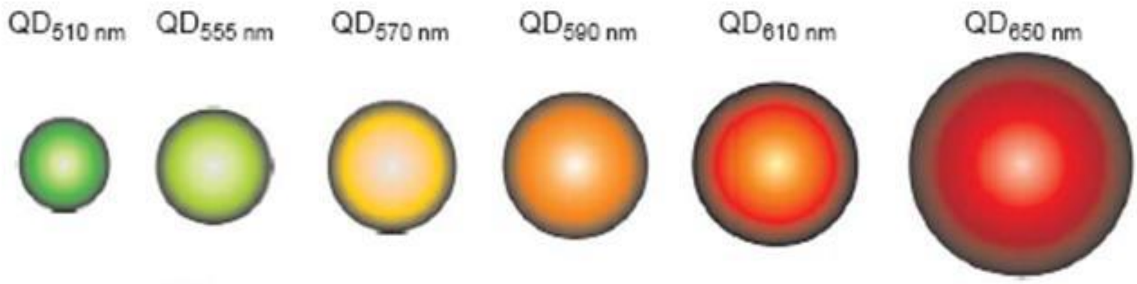
SPR in AgNPs gives rise to sharp & intense absorption band in visible region. Plasmon band red shift with increasing particle size. The increase of both absorption wavelength and peak width with increasing particle size. Thus the reduction of material dimension has pronounced effect on *optical properties*.

Quantum Size Effects:

The unique optical properties of nanomaterials also arise due to quantum size effects. When the size of nanocrystal is smaller than De-Broglie wavelength ($\lambda = h / m\upsilon$), electrons and holes are spatially confined and discrete energy levels are formed. Similar to particle in box, energy separation between adjacent levels increases with decreasing dimensions.

These changes arise through systematic transformations in density of electronic energy levels as a function of size which results in strong variation in the optical and electrical properties with size. This effect occurs mostly in case of semiconductor NPs, where band gap increases with decreasing size, resulting in inter-band transition shifting to higher frequencies.





Optical Properties of Gold NPs

Bulk gold appears yellow in colour. Nano sized gold appears red in colour. The particles are so small that electrons are not free to move as in bulk. Because this movement is restricted, the particles react differently with light. This colour change will be due to the variation in band gap of the material .e., blue shift in adsorption and emission due to an increased band gap.

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Magnetic Properties

Magnetic nanoparticles belong to the class of particular materials having **particle size <100nm** that can be manipulated *under the influence of an* **external magnetic field,** and can display **super-paramagnetism.**

Ex: Fe, Ni, Co, Fe_3O_4, Fe_2O_3, Fe_2CO_4, CrO_2, etc..

Magnetic materials exhibit size-dependent magnetic properties that range from ferromagnetic to paramagnetic to super-paramagnetic with decreasing size.

Usually, the strength of a magnet is measured in terms of coercivity and saturation magnetization values. These values increase with a decrease in the grain size and an increase in the specific surface area (surface area per unit volume) of the grains.

Therefore, nanomaterials present good properties in this field also. Bulk gold and Pt are non-magnetic, but at the nano size they are magnetic.

Some of the possibilities when we go from bulk to nano are:

- Physical & chemical properties of magnetic NPs mainly depend upon the chemical structure & method of synthesis.
- Ferromagnetic particles become single domain (with decrease in size).
- Super-paramagnetism in small ferromagnetic particles (i.e. particles which are ferromagnetic in bulk).

- Giant Magneto Resistance (GMR) effect in hybrids (layered structures).
- Anti-ferromagnetic particles (in bulk) behaving like ferromagnets etc.
- The small particles are more magnetic than the bulk material.

Metal	Bulk	Cluster
Na, K	Paramagnetic	Ferromagnetic
Fe, Co, Ni	Ferro magnetic	Super paramagnetic
Gd, Tb	Ferromagnetic	Super paramagnetic
Rh	Paramagnetic	Ferromagnetic

	Magnetic Moment (μ_B/atom)			
	0D	1D	2D	Bulk
Ni	2.0	1.1	0.68	0.56
Fe	4.0	3.3	2.96	2.27

Increasing magnetic moment/atom

Super-paramagnetism <u>(used for biomagnetic separation)</u>

Super-paramagnetic nanoparticles are not magnetic, when located in a zero magnetic field, but they quickly become magnetized when an external magnetic field is applied. This is due to the presence of only one domain in magnetic nanoparticles as compared with the multiple domains of bulk. *When returned to a zero magnetic field* they quickly *revert to a non-magnetized state*.

When particles become very small, the coercive force approaches zero, because the thermal fluctuations prevents the existence of a stable magnetization. This super-paramagnetism mechanism is based on relaxation time of the net magnetization of a magnetic particle.

Magnetic nanoparticles have variety of applications such as in nanoelectronics, biomedical sensors, drug delivery, magnetic resonance imaging, data storage, color imaging, bioprocessing, magnetic refrigeration & ferrofluids etc.

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Thermal Properties

Thermal conductivity

Thermal conductivity is the ability of material to transport heat energy through it, from a high temperature to low temperature region. With increase in temperature both number of carrier electrons and contribution of lattice vibrations increase- electron mobility decreases

- Nanoparticles offer a very large surface area for heat transfer, since one in five of their atoms are found on the surface. This makes plenty of electrons available for heat transfer. Different types of nanoparticles offer different levels of thermal transfer enhancement. Carbon nanotubes (CNTs) have a thermal conductivity of about 3000 W/mK, and a high aspect ratio of about 2000.
- Nanoparticles have low particle momentum and very high mobility.
- The small size of the molecules allows for free movement and hence microconvection, which promotes heat transfer.
- The nano fluid may show much faster heat dispersion owing to these two factors.
- Nanoparticles are ideal for use in microchannels which handle large heat inputs, because of their high conductivity and aspect ratio. Their use avoids the danger of clogging that is associated with larger particles. In addition, the small particle size reduces wear and tear, extending system life.
- The use of nanofluids is cost effective
- With oxide nanoparticles, heat transfer by convection actually increases moderately, but viscosity also increases. With the use of metallic nanoparticles, a very small increase in particle concentration leads to almost unchanged viscosity but a high enhancement in heat transfer. With CNT nanofluid use, effective thermal conductivity goes up with temperature and with particle concentration, but more with temperature.
- Heat conduction in two-dimensional and one-dimensional crystals show that they have unique qualities that result in a substantial thermal conductivity.

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