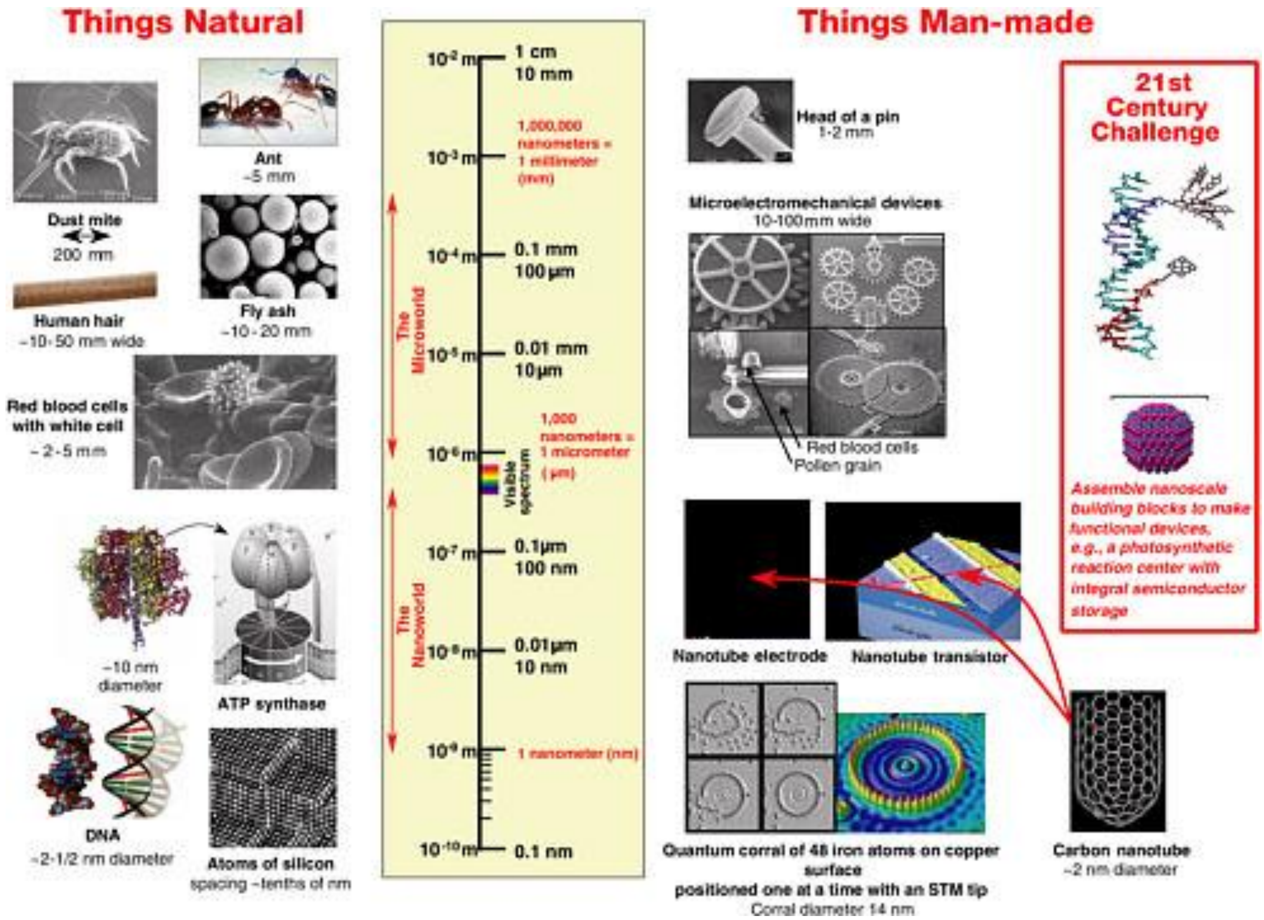
Physics of Nanomaterials

Module I

Nanotechnology

Learning objectives

Introduction to nanocrystalline materials, Brief history of research in nanomaterials, Significance of nanotechnology,Finite size effects and properties, Classification of nanostructure materials, Challenges and future prospects



The size of nanoscale objects and phenomena compared with the size of small everyday objects. Courtesy of Office of Basic Energy Sciences, Office of Science, U.S. Department of Energy.

1.What are nanomaterials? Compare nanoscale with bulk observable things.

Nanomaterials:

1. The materials which are created from blocks of nanoparticles or they are defined as a set of substances where at least one dimension is less than approximately 100 nanometers.
2. Nanoscience is a new discipline concerned with the unique properties associated with nanomaterials, which are assemblies of atoms or molecules on a ***nano scale***. '**Nano'** refers a scale of size in the metric system.
3. It is used in scientific units to denote one-billionth of the base unit - approximately 100,000 times smaller than the diameter of a human hair. **'Scale'** refers an order of magnitude - of size or length- reference to objects that are sized on a scale that is relevant to nanometer.
4. A nanometer is 10^{-9}meter (1nm = 10^{-9}meter), a dimension in the world of atoms and molecules (the size of H atom is 0.24 nm and for instance, 10 hydrogen atoms lined up measure about 1 nm).
5. For comparison, a red blood cell is approximately 7,000 nm wide and a water molecule is almost 0.3nm across.
6. People are interested in the nanoscale (which we define to be from 100nm down to the size of atoms (approximately 0.2nm)) because it is at this scale that the properties of materials can be very different from those at a larger scale.
7. Nanomaterials are of interest because at this scale unique optical, magnetic, electrical, and other properties emerge. These emergent properties have the potential for great impacts in electronics, medicine, and other fields.
8. Nano carbons such as fullerenes and carbon nanotubes are excellent examples of nanomaterials.

