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 nano-scale 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 ($1\text{nm} = 10^{-9}\text{meter}$), 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**

**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 the 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 1m³ volume (Fig.), it has surface area of 6m². If this cube of same volume is divided into eight small cubes, then the total surface area increases to 12m². 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

**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).


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
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.
<table>
<thead>
<tr>
<th>Property</th>
<th>Influence of size reduction on properties of nanoparticle</th>
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<tbody>
<tr>
<td>Structural</td>
<td>Decrease or increase of lattice parameter</td>
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<td>Structure transformations</td>
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<td>Mechanical</td>
<td>Enhancement of hardness, strength, fracture ductility</td>
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<td>Arise of superplasticity</td>
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<td>Raising of wear resistance</td>
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<td>Thermal</td>
<td>Decrease of melting point</td>
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<td>Decrease of phase transition temperatures</td>
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<td>Decrease of melting entropy</td>
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<td>Softening of phonon spectra</td>
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<td>Thermo-dynamical</td>
<td>Increase of heat capacity</td>
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<td>Increase of thermal expansion</td>
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<td>Decrease of Debye temperature</td>
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<td>Stabilization of high temperature phases</td>
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<td>Kinetic</td>
<td>Increase of diffusion coefficient</td>
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<td>Sharp drop of thermal conductance under some critical size d*</td>
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<td>Oscillation of kinetic coefficients</td>
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<td>Electrical</td>
<td>Increase of conductivity for nanometals</td>
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<td>Arise of conductivity for nanodielectrics</td>
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<td>Increase of dielectric inductivity for ferroelectrics at d*</td>
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<tr>
<td>Electronic</td>
<td>Increase of band gap</td>
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<td>Arise of phonon generation</td>
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<td>Raising of conductivity under low temperatures in semimetallic Bi</td>
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<td>Magnetic</td>
<td>Increase or decrease of coercive force at d*</td>
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<td>Decrease of Curie temperature</td>
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<td>Rise of paramagnetism in ferromagnetics at some d*</td>
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<td>Rise of gant magnetoresistance</td>
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<td>Rise of maximal temperature of magnetoresistance</td>
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<td>Increase of magnetic permeability in ferromagnetics at d*</td>
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<tr>
<td>Optical</td>
<td>Diffraction and interference</td>
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<td>Increase of absorption in ultraviolet range (blue shift)</td>
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<td></td>
<td>Oscillation of optical absorption</td>
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<td>Arise of nonlinear optical properties</td>
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<td>Chemical</td>
<td>Increase of catalytic activity</td>
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<td>Increase of velocity of physico-chemical interactions</td>
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<td>Swap of solubility</td>
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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 $\Delta a$ 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

$$\frac{\Delta a}{a} = \frac{200 \cdot 10^9 Pa}{10^{11} Pa} = 2 \cdot 10^{-3}$$

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:

$$\tau_p = \tau_0 + \frac{K_1}{\sqrt{d}}$$

where $\tau_0$ deformation strength of monocrystal is, $\tau_p$ is a strength of polycrystal, $K1$ is a coefficient of fracture ductility. The dependence is shown in fig. and successfully used in the industry. However in extreme case $d \rightarrow 0$ this relation do not works. The critical size $d = d^*$ exists when $\tau$ 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 \( d < \lambda_{\text{spin}} \), causes a decrease of the number of atomic magnetic moments, their correlation energy is decreased and at some critical value \( d^* \sim 10 \text{ nm} \) 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 \( E_n \).
In accordance with Pauli principle two or more electrons cannot occupy the same place or take the same energy. Therefore the energy levels are spliten to some small value \( \Delta n \), forming an energetic band, a width of which is proportional to a number of the levels or atoms \( N \), \( \Delta E^E = \sum \Delta n = N \Delta n \). It means that the band gap increases simultaneously when reducing the size of particle, hence \( \Delta E^\text{nano} > \Delta E^\text{bulk} \). 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 \( \omega^* > \omega^0 \), that in physical sense is just the blue shift.
6. Write a short note on challenges and future prospects of nanomaterials?

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

1. Providing Renewable Clean Energy
Balancing humanity’s energy demands while protecting the environment is a major challenge. Nanotechnology will help to solve the dilemma of energy needs and limited planetary resources through more efficient generation, storage and distribution.

Challenge and Problem
Balancing humankind’s need for energy with the environmental cost to our planet is a major challenge. Demand for energy is forecasted as increasing 50% by the year 2025 with most of these being fossil fuels. Currently over 1.6 billion humans have no access to electricity and 2.4 billion rely on plant material, vegetation, or agricultural waste as an energy and heating source. Our fossil fuel consumption is escalating and could double. Meanwhile, Earth’s glaciers are receding, the CO₂ concentrations in the atmosphere have nearly doubled, and world temperatures, recorded since 1861, were the hottest in three of the past five years. 1998 was the warmest of record, 2001 came in the second warmest and 2004 was the fourth warmest.

Nanotechnology Solutions
Nanotechnology will help fill our need for energy solutions through more efficient lighting, fuel cells, hydrogen storage, solar cells, locally distributed power generation, and decentralized generation and storage by reinventing the power grid

2. Supplying Clean Water Globally
The demand for fresh water is increasing. Considering the current rate of consumption and projected population growth, some two-thirds of the world will be affected by drought by the year 2050. Nanotechnology can help solve this problem through improved water purification and filtration.

Challenge and Problem
Water is one of the Earth's most precious natural resources. Most of it is saltwater. Fresh usable water is only 3% of the world’s supply and two-thirds of that is frozen in glaciers, ice caps and icebergs. The remaining 1% is available for human consumption.
Today 1.1 billion people don’t have access to safe water and 2.4 billion lack sanitation facilities. 80% of developing world diseases are water-borne with an estimate of 3.4 million deaths, mostly children, in 1998 of water-related diseases.
Demand for fresh water is increasing. Agriculture currently uses 70% of the world’s water supply. To feed 2 billion more by the year 2030 there will be a 60% increase in demand on the water supply. Considering the current rates of consumption, population and development, some two-thirds of the world population will be affected by droughts by the year 2050.

Nanotechnology Solutions
Nanotechnology will provide part of the solution for this challenge through inexpensive decentralized water purification, detection on the molecular level of contaminants, and greatly improved filtration systems.

3. Improving Health and Longevity
Humans are living longer lives, yet infectious diseases and cancer continue to kill millions annually. Because of an aging population there could be a 50% increase of new cancer cases by the year 2020. Nanotechnology will enhance the quality of life for human beings through medical diagnostics, drug delivery and customized therapy.

Challenge and Problem
Humans are living longer lives. At the turn of the century, men and women expected to live to 48 and 51 years respectively. That life expectancy is now 74 and 80 years and could be significantly longer with anti-aging advancements currently being researched.

At the same time, 30 new highly infectious diseases have been discovered in the last 20 years. These diseases account for 30% of the deaths worldwide and include HIV/AIDS, Ebola and the Avian Flu. HIV/AIDS, the most critical threat, has killed 22 million and infected 42 million. In 2003 roughly 5 million people became infected worldwide. AIDS