# Nanoscience & Nanotechnology
# An Introduction


Dr. Sanjay Panwar
Professor & Director

SCHOOL OF BASIC & APPLIED SCIENCES
MAHARAJA AGRASEN UNIVERSITY
BADDI (SOLAN) – 174 103

# OUTLINE

1. Materials and Civilizations
2. What is Nanotechnology?
3. Standard Definitions and Terms
4. Nanomaterials & their Classifications.
5. Emergence of nanotechnology
6. Milestones in the evolution of NT
7. Challenges in NT
8. Applications
9. FundamentalIssues in NM
10. Causes of interests in NM
11. Role of BU and TD approaches
12. Characteristics of Nanoparticles that should possess by any fabrication technique

# Materials and civilization

Stone age (Before 5000 BC)

Copper age (5000 - 3000 BC)

Bronze age (3000 - 800 BC)

Iron age (800 BC - 40 AD)

Plastic age

Nanomaterials?

# NANOSCIENCE

The most common working definition of nanoscience is:

"Nanoscience is the *study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales*, where **properties differ significantly** from those at a larger scale"

Bulk materials (the "big" pieces of materials we see around us) possess continuous (macroscopic) physical properties.

**The same applies to micron-sized material (e.g., a grain of sand).**

But when particles assume nano-scale dimension, the principles of classical physics are no longer capable of describing their behaviour (movement, energy, etc). At these dimensions, quantum mechanics principles apply.

**The same material (e.g., gold) at the nanoscale can have properties (e.g., optical, mechanical, electrical, etc.) which are very different from (even opposite to!) the properties the material has at the macro scale (bulk).**

# WHAT IS NANOTECHNOLOGY?

Nanotechnology is the ability to observe, measure, manipulate, and manufacture things at the nanometer scale.

A nanometer (nm) is an SI (*Syst`eme International d'Unit´es*) unit of length $10^{-9}$ or a distance of one-billionth of a meter. That's very small. (At this scale, you are talking about the size of atoms and molecules.

- To create a visual image of a nanometer, observe the nail on your little finger. The width of your nail on this finger is about 10 million nanometers across.
- To get a sense of some other nano-scaled objects, a strand of human hair is approximately 75,000 to 100,000 nanometers in diameter.
- A head of a pin is about a million nanometers wide and it would take about 10 hydrogen atoms end-to-end to span the length of one nanometer.

The word “nanotechnology” was first introduced in the late 1970s. While many definitions for nanotechnology exist, most groups use the National Nanotechnology Initiative (NNI) definition. The NNI calls something “nanotechnology” only if it involves all of the following:

- ✓ Research and technology development at the atomic, molecular, or macromolecular levels, in the length scale of approximately 1 to 100-nanometer range.
- ✓ Creating and using structures, devices, and systems that have novel properties and functions because of their small and/or intermediate size.
- ✓ Ability to control or manipulate on the atomic scale.

# Some Common Objects in Nanometers

| How Many Nanometers? | Approximately (nm) |
|---|---|
| The Width of an Atom | 1 |
| The Width Across a DNA Molecule | 2 |
| The Width of a Wire in a Computer | 100 |
| The Wavelength of Ultraviolet Light | 300 |
| The Width of a Dust Particle | 800 |
| The Length of Some Bacteria | 1,000 ($10^3$) |
| The Width of a Red Blood Cell | 10,000 ($10^4$) |
| The Width of a Hair | 75,000 to 100,000 ($10^4$ - $10^5$) |
| The Width Across a Head of a Pin | 1,000,000 ($10^6$) |
| The Width Across the Nail of a Little Finger | 10,000,000 ($10^7$) |

**Nanotechnologies are thus defined:**

"Nanotechnologies are the design, characterization, production and application of structures, devices and systems by controlling shape and size at nanometer scale."

# Standard Definitions and Terms

<u>**Nanotechnology**</u>

**ASTM International: E 2456 – 06**

nanotechnology, *n*—A term referring to a wide range of technologies that measure, manipulate, or incorporate materials and/or features with ***at least one dimension between approximately 1 and 100 nanometers (nm).*** Such applications exploit the properties, distinct from bulk/macroscopic systems, of nanoscale components.

**British Standards Institute PAS 71: 2005**

design, characterization, production and application of structures, devices and systems by controlling shape and size at the ***nanoscale.***

***nanoscale****: having one or more dimensions of the order of 100 nm or less*

**OSHA *(Occupational Safety and Health Administration, U.S. Department of Labor)***

Nanotechnology is the understanding, manipulation, and control of matter at dimensions of roughly 1 to 100 nanometers, which is near-atomic scale, to produce new materials, devices, and structures.

## Nanoparticle

**ASTM International: E 2456 – 06**

nanoparticle**,** *n—in nanotechnology,* a sub-classification of ***ultrafine particle*** with lengths in two or three dimensions greater than 0.001 micrometer (1 nanometer) and smaller than about 0.1 micrometer (100 nanometers) and which may or may not exhibit a size-related intensive property.

***ultrafine particle****, n—in nanotechnology,* a particle ranging in size from approximately 0.1 micrometer (100 nanometers) to 0.001 micrometers (1 nanometer).

DISCUSSION—The term is most often used to describe aerosol particles such as those found in welding fumes and combustion by-products…

**British Standards Institute PAS 71: 2005**

particle with one or more dimensions at the ***nanoscale.***

**How small is a nanometer?**

1 nm = 0.000000001 m
= $10^{-9}$ m
= one billionth meter

**The nanometer scale**

The nanometer scale is conventionally defined as 1 to 100 nm. One nanometer is one billionth of a meter ($10^{-9}$ m). The size range is set normally to be minimum 1nm to avoid single atoms or very small groups of atoms being designated as nano-objects.

**Therefore nanoscience and nanotechnologies deal with at least clusters of atoms of 1nm size**.

The **upper limit** is normally 100 nm, but this is a “fluid” limit; often objects with greater dimensions (even 200nm) are defined as nanomaterials.
A valid **question** a student might ask is “why 100 nm, and not 150nm?”, or even “why not 1 to 1000nm?”

**The reason why the “1 to 100nm range”** is approximate is that the **definition itself focuses on the effect that the dimension has on a certain material – e.g., the insurgence of a quantum phenomenon – rather than at what exact dimension this effect arises**.

Nanoscience is not just the science of the small, but the **science in which materials with small dimension show new physical phenomena**, collectively called quantum effects, which are size dependent and dramatically different from the properties of macro-scale materials. m).