2. How nanomaterials are more interest than bulk materials? Give significance of Nanotechnology.

1. The bulk properties of materials often change dramatically with nano ingredients. Composites made from particles of nano-size ceramics or metals smaller than 100 nanometers can suddenly become much stronger than predicted by existing materials-science models.
2. For example, metals with a so-called grain size of around 10 nanometers are as much as seven times harder and tougher than their ordinary counterparts with grain sizes in the hundreds of nanometers.
3. The properties of materials can be different at the nanoscale for two main reasons:

First, nanomaterials have a relatively larger surface area when compared to the same mass of material produced in a larger form. This can make materials more chemically reactive, and affect their strength or electrical properties.

Second, quantum effects can begin to dominate the behaviour of matter at the nanoscale - particularly at the lower end - affecting the optical, electrical and magnetic behaviour of materials. Materials can be produced that are nanoscale in one dimension (for example, very thin surface coatings), in two dimensions (for example, nanowires and nanotubes) or in all three dimensions (for example, nanoparticles)

4. Properties like color, melting point, electrical, magnetic properties etc. for bulk materials doesn't depend on size, but after a certain size limit which is less than 100 nm the properties

changes. For example, bulk gold is yellowish in color but at nanoscale it is ruby red. Therefore, the properties of materials change when we approach nanoscale. Thus, it is possible to arrange molecules in a manner/way that is different from their natural or normal occurrence and hence bring about a change in the properties of materials. Nanotechnology, thus possesses the ability to create better materials, and devices.

Significance

Nanomaterials in Automobile industry: The Auto mobile parts prepared from Nano materials are flexible, light weight and exhibiting high strength compared to the bulk. We can use these nanomaterials in cars, aero planes etc.
Example nanomaterials: Carbon nanosheets, Graphene sheets.
Nanomaterials in Electronics: Many electronic products such as computers, mobile phones, photographic cameras and memory cards/hard disk drives etc., were already reduced in their size and also improvement in their performance. This is mainly due to the transistor size reduction by Nanotechnology/nanomaterials.
Example nanomaterials: Carbon nanotubes, semiconductor nanowires, nanorods.
Nanomaterials in Energy: Solar cells prepared from Nanomaterials are able to produce much power/efficiency compared to the bulk. This high efficiency is attributed to the large surface area and light trapping capability of the nano material. We are also able to produce high storage Li-ion batteries using nanomaterials. These Li-ion batteries are very useful in cell phones, automobiles etc.
Example nanomaterials: Silicon nanowires, Zinc oxide, Titanium oxide nanowires.
Nanomaterials in water purification: Due to large surface area of Nanomaterials, water purification by these nanomaterials are efficient, clean and also cost effective (cheap) compared to bulk.
Example nanomaterials: Nano $TiO2$, Carbon nanotubes,
Nanomaterials in medicine: Nanomaterials are very helpful in the drug delivery with precise control over the delivery location. Nanomaterials are reacting only with the infected cells without damaging the healthy cells in thehuman body.
Example nanomaterials: Au, Ag nanoparticles.
Super hydrophobicity: Nanomaterial coating on any surface act as a super hydrophobic surface like as a lotus leaf. This behavior is due the air trapped between the nano materials,which pushes the water drop up. We can coat water repellent (super hydrophobic) coating on any surface such as clothes, metals, shoes, car windshield, window glasses and tissue papers etc. The above said surfaces act as a super hydrophobic surfaces like shown in below.
Example nanomaterials: Silicon nanowires,

Nanotech and Nature

Nanotechnology is a new word but not a new process and field. Nature, is filled with objects that function on micro to nano scale. The bacterial flagella rotates at over 10,000 rpm (revolutions per minute) giving us a classic example of biological molecular machine. Another example would be the Lotus effect, which refers to high water repellence exhibited by leaves of lotus plant. Dirt particles are taken up and removed by water droplets due to complex architecture at the surface of leaves of lotus plant involving manipulation at micro-nanoscopic scale! This principle has been used to develop treatments, coatings, paints, fabrics on other surfaces that can stay dry and clean themselves in a similar way.

Nanotechnology and Biology

Nanotechnology and Biology are strongly interlinked; there are many biological systems with nanoscale dimensions.For example, diameter of DNA molecule is around 2 nm and size range of many enzymes is few nanometers. Applications of Nanotechnology in Biology ranges from detection of pathogens and biomolecules, Drug and Gene delivery, Diagnostic and Treatment of cancer, Tissue Engineering and Creation of nanostructures mimicking biomolecules.

Nanobiotechnology or Bionanotechnology

Nano-biotechnology is defined as a field that uses nanoscale principles and techniques to understand and transform biosystems. The field of nanobiotechnology is best described as helping modern medicine in overcoming barriers in effective treatment and diagnostic of disease. Small magnetic nanoparticles have opened a new window of diagnostic and treatment of cancer, these small magnetic nanoparticles can be used as contrast agent for Magnetic Resonance Imaging(MRI) and for hyperthermia (heating of tumor cells in temperature range of 42-45˚C) treatment of cancer. Non-Cancerous cells are less susceptible to high temperature so hyperthermia treatment do not affect non-cancerous cells.

Bio-nanotechnology is defined as a field that uses biological systems to develop nanoscale systems, like DNA nanotechnology which utilizes properties of nucleic acids (DNA) to create useful materials. It is best described as development of new nanostructures, devices and materials taking inspiration from nature.

The primary objective of this field of nanobiology (Nanobiotechnology and Bionanotechnology) is to apply nanotools in biological systems to overcome the current problems in medical/biological world and also developing better nanotools by mimicking processes happening in biology.

3. What is Size effect? Explain surface to volume ratio and Quantum confinement? Or

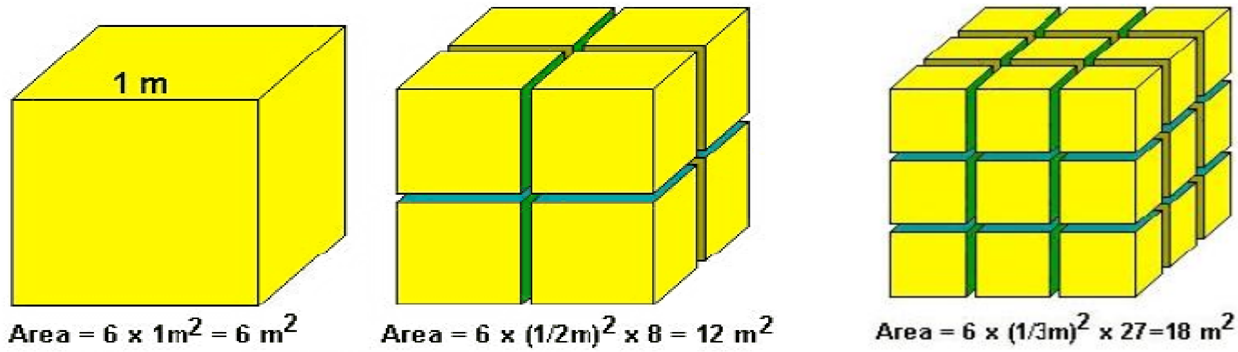
Why the properties of nanoparticles are different?

The properties of nanomaterials are very much different from those at a larger scale.
Two principal factors cause the properties of Nano Materials to differ significantly from other materials (1) Increased relative surface area and (2) Quantum confinement effect. These factors can charge or enhance properties such as reactivity, strength and electrical characteristics.

Why properties of nanomaterials are different? The following two factors make the nanomaterials to have considerably different properties that its bulk one. 1. Increase in relative surface area 2. Quantum confinement effect

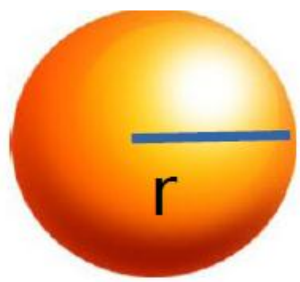
Increase in surface area to volume

Nanomaterials have a relatively greater surface area when compared to the same volume or mass of the same material in bulk form. For example, consider cube of $1m^3$ volume (Fig.), it has surface area of $6m^2$. If this cube of same volume is divided into eight small cubes, then the total surface area increases to $12m^2$. Further dividing cube leads to increase in surface area. This is illustrated in the following figure. Also if the size of nanomaterials decreases, a greater proportion of atoms are found at the surface compared to those inside. This makes materials more chemically reactive.



Increase in surface area of cube

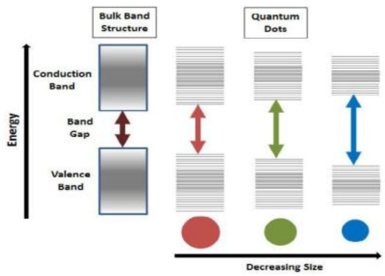
Large surface to Volume ratio: Nanomaterials have a relatively large surface to Volume ratio when compared to the same volume of the material in bulk form. For example consider a sphere of radius "r"



Surface area = $4\pi r^2$
Volume=$4\pi r^3/3$
Surface/ Volume = 3/r
As "r" decreases Surface/Volume ratio increases

Quantum Confinement: In nanocrystals, the electronic energy levels are not continuous as in the bulk but are discrete (finite density of states), because of the confinement of the electronic Wave function to the physical dimensions of the particles**.** This phenomenon is called Quantum confinement

If one length of three dimensional nanostructures is at nano-dimension, then it is called a ***Quantum Well***. If two sides of three dimensional nanostructures are at nano-dimension, then it is called a ***Quantum Wire***. If all three dimensional nanostructures is at nano-dimension (***Nano Crystals)***, are referred as ***Quantum Dots*** (***QDs***).