**Nanoscience is the study of materials that exhibit remarkable properties, functionality and phenomena due to the influence of small dimensions.**

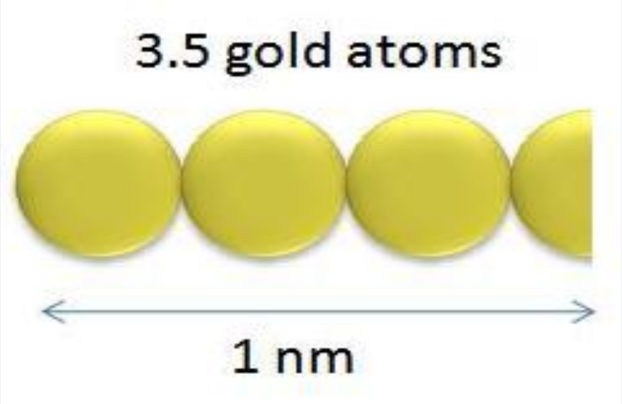
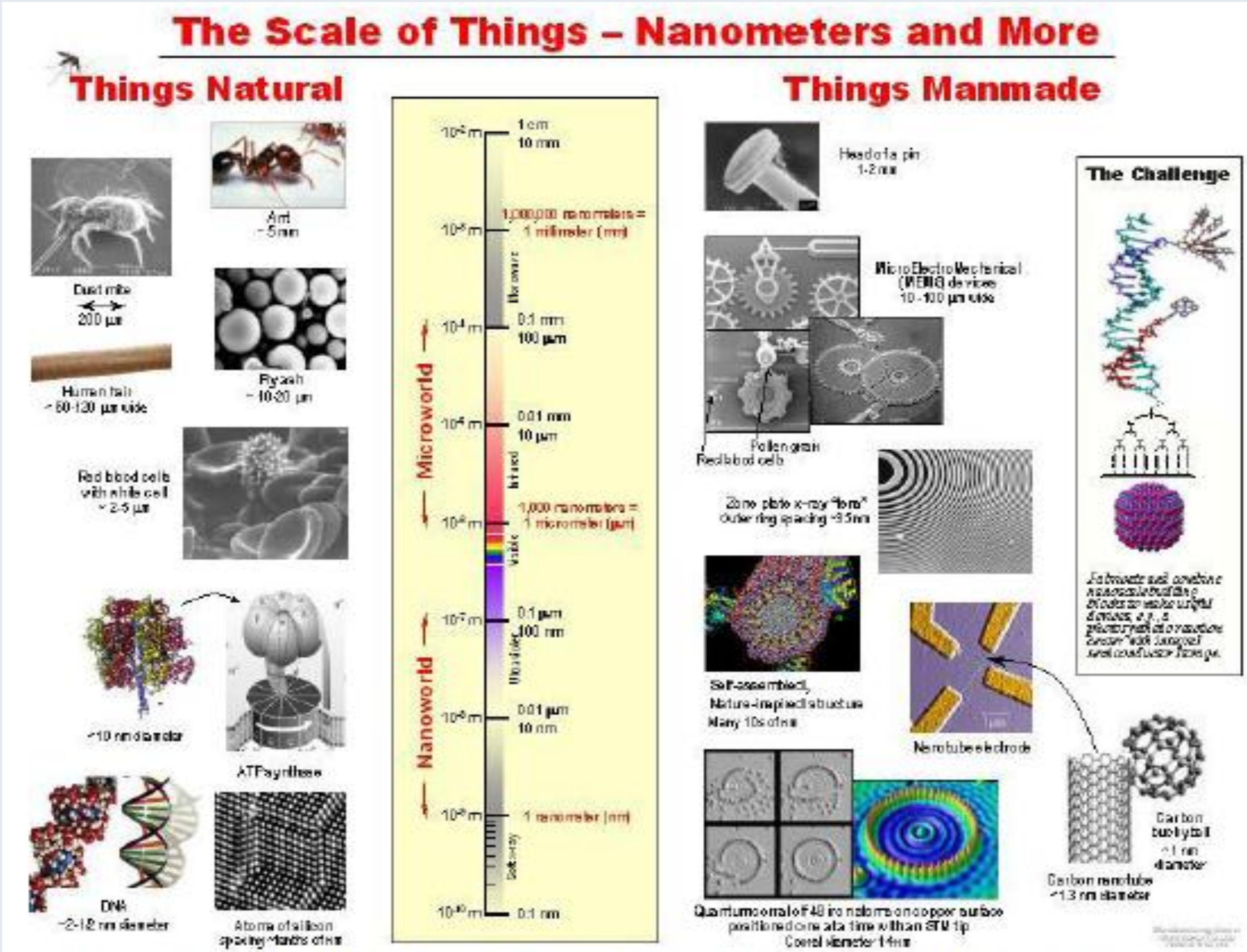



**Figure 1**. Three and a half gold atoms placed in a row equal to 1nm (assuming a ***covalent radius of 0.144 nm*** each). (L. Filipponi, iNANO, Aarhus University. Creative Commons Share Alike 3.0)


The Scale of Things – Nanometers and More
Things Natural
Things Manmade
Ant
~5 mm
Dust mite
200 μm
Human hair
~ 60-120 μm wide
Fly ash
~ 10-20 μm
Red blood cells
with white cell
~ 2-5 μm
~10 nm diameter
ATP synthase
DNA
~2-1/2 nm diameter
Atoms of silicon
1 cm
10 mm
1,000,000 nanometers =
1 millimeter (mm)
0.1 mm
100 μm
0.01 mm
10 μm
1,000 nanometers =
1 micrometer (μm)
0.1 μm
100 nm
0.01 μm
10 nm
1 nanometer (nm)
0.1 nm
Microworld
Nanoworld
Microwave
Infrared
Visible
Ultraviolet
Soft x-ray
Head of a pin
1-2 mm
MicroElectroMechanical
(MEMS) devices
10 -100 μm wide
Pollen grain
Red blood cells
Zone plate x-ray "lens"
Outer ring spacing ~35 nm
Self-assembled,
Nature-inspired structure
Many 10s of nm
Nanotube electrode
Carbon
buckyball
~1 nm
diameter
Carbon nanotube
~1.3 nm diameter
Quantum corral of 48 iron atoms on copper surface
positioned one at a time with an STM tip
Corral diameter 14 nm
The Challenge

**Remember that "nano" does not simply mean "very small".**
**There are many forms of matter much smaller than a nanometer, including electrons, atoms and most molecules.**
**The nanoscale is *in between* the very small atomic regime and the larger regime of microparticles and colloids. On the left of the diagram are naturally occurring objects of various sizes. On the right are human-designed objects of various sizes.**

# Nanomaterial

**British Standards Institute PAS 71: 2005**
material with one or more external dimensions, or an internal structure, on the ***nanoscale***, which could exhibit novel characteristics compared to the same material without ***nanoscale*** features

**OSHA *(Occupational Safety and Health Administration, U.S. Department of Labor)***

**Engineered nanoscale materials or nanomaterials** are materials that have been purposefully manufactured, synthesized, or manipulated to have a size with at least one dimension in the range of approximately 1 to 100 nanometers and that exhibit unique properties determined by their size.