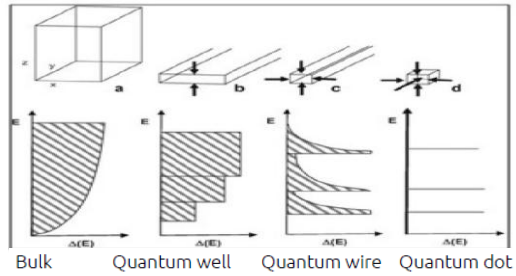


Figure : Density of electron states (ΔE) of a semiconductor as a function of dimension

4. Define nanoscale materials and give classification of nanomaterials. OR
Give classification of nanomaterials based on dimension? OR
What are low dimensional nanoparticles? Give classification of nanomaterials.

Nanoscale materials: The materials which are created from blocks of nanoparticles or they are defined as a set of substances where at least one dimension is less than approximately 100 nanometers

A **Nanocrystallite** is generally understood to possess crystalline order in addition to nanoscale size. They can exist in single, fused, aggregated or agglomerated forms with spherical, tubular, and irregular shapes.

Classification of nanomaterials:
Nano-structured materials are classified as
1.Zero Dimensional(0 D),2.One Dimensional (1D),3.Two Dimensional (2 D),4.Three Dimensional(3 D)

1. Zero Dimensional (0 D): If all the three dimension of the nanostructure is at nano scale, then it is called Zero Dimensional(0 D) materials

a. Nanocrystallites are also called quantum dot.
b. e.g., precipitates, colloids

2. One Dimensional (1D): If two dimension of the three dimensional nanostructure is at nano scale, then it is called One Dimensional (1D) materials

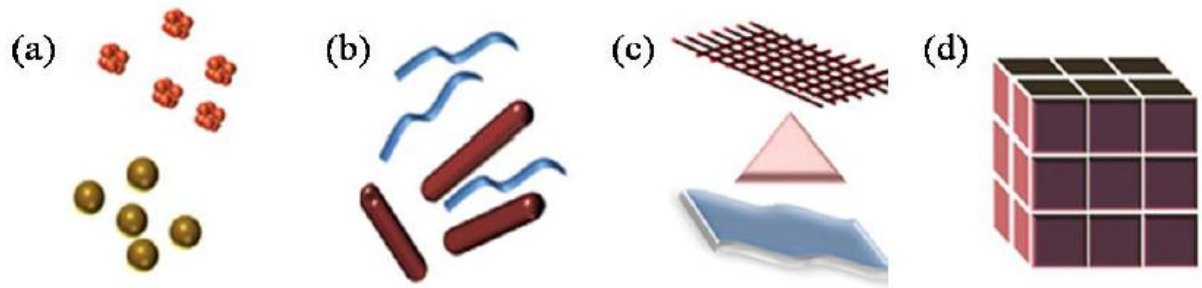
a. Nanocrystallites are also called quantum wire.
b. e.g., nano fibers, nano rods

3.Two Dimensional (2 D): If one dimension of the three dimensional nanostructure is at nano scale, then it is called Two Dimensional (2 D) materials

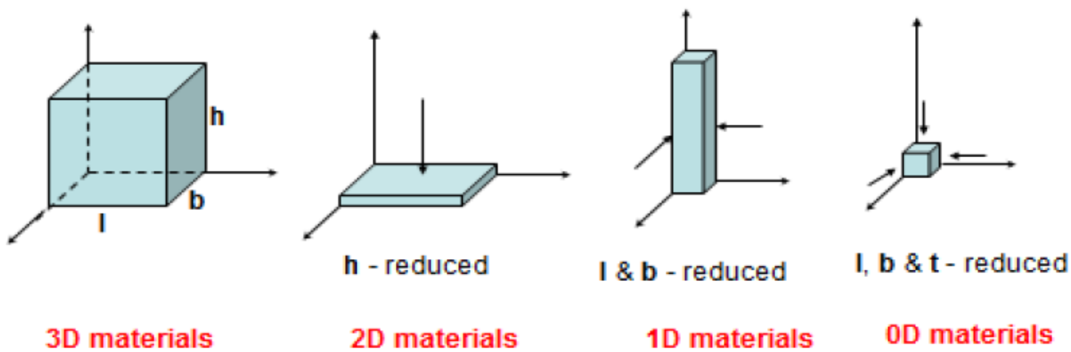
a. Nanocrystallites are also called quantum well.
b. e.g. surface films,

4.Three Dimensional(3 D): If all dimensions of the three dimensional nanostructure is at bulk scale, then it is called Three Dimensional (3 D) materials

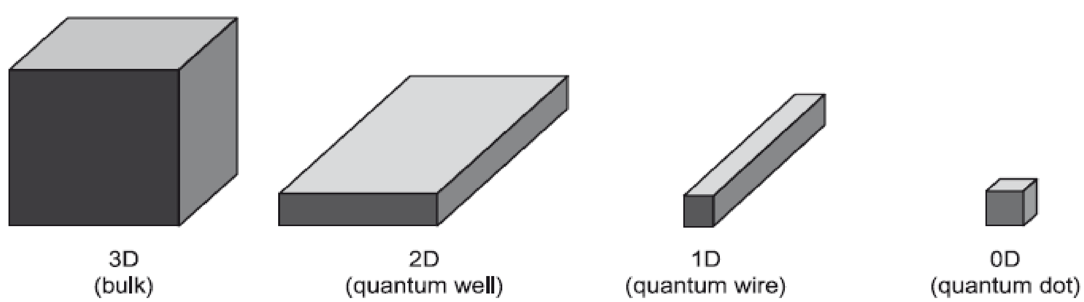
a. e,g.Grains and grain boundaries



Classification of Nanomaterials (a) 0D spheres and clusters, (b) 1D nanofibers, wires, and rods, (c) 2D films, plates, and networks, (d) 3D nanomaterials.



Schematic representation of various forms of low dimensional materials



5. Almost every element in the periodic table, together with various alloys and compounds, can form nanoparticles. They can be metallic, semiconducting, or insulating and typically their properties are very different to those of the corresponding bulk material.
6. An important idea that underpins much of nanotechnology is that by controlling composition, size, and structure at the nanoscale one can engineer almost any desired properties.
7. For an object of the macroscopic size, the surface atoms comprise a negligible proportion of the total number of atoms and will therefore play a negligible role in the bulk properties of the material. When the size of the object is reduced to the nanometric range the proportion of surface atoms no longer negligible. So a large fraction of the atoms are located at the surface of the

object in the nanomaterials, it will modify its properties. The properties of nanomaterials become totally different from what is observed in the bulk solid system

5. Give different properties of nanomaterials? Explain variation of properties with nano size

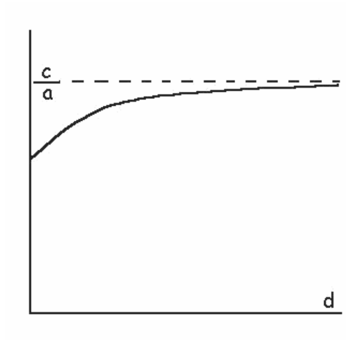
Properties of Nanomaterials: Nanomaterials have properties that are different from those of bulk materials**.** Most nanostructure materials are crystalline in nature and they have unique properties. Filling polymers with nanoparticles or nanorods and nanotubes, respectively, leads to significant improvements in their mechanical properties.
Physical Properties: Crystal structure of nanoparticles is same as bulk structure with different lattice parameters**.** The inter-atomic spacing decreases with size and this is due to long range electrostatic forces and the short range core-core repulsion**.** The melting point of nanoparticles decreases with size.
Optical Properties: Nanocrystalline systems have novel optical properties. Depending on the particle size different colors are seen. Gold nanospheres of 100 nm appear orange in colour while 50 nm appear green in colour. If semiconductor particles are made enough small, quantum effects come into play, which limit the energies at which hole and electrons exist inside the particles. The particle are made to emit or absorb specific wavelengths (colours) of light,merely by controlling their size.
Chemical Properties: A large fraction of the atoms are located at the surface of the nanomaterial which increase its reactivity and catalytic activity. The large surface area to volume ratio, the variations in geometry and the electronic structure of nano particles have a strong effect on catalytic properties.
Electrical properties: The energy band structure and charge carrier density in the materials can be modified quite differently from their bulk and in turn will modify the electronic properties of the materials. Nanoparticles made of semiconducting materials like Germanium, Silicon and Cadmium are not semiconductor. Nanoclusters of different sizes will have different electronic structures and different energy level separations. So they show diverse electronic properties which depend on its size.
Magnetic Properties: The magnetic moment of nano particles is found to be very less when compared them with its bulk size**.** Actually, it should be possible that non-ferromagnetic bulk exhibit ferromagnetic-like behavior when prepared in nano range. Bulk Gold and Pt are non-magnetic, but at the nano size they are magnetic.