**Nanomaterials** is a field that takes a **materials science**-based approach on **nanotechnology**. It studies materials with morphological features on the **nanoscale**, and especially those that have special properties stemming from their nanoscale dimensions. Nanoscale is usually defined as smaller than a one tenth of a micrometer in at least one dimension, though sometimes includes up to a micrometer.

The **European Commission** (18 October 2011) adopted the following definition of a nanomaterial:
***"A natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1 nm – 100 nm. In specific cases and where warranted by concerns for the environment, health, safety or competitiveness the number size distribution threshold of 50% may be replaced by a threshold between 1 and 50%."***

An important aspect of nanotechnology is the vastly increased **ratio** of surface area to volume present in many nanoscale materials, which makes possible new quantum mechanical effects.

One example is the “quantum size effect” where the electronic properties of solids are altered with great reductions in particle size.

Nanoparticles, for example, take advantage of their dramatically increased surface area to volume ratio.

Their optical properties, e.g. **fluorescence**, become a function of the particle diameter. This effect does not come into play by going from macro to micro dimensions. However, it becomes pronounced when the nanometer size range is reached.

**Nanomaterials** are made of many different chemicals and compounds. Once formed, these materials are extremely small which give the nano product unique properties.

There are four main classes of materials that are used to make nano sized products including ***metal, carbon, composites, and dendrimers***. These products have a variety of applications and are used in the automotive industry, biomedical industry, in films, and much more.

**Metal based nanomaterials** are those such as nanogold, quantum dots and nanosilver. Quantum dots come in several sizes with a maximum size of several hundred nanometers. The dot contains semiconductor crystals that are packed together so thousands of atoms are all in a very small area. Other metal based chemicals used at this small scale include types of metal oxides.

**Carbon based nanomaterials** are those that are mostly made of carbon. The carbon is shaped into hollow tubes, ellipsoids or spheres. Ellipsoidal and spherical carbon nanomaterials are called fullerenes. Hollow tube shaped materials are called nanotubes.

Some of the applications of carbon based products include making film stronger and lighter. They will also improve the quality and life of different coatings used on mechanical parts. These materials are also commonly used for electronic applications.

**Composites** combine nanoparticles with other nanoparticles or with larger, bulk-type materials. These composites are used for flame retardant properties, enhancing mechanical performance and acting as a barrier for packaging.
A small amount of composites, as little as two percent, can increase the strength of items by as much as 100 percent.
Creating composites can be quite simple, using ion exchange technology and heating. Reactions using polymerization are another way to create composites quickly.

A **dendrimer** is another type of nanomaterial. These are polymers that contain many branches.
They typically look like chains, and will have numerous chain ends that can be made to have specific functions normally used for chemical reactions.
Some dendrimers can be three dimensional and have an interior cavity into which other molecules can fit. Drug delivery is one use of this internal cavity found in dendrimers. These also have applications in gene therapy and medical diagnosis.

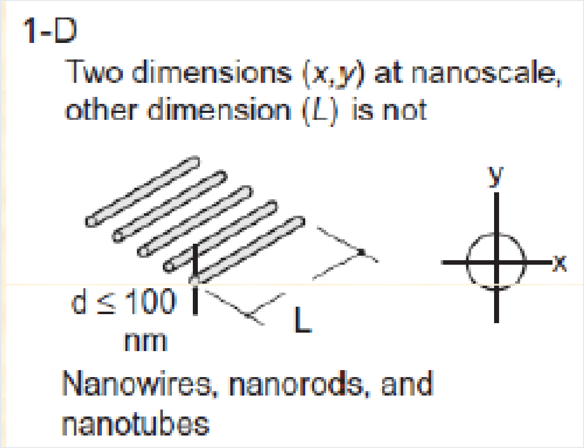
The unique properties of these various types of intentionally produced nanomaterials give them novel electrical, catalytic, magnetic, mechanical, thermal, or imaging features that are highly desirable for applications in commercial, medical, military, and environmental sectors. These materials may also find their way into more complex nanostructures and systems. As new uses for materials with these special properties are identified, the number of products containing such nanomaterials and their possible applications continues to grow.

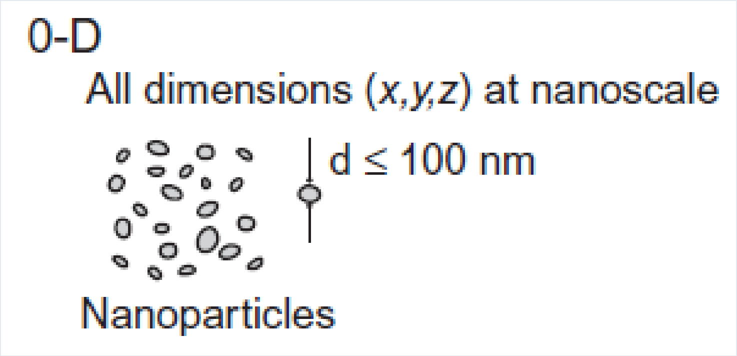
Source: United States Environmental Protection Agency

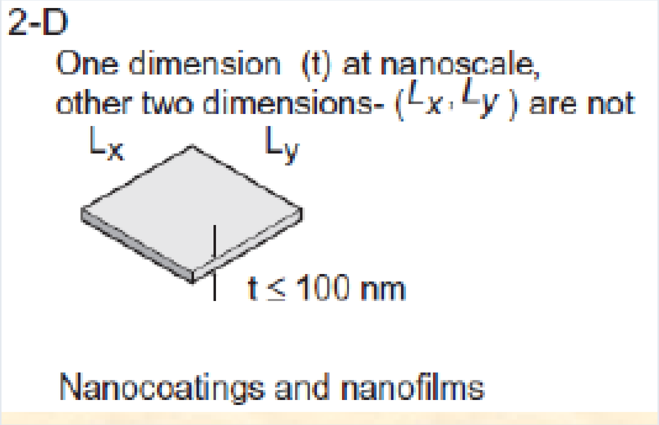
# Classification of nanomaterials

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

**(1) zero-dimensional (0-D),**
**(2) one-dimensional (1-D),**
**(3) two-dimensional (2-D), and**
**(4) three-dimensional (3-D).**