Property	**Influence of size reduction on properties of nanoparticle**
Structural	Decrease or increase of lattice parameter Structure transformations
Mechanical	Enhancement of hardness, strength, fracture ductility Arise of superplasticity Raising of wear resistance
Thermal	Decrease of melting point Decrease of phase transition temperatures Decrease of melting entropy Softening of phonon spectra
Thermo-dynamical	Increase of heat capacity Increase of thermal expansion Decrease of Debye temperature Stabilization of high temperature phases
Kinetic	Increase of diffusion coefficient Sharp drop of thermal conductance under some critical size d* Oscillation of kinetic coefficients
Electrical	Increase of conductivity for nanometals Arise of conductivity for nanodielectrics Increase of dielectric inductivity for ferroelectrics at d*
Electronic	Increase of band gap Arise of phonon generation Raising of conductivity under low temperatures in semimetallic Bi

Property	Influence of size reduction on properties of nanoparticle
Magnetic	Increase or decrease of coercive force at d* Decrease of Curie temperature Rice of paramegnetism in ferromagnetics at some d* Rice of gaint magnetoresistance Rise of maximal temperature of magnetoresistance Increase of magnetic permeability in ferromagnetics at d*
Optical	Diffraction and interference Increase of absorption in ultraviolet range (blue shift) Oscillation of optical absorption Arise of nonlinear optical properties
Chemical	Increase of catalytic activity Increase of velocity of physico-chemical interactions Swap of solubility

Reduction of lattice parameter

Laplace tension *PL* for nanoparticle is so big that can cause a bulk compression that in turn reduces a lattice parameter on the Δ*a* value shown in fig. It may be estimated from the rule of proportionality:



$$\frac{\Delta a}{a} = \frac{P_L}{K_T}$$

where $K_T \approx 10^{11}$ Pa is a compressibility modulus, therefore $\frac{\Delta a}{a} = \frac{200 \cdot 10^6 Pa}{10^{11} Pa} = 2 \cdot 10^{-3}$

The value is small but it is able to cause phase transitions under some conditions. For example, the inclusions of Y2O3 in oxide ZrO2 change its structure from monoclinic into triclinic.

For some alloys the reversible effect is arisen, e.g. the increasing of lattice parameter in nanoparticles. That means that sign of the effect depends not only Laplace pressure but on a change of interatomic potential and forces under transition from a bulk to surface.

Decrease in melting point

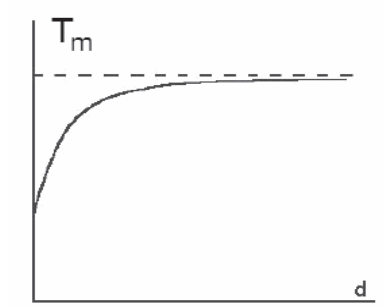
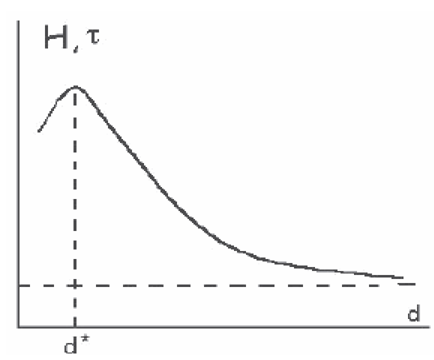


Fig. illustrates the general experimental dependence of a melting point T_m on the nanoparticle size *d* showing a decrease in T_m with *d* reduction. Its physical origin is the increase of surface energy, the increase of amplitude of atomic vibrations, and the additional surface growth of thermal vibration energy in the result.

Increasing of plastic yield strength and hardness of polycrystal

In physics of strength the Hall-Petch relation is well known of which accordance a hardness and yield strength are increased under the reduction of the grain size *d* of polycrystal:

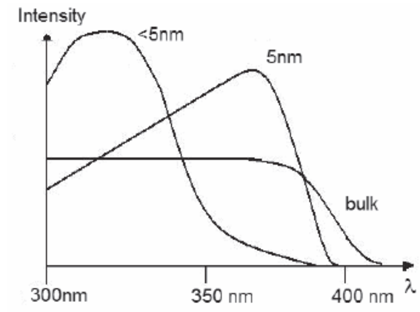


$$\tau_{\Pi} = \tau_0 + \frac{K_1}{\sqrt{d}}$$

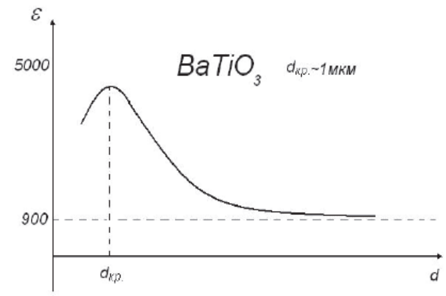
where τ_0 deformation strength of monocrystal is, τ_P is a strength of polycrystal, *K*1 is a coefficient of fracture ductility. The dependence is shown in fig. and successfully used in the industry. However in extreme case $d \to 0$ this relation do not works. The critical size *d* =*d* * exists when τ approaches its maximal value $\tau = \tau*$ and then drops again. The reason is disappearance of dislocation, the carriers of plastic deformation, due to nanoparticle size becomes to be smaller than a dislocation length, $d < l_{dislocation}$, because of which all dislocations come to a surface.

Blue shift – the increasing of band gap and luminescence frequency

Fig. Shows the transformation of a luminescence spectrum of ZnO under conversion to nanostructured state. A blue shift of luminescence spectrum under a reduction of the particle (grain) size is seen

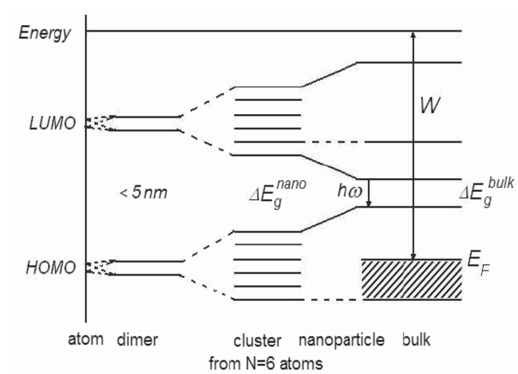


Dependence of dielectric permittivity of barium-titanate ceramics BaTiO3 on size of nanoparticles



Under decreasing of size of polycrystal the size of single domain is constant or weakly changes, so the number of domains is decreased at first stage of the size decreasing, that result in decrease of total magnetic moment. At d=d* (~100 nm), the total moment of polycrystal decreases to a moment of single domain. Further decreasing of domain size, when a nanoparticle size becomes smaller than a spin wave length $d < \lambda_{spin}$, causes a decrease of the number of atomic magnetic moments, their correlation energy is decreased and at some critical value (d*~10 nm) it becomes to be smaller than induced magnetic moment of single atom. From this size all magnetic properties of nanoparticle with $d < d^*$ depends on the induced magnetic moment of single atom, meaning a phase transition in a paramagnetic state.

Broadening of energetic bands



Electronic spectra of atoms are known to be the discrete spectrum of energy levels En.

In accordance with Pauli principle two or more electrons cannot occupy the same place or take the same energy. Therefore the energy levels are splitten to some small value Δn, forming an energetic band, a width of which is proportional to a number of the levels or atoms N, $\Delta E_g^0 = \Sigma\Delta_n = N\Delta_n$. It means that the band gap increases simultaneously when reducing the size of particle, hence $\Delta E_g^{nano} > \Delta E_g^{bulk}$. From fig. is seen that the luminescence frequency is proportional to $g\ \Delta E$ due to $\Delta E_g = \hbar\omega$. Hence for nanoparticles the luminescence frequency is increased $\omega^n > \omega^0$, that in physical sense is just the blue shift.

6. Write a short note on challenges and future prospects of nanaomaterials?
Nanotechnology Challenges

1. Providing Renewable Clean Energy
2. Supplying Clean Water Globally
3. Improving Health and Longevity
4. Healing and Preserving the Environment
5. Making Information Technology Available To All
6. Enabling Space Development

Challenge -1
Synthesis/Preparation: The challenge is to design, to synthesize, and to characterize new functional nanomaterials with controllable sizes, shapes, composition, and/or structures.
Ex: Preparing a p-n junction in the form of a nanowire.
Challenge -2
Nanomanipulation: Handling nanomaterials/manufacturing nanodevices using nanomaterials is an another challenge due to nanoscale features.
Ex: Preparing single nanowire transistor.
Challenge -3
Risk with the Nanotechnology:
(a)Human health risks
Inhaled nanoparticles can reach the blood and may reach other target sites such as the liver, heart or blood cells. The challenge is to study the interaction of nanoparticles and biological systems (human body).
(b) Environmental health risks
All the electronics waste (Computer,Phone IC chips, Batteries contains nanomaterials) recycling is a major challenge. Improper recycling leads to polluting the environment with nano materials specially nanoparticles. Similarly, nanowaste (super hydrophobic nano film coated shoes, cloths, car wind shield, nano water filter filters,damaged solar panels etc) recycling is a major challenge.
Challenge -4
Providing Renewable Clean Energy
Balancing humankind’s need for energy to our planet is a major challenge infront of the nanomaterials. Nanomaterials based solar cells already under production but the challenge is preparing solar cells with more conversion efficiency, long period usage, less expensive and easy recycling.
Challenge -5
Supplying Clean Water Globally
Nanomaterial based water filters already producing clean water but the challenge is preparing water filters with more purification, long period usage, less expensive and easy recycling.
Challenge -6
Making Information Technology Available To All
The use of nanotechnology/nanomaterials will drastically reduce the cost and increase the performance of memory, displays, and processors. Making technology available for remote places is a challenge.
Challenge -7
Health and safety (Medicine)

New methods of drug delivery, faster development of new drugs, repairing DNA and cellular damage are the major challenges in medical field

Applications of Nanomaterials:

(1) **Chemical Industry:** Fillers for point systems. Coating systems based on nano composites, Magnetic fluids

(2) **Automotive Industry:** Light weight construction, Painting, Catalysts, Sensors

(3) **Medicine**: Drug delivery systems, Active agents, Medical rapid tests, Antimicrobial agents and coatings, Agents in cancer therapy

(4) **Electronic Industry:** Data memory, Displays, Laser diodes, Glass fibers, Filters, Conductive,antistatic coatings

(5) **Energy Sources:** Fuel cells, Solar cells, Batteries, Ultracapacitors

(6) **Cosmetics**: Sun protection creams, Tooth paste

Applications of Nanomaterials in Medicine: Medical application of nanomaterials include