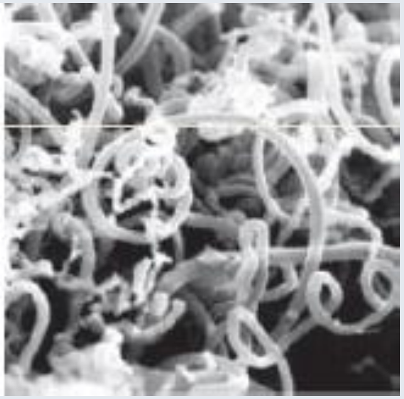
# Zero-dimensional nanomaterials

- **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.**
  - **Nanoparticles can:**
- **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.

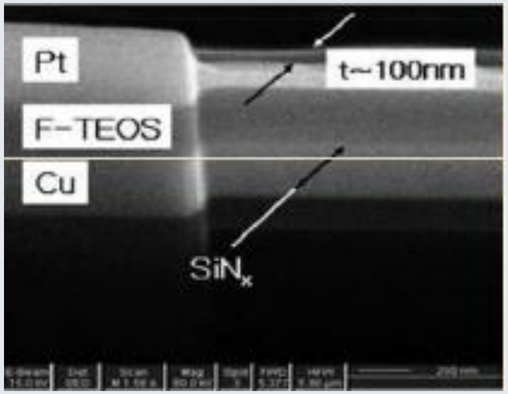
1-D nanomaterials can be



- 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**.



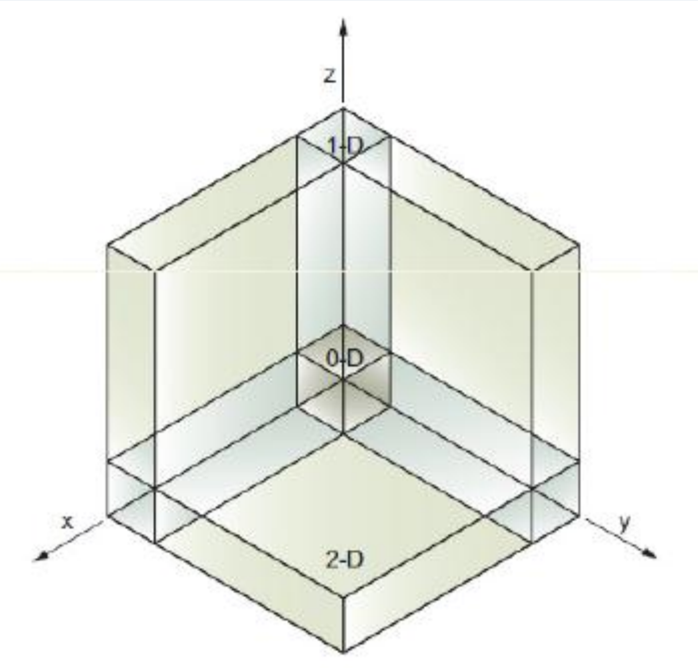

**2-D nanomaterials can be**:

- 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.

# Three-dimensional space showing the relationships among 0-D, 1-D, 2-D, and 3-D nanomaterials.



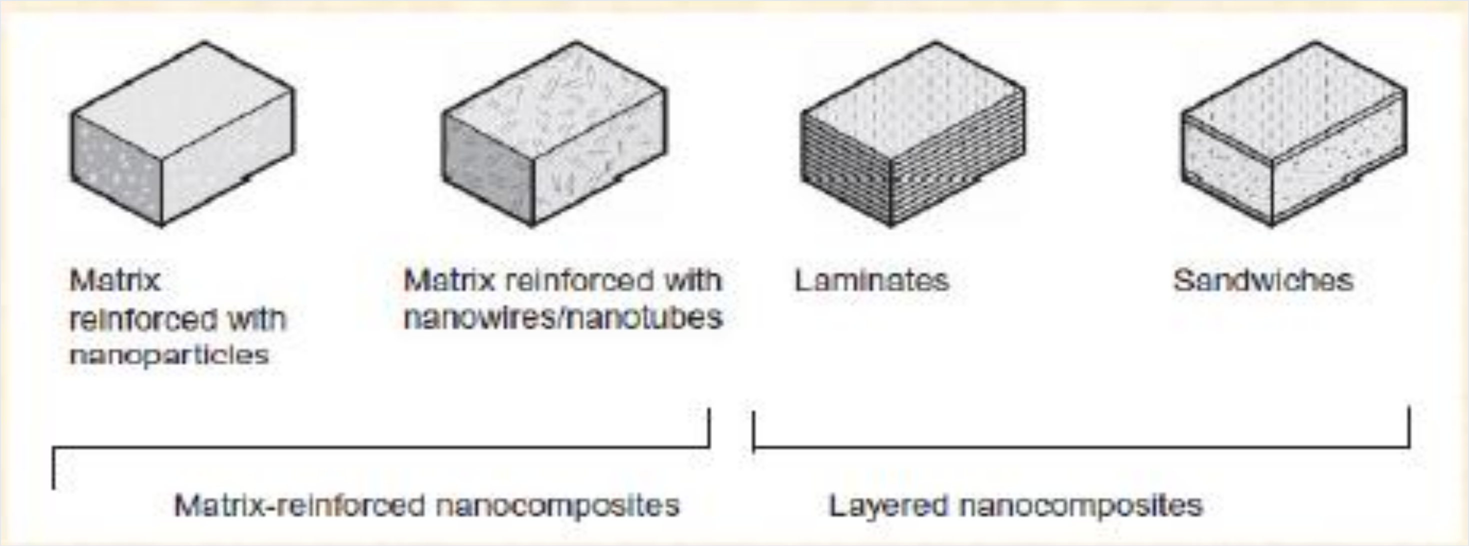

**0-D:** All dimensions at the nanoscale

**1-D:** Two dimension at the nanoscale.
One dimension at the macroscale

**2-D:** One dimension at the nanoscale.
Two dimension at the macroscale

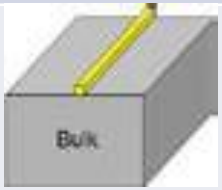
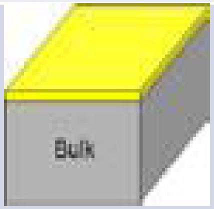
**3-D:** No dimension at the nanoscale.
All dimension at the macroscale

# Matrix-reinforced and layered nanocomposites




These materials are formed of **two or more materials** with very **distinctive properties** that act synergistically to create properties that cannot be achieved by each single material alone.

The matrix of the nanocomposite, which can be polymeric, metallic, or ceramic, has dimensions larger than the nanoscale, whereas the **reinforcing phase** is commonly at the nanoscale.

| Nanomaterial Dimension | Nanomaterial Type | Example |
|---|---|---|
| All three dimensions <100 nm | Nanoparticles, Quantum dots, nanoshells, nanorings, microcapsules |  |
| Two dimensions <100 nm | Nanotubes, fibres, Nanowires |  |
| One dimension <100 nm | Thin films, layers and coatings |  |

# Quantum Wells, wires and dots

When the size or dimension of a material is continuously reduced from a large or macroscopic size, such as a meter or a centimeter, to a very small size, the properties remain the same at first, then small changes begin to occur, until finally when the size drops below 100 nm, dramatic changes in properties can occur.

If **one dimension is reduced to the nanorange** while the other two dimensions remain large, then we obtain a structure known as a ***quantum well.***

If **two dimensions are so reduced** and one remains large, the resulting structure is referred to as a ***quantum wire*.**

The extreme case of this process of size reduction in which all **three dimensions reach the low nanometer range** is called a ***quantum dot***.

The word *quantum* is associated with these three types of nanostructures because the changes in properties arise from the quantum-mechanical nature of physics in the domain of the ultrasmall.

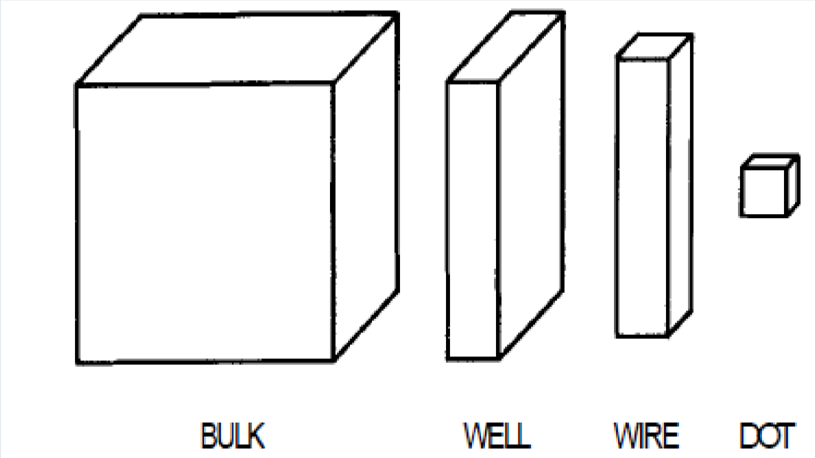


**Figure 1.** Progressive generation of rectangular nanostructures.

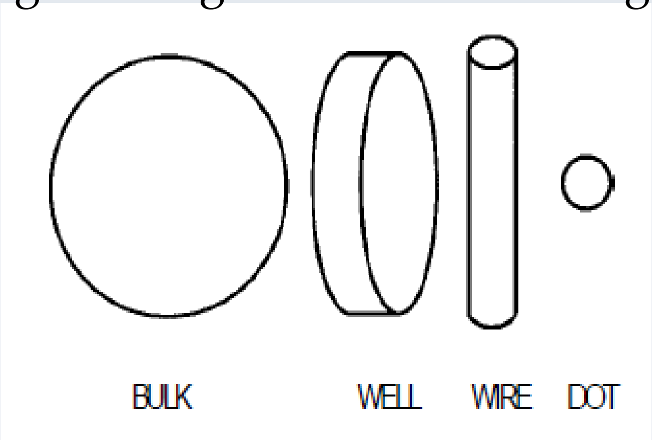



**Figure 2.** Progressive generation of curvilinear nanostructures.

# BULK NANOSTRUCTURED MATERIALS

Bulk nanostructured materials are solids having a nanosized microstructure. The basic units that make up the solids are nanoparticles. The nanoparticles can be disordered with respect to each other, where their symmetry axes are randomly oriented and their spatial positions display no symmetry. The particles can also be ordered in lattice arrays displaying symmetry.

# Nanostructured Multilayers

- ✓ Bulk nanostructure consists of periodic layers of nanometer thickness of different materials such as alternating layers of TiN and NbN.
- ✓ These layered materials are fabricated by various vapor-phase methods such as sputter deposition and chemical vapor-phase deposition. They can also be made by electrochemical deposition.
- ✓ The materials have very large interface area densities. This means that the density of atoms on the planar boundary between two layers is very high.
- ✓ For example, a square centimeter of a 1-µm-thick multilayer film having layers of 2nm thickness has an interface area of 1000 $cm^2$.
- ✓ Since the material has a density of about 6.5 $g/cm^3$, the interface area density is 154m2/g, comparable to that of typical heterogeneous catalysts.

The interfacial regions have a strong influence on the properties of these materials. These layered materials have **very high hardness**, which depends on the thickness of the layers, and **good wear resistance**.

## Metal Nanocluster Composite Glasses

- One of the oldest applications of nanotechnology is the colored stained-glass windows in medieval cathedrals which are a result of nanosized metallic particles embedded in the glass.
- Glasses containing a low concentration of dispersed nanoclusters display a variety of unusual optical properties that have application potential.
- The peak wavelength of the optical absorption, which largely determines the color, depends on the size, and on the type of metal particle.

# NANOSTRUCTURED CRYSTALS

**Crystals made of ordered arrays of nanoparticles**

# Natural Nano-crystals

There are some instances of what might be called "natural nanocrystals."

An example is the 12-atom boron cluster, which has an **<u>icosahedral structure, that is, one with 20 faces</u>**.

There are a number of crystalline phases of solid boron containing the $B_{12}$ cluster as a subunit.

One such phase with tetragonal symmetry has **<u>50 boron atoms in the unit cel</u>**l, comprising ***four $B_{12}$ icosahedral bonded to each other by an intermediary boron atom that links the clusters***.

Another phase consists of $B_{12}$ icosahedral clusters shown in Fig. 6.22 arranged in a hexagonal array.