(a) Fluorescent biological labels

(b) Drug and gene delivery

(c) Bio-detection of pathogens

(d) Detection of proteins

(e) Probing of DNA structure

(f) Tissue engineering

(g) Tumour destruction

(h) Separation and purification of biological molecules and cells**.**

Future application of Nanomedicine is as follows:

(1) The elimination of bacterial infections in a patient within minutes

(2) The ability to perform surgery at the cellular level, removing individual diseased cells and even repairing defective portions of individual cells

(3) **Qdots:** that identify the location of cancer cells in the body, here nanomaterials that deliver chemotherapy drugs directly to cancer cells to minimize damage to healthy cells

(4) **Nanocells:** that concentrate the heat from infrared light to destroy the cancer cells with minimal damage to surrounding health cells.

• The cell membranes, and several other functional organelles within the biological cell of living beings are in fact of nanometric size.

• It is envisaged that nanotechnology will lead to tiny robotic devices, utilizing nanoelectronics, sensors and MEMS for invivo monitoring and diagnosis of deficiencies and malfunctions of human systems.

Module II

MICROSTRUCTURE AND DEFECTS IN NANOCRYSTALLINE MATERIALS

In order to understand the novel properties of nanostructured materials, we need to understand the structure and its interrelationship with properties. The microstructural features of importance in nanomaterials include:

• Grain size, distribution and morphology
• The nature of grain boundaries and interphase interfaces
• Nature of intragrain defects
• Composition profiles across grains and interfaces
• Residual impurities from processing

Crystal lattice imperfections, such as point, linear, planar and volume defects, lead to the structure-sensitive properties of materials.

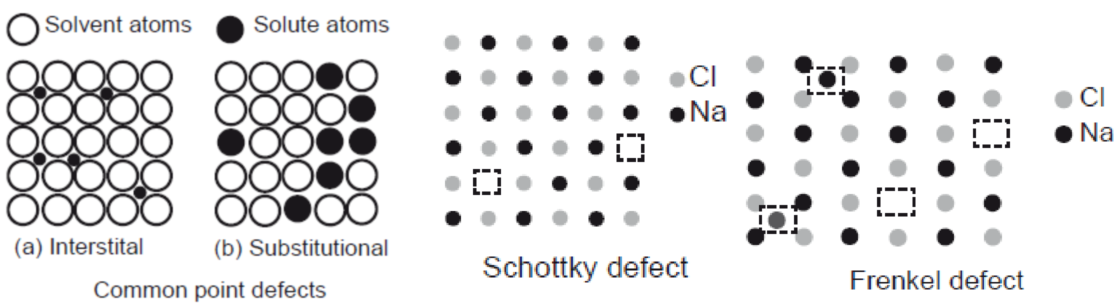
Crystals: Crystals are three-dimensional, periodic arrangements of atoms/molecules in space

Defect: Any imperfection leading to disruption of periodicity is referred to as a 'crystalline defect

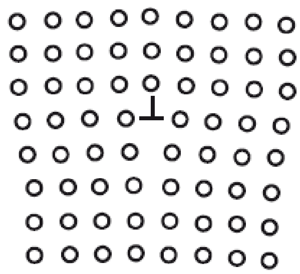
These defects are usually classified based on their dimensionality, namely,

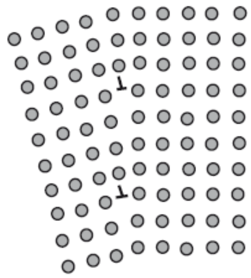
1. point defects (0D),
2. line defects (1D),
3. surface defects (2D) and
4. volume defects (3D).

Point defects: Vacancies and substitutional and interstitial solutes are the common point defects observed in metals and alloys. In case of ionic solids, Schottky (anion–cation vacancy pairs) and Frenkel (vacancy-interstitial pairs of the same ions) defects may also be observed.

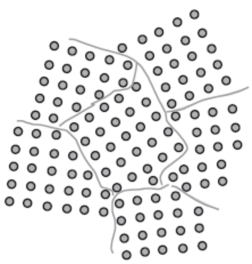


Line defects: Dislocations are the most commonly observed line defects and refer to a missing plane of atoms. Among the surface defects, grain boundaries, twins, stacking faults and free surfaces are the most common.





Volume defects: Inclusions, voids and micro cracks constitute the volume defects.



Dislocations

Missing rows of atoms in a crystal are regions of high energy and stress due to disruption of the atomic bonds in the plane. This provides a driving force for dislocations to be annihilated at surfaces or grain boundaries to minimize the strain energy of the crystal.

Types of Dislocations

1. Edge dislocation
2. Screw dislocation

Voids: Voids in nanocrystallites may be situated at either triple junctions or as large porosities due to insufficient compaction and sintering of nanocrystallites synthesized from the powder route.

Stacking faults: crystallographic defects arising due to wrong stacking sequence of planar arrangement of atoms

Twins: are generally observed in crystals subjected to deformation under high strain rate or at low temperatures.