Of course there are other analogous nanocrystals such as the fullerene $C_{60}$ compound, which forms the lattice shown in Fig. 5.7**)**

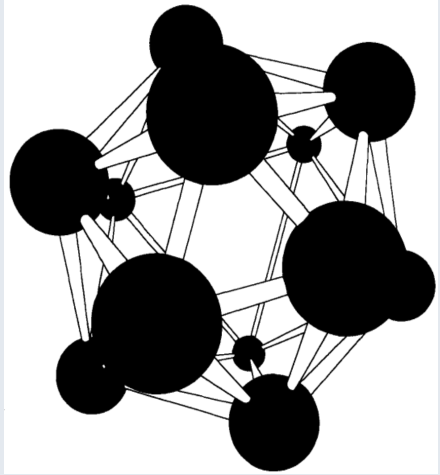


Fig. 6.22. The icosohedral structure of a boron cluster containing 12 atoms. This cluster is the basic unit of a number of boron lattices.

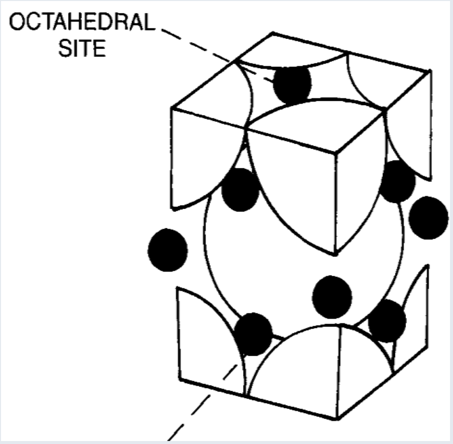



Fig. 5.7. Crystal lattice unit cell of Cso molecules (large spheres) doped with alkali atoms (dark circles)

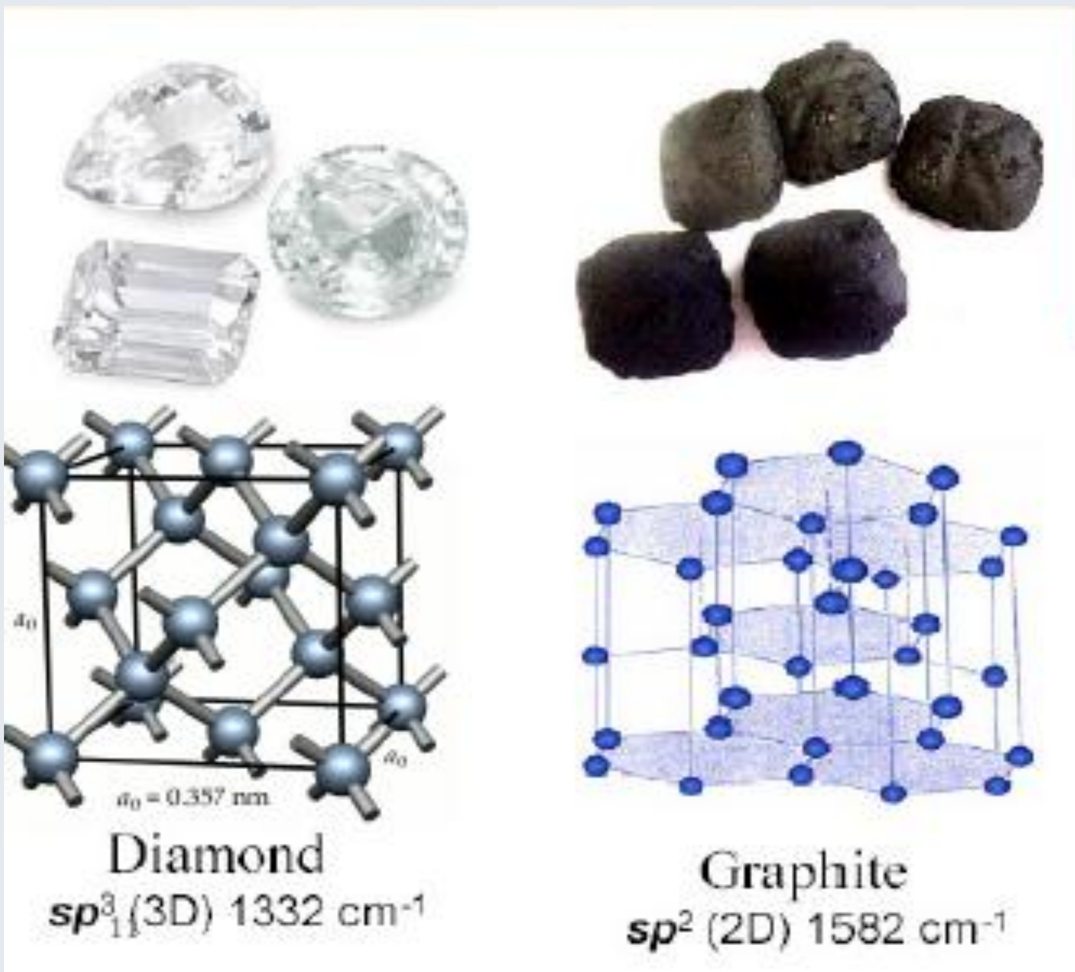
# Carbon

- 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

# Carbon materials

2s and 2p electrons available for bonding

Diamond and graphite are two allotropes of carbon: pure forms of the same element that differ in structure.




# Emergence of Nano technology:

Nanotechnology is new, but research on nanometer scale is not new at all.

- ✓ The Chinese are known to use Au nano particles as in inorganic dye to introduce red color into their ceramic porcelains more than thousand years ago.
- ✓ A comprehensive study on the preparation and properties of colloidal gold was first published in the middle of the $19^{th}$ century.
- ✓ Colloidal dispersion of gold prepared by Faraday in 1857 was stable for almost a century before being destroyed during world war-II.
- ✓ Colloidal gold is used for treatment of arthiritis.
- ✓ In 1947 Dec 23 at AT&T Bell lab, the original Cm scale transistor made by Bardeen, Brattain, and Shockley at AT&T Bell lab.

- ✓ With the evolution of semiconductor industry, there is continuous decrease in device dimensions, today's transistors have well fallen in nanometer range.
- ✓ The discovery of synthetic materials, such as carbon fullerenes, carbon nano tubes and ordered mesomorphous materials has further fuelled the research in nanotechnology and nanomaterials.
- ✓ With the invention and development of scanning tunneling microscopy in the early 1980's and subsequently SPM, AFM, TEM, it is possible to study and manipulate the nanostructures and nanomaterials to a great detail and often down to the atomic level.
- ✓ Nanotechnology is not new, it is the combination of existing technologies and our new found ability to observe and manipulate at the atomic scale, this makes NT so compelling from scientific point.

# Mile Stones in the evolution of Nanotechnology

3.5 Mrd. years: First cells with nano machines.

- **400 B.C**: Demokrit: Reasoning about atoms and matter.
- **1905:** Albert Einstein: Calculated molecular diameter.
- **1931:** Max knoll & Ernst Ruska: Electron microscope
- **1959:** Richard Feynman: There is plenty of room at the bottom.
- **1968:** Alfred Y.Cho & JohnArthur (Bell Labs): MBE (atomic layer growth).
- **1974:** Norio Taniguchi: Nanotechnology for fabrication methods below 1μm.
- **1981:** Gerd Binnig& Heinrich Rohrer: Noble prize for inventing STM.
- **1985:** Robert F.Carl, Harald W.Kroto: Richard smalley: Bucky balls.
- **1986:** K. Eric Drexler: writing with a STM tool.
- **1991:** Sumio Ligima: Carbon Nanotubes.
- **1993:** Warren robinett, R.Stanley Williams: Combination of SEM and VR (virtual reality system).
- **1998:** Cees Dekkar et all: Carbon nanotube transistor.
- **1999:** James M.Tour& Mark.A.Read: Single molecule switch.
- **2000:** Eigler et all: Construction of quantum mirrors.
- **2001:** Florian Bambers: Soldering of nanotube with e-beam.
- **2004:** Intel launches the Pentium IV ‘PRESCOFT’ processor based on 90 nm technology.

**Moore's Laws:**

- Gordon Moore, one of the founders of the Intel corporation, came up with two empirical laws to describe the amazing advances in integrated circuit electronics.
- Moore's first law (usually referred to simply Moore's law) says that the amount of space required to install a transistor on a chip shrinks by roughly half every 18 months. This means that the spot that could hold one transistor 15 years ago can hold 1000 transistors today. Moore's first law is good news.
- The bad news is Moore's second law. It is really a corollary to the first, which gloomily predicts that the cost of building a chip manufacturing plant (also called a fabrication line or just fab) doubles with every other chip generation, or roughly every 36 months. The following figure shows Moore's laws in a graphical way.

## Challenges in Nano technology

Although many of the fundamentals have long been established in different fields such as in physics, chemistry, materials science and device science and technology, and research on nanotechnology is based on these established fundamentals and technologies, researchers in the field face many new challenges that are unique to nanostructures and nanomaterials.

- *Challenges in nanotechnology include the* ***integration of nano structures and nano materials into or with macroscopic systems that can interface with people.***
- Challenges include the ***building and demonstration of novel tools to study at the nanometer level what is being manifested at the macro level****.*
- The **small size and complexity of nanoscale structures** make the development of new measurement technologies more challenging than ever. *New measurement techniques need to be developed at the nanometer scale and may* ***require new innovations in metrological technology****.*
- **Measurements of physical properties** of nanomaterials require extremely sensitive instrumentation, while the noise level must be kept very low. Although material properties such as electrical conductivity, dielectric constant, tensile strength, are independent of dimensions and weight of the material in question, in practice, system properties are measured experimentally.

**For example**, electrical conductance, capacitance and tensile stress are measured and used to calculate electrical conductivity, dielectric constant and tensile strength.

As the dimensions of materials shrink from centimeter or millimeter scale to nanometer scale, the system properties would change accordingly, and mostly decrease with the reducing dimensions of the sample materials. Such a decrease can easily be as much as 6 orders of magnitude as sample size reduces from centimeter to nanometer scale.

Other challenges arise in the nanometer scale, but are not found in the macro level. For example, **doping in semiconductors** has been a very well established process. However, **random doping fluctuations become extremely important at nanometer scale**, since the fluctuation of doping concentration would be no longer tolerable in the nanometer scale. With a typical doping concentration of $10^{18}/ cm^3$, there will be just one dopant atom in a device of $10x10x10nm^3$ in size. Any distribution fluctuation of dopants will result in a totally different functionality of device in such a size range.

One more challenge faced by researchers is "*all the mathematical models available for macro materials are not applicable to nanoscale materials. They must be developed to predict the behaviour of nano materials.*"

**For the fabrication and processing of nanomaterials and nanostructures, the following challenges must be met**:

1. Overcome the huge surface energy, a result of enormous surface area or large surface area to volume ratio.
2. Ensure all nanomaterials with desired size, uniform size distribution, morphology, crystallinity, chemical composition, and microstructure,that altogether result in desired physical properties.
3. Prevent nanomaterials and nanostructures from coarsening through either Ostwald ripening or agglomeration as time evolutes.

# Some present and future applications of nanomaterials

**In electronics & optoelectronics:**

- ‘nanophosphors’ for affordable high-definition television and flat panel displays.
- Electroluminescent nanocrystalline silicon, opening the way for optoelectronic chips and possibly new type of color displays.
- efficient light-emitting diodes based on quantum dots with a voltage-controlled, tunable output color.
- powder or plastic layers using nanoparticles as an active scattering medium.
- optical switches and fibers based on nonlinear behavior.
- transparent conducting layers.
- three-dimensional optical memories.

**Electronics**

- materials for the next-generation computer chips.
- single-electron tunneling transistors using nanoparticles as quantum dots.
- efficient electrical contacts for semiconductor devices.
- electrically conducting nanoceramics.
- capacitive materials for, e.g., dynamic random access memories (DRAM).

**Magnetic Applications**

- magnetic memories based on materials with a high coercivity.
- magnetorestrictive materials, important for shielding components and devices.
- soft magnetic alloys such as Finemet resistors and varistors (voltage-dependent resistors).
- high-temperature superconductors using nanoparticles for flux pinning.

**In optics**

- Graded refractive index (GRIN) optics: special plastic lenses.
- Anti-fogging coating for spectacles and car windows.
- Inexpensive colored glasses and optical filters.

**In energy storage:**

- Novel solar cells, such as the Gratzel cell based on TiO2 materials.
- Window layers in classical solar cells utilizing the increased band gap due.
- High energy density (rechargeable) batteries.
- Smart windows based on the photochrome effect or electrical magnetic orientation effects.
- Better thermal or electrical insulation materials, again using the higher gap.
- Nanocrystalline hydrogen storage materials.
- Magnetic refrigerators from superparamagnetic materials.

**Gas sensing devices:**

- Gas sensors for Nox, Sox, CO, $CO_2$, $CH_4$ and aromatic hydrocarbons.
- UV sensors and robust optical sensors based on nanostructured silicon carbide (SiC).
- Smoke detectors.
- Ice detectors.
- Ice detectors on aircraft wings.

**Protection coatings:**

- Cost-effective corrosion protection materials.
- Elimination of pollutants in catalytic converters utilizing the large surface area of nanomaterials.
- Scratch-resistance top-coat using hybrid nanocomposite materials.

**Medical applications:**

- longer-lasting medical implants of biocompatible nanostructured ceramic and carbides.
- bio-compatible coating for medical applications.
- magnetic nanoparticles for hyperthermia.
- controlled drug release and drug delivery.

**Catalysis:**

- photocatalyst air and water purifiers.
- better activity, selectivity and lifetime in chemical transformations and fuel cells.
- precursors for a new type of catalyst (Cortex-catalysts).
- stereoselective catalysis using chiral modifiers on the surface of metal nanoparticles.

# Fundamental issues in nanomaterials

**The fundamental issues in this domain of nanomaterials are:**

1. ability to control the scale (size) of the system,
2. ability to obtain the required composition-not just the average composition –but details such as defects, concentration gradients, etc.,
3. ability to control the modulation dimensionality,
4. during the assembly of the nano-sized building blocks, one should be able to control the extent of the interaction between the building blocks as well as the Architecture of the material itself.

**More specifically the following issues have to be considered for the future development of nanomaterials:**

- Development of synthesis and/or fabrication methods for raw materials (powders) as well as for the nanostructured materials.
- Better understanding of the influence of the size of building blocks in nano structured materials as well as the influence of microstructure on the physical, chemical and mechanical properties of this material.
- Better understanding of the influence of interfaces on the properties of nanostructured material.
- Development of concepts for nanostructured materials and in particular their elaboration.
- Investigation of catalytic applications of mono- and plurimetallic nanomaterials
- Transfer of developed technologies into industrial applications including the development of the industrial scale of synthesis methods of nanomaterials and nanostructured systems.

## Causes of interest in nanomaterials

**These materials have created a high interest in recent years by virtue of their unusual mechanical, electrical, optical and magnetic properties.**

- ***Nanophase ceramics*** are of particular interest because they are more ductile at elevated temperatures as compared to the coarse-grained ceramics.
- ***Nanostructured semiconductors*** are known to show various non-linear optical properties. Semiconductor Q-particles also show quantum confinement effects which may lead to special properties, like the luminescence in silicon powders and silicon germanium quantum dots as infrared optoelectronic devices.
  - Nanostructured ***semiconductors*** are used as window layers in solar cells.

- **Nanosized *metallic powders*** have been used for the production of gas tight materials, dense parts and porous coatings. Cold welding properties combined with the ductility make them suitable for metal-metal bonding especially in the electronic industry.

- **Single nanosized *magnetic particles*** are mono-domains and one expects that also in magnetic nanophase materials the grains correspond with domains, while boundaries on the contrary to disordered walls. Very small particles have special atomic structures with discrete electronic states, which give rise to special properties in addition to the super-paramagnetism behaviour. Magnetic nanocomposites have been used for mechanical force transfer (ferrofluids), for high density information storage and magnetic refrigeration.

- **Nanostructured *metal clusters and colloids* of mono- or plurimetallic composition**
  - Have a special impact in catalytic applications. They may serve as precursors for new type of heterogeneous catalysts (Cortex-catalysts) and have been shown to offer substantial advantages concerning activity, selectivity and lifetime in chemical transformations and electrocatalysis (fuel cells). Enantioselective catalysis were also achieved using chiral modifiers on the surface of nanoscale metal particles.

- **Nanostructured *metal-oxide thin films*** are receiving a growing attention for the realisation of gas sensors (NO**x**, CO, $CO_2$, $CH_4$ and aromatic hydrocarbons) with enhanced sensitivity and selectivity. Nanostructured metal-oxide (MnO**2**) finds application for rechargeable batteries for cars or consumer goods. Nanoc*rystalline silicon films* for highly transparent contacts in thin film solar cell and *nano-structured titanium oxide porous films* for its high transmission and significant surface area enhancement leading to strong absorption in dye sensitized solar cells.
- ***Polymer based composites*** with a high content of inorganic particles leading to a high dielectric constant are interesting materials for photonic band gap structure produced by the LIGA.

# Role of Bottom-up and Top-Down approaches in Nano technology:

- There are ***two*** approaches for synthesis of nano materials and the fabrication of nano structures.
  - ***Top down approach*** refers to slicing or successive cutting of a bulk material to get nano sized particle.
  - ***Bottom up approach*** refers to the build up of a material from the bottom: atom by atom, molecule by molecule or cluster by cluster.
- Both approaches play very important role in modern industry and most likely in nano technology as well. There are advantages and disadvantages in both approaches.
- **Attrition or Milling is a typical top down method** in making nano particles, where as the **colloidal dispersion is a good example of bottom up approach** in the synthesis of nano particles.

- The **biggest problem with top down approach** is the **imperfection of surface structure and significant crystallographic damage to the processed pattern**s. These imperfections which in turn leads to extra challenges in the device design and fabrication. But this approach leads to the bulk production of nano material.
    - Regardless of the defects produced by top down approach, they will continue to play an important role in the synthesis of nano structures.
- Though the **bottom up approach** oftenly referred in nanotechnology, it is ***not a newer concept***. ***All the living beings in nature observe growth by this approach*** only and also it has been in industrial use for over a century.
    - For example, the production of salt and nitrate in chemical industry.

- Although the **bottom up approach** is nothing new, it plays an important role in the fabrication and processing of nano structures. There are several reasons for this and explained as below.
  - When structures fall into a nanometer scale, there is a little chance for top down approach. All the tools we have possessed are too big to deal with such tiny subjects. Bottom up approach also promises a ***better chance to obtain nano structures with less defects, more homogeneous chemical composition***.

- On the contrary, **top down approach** most likely ***introduces internal stress, in addition to surface defects and contaminations***.

# Characteristics of Nano particles that should possess by any fabrication technique

Getting merely a small size is not the only requirement. It should have

1. **Identical size** of all particles (also called mono sized or with uniform size distribution.
2. **Identical shape or morpholo**gy.
3. **Identical chemical composition and crystal structure** that are desired among different particles and within individual particles, such as core and composition must be the same.
4. **Individually dispersed or mono dispersed** i.e., no agglomeration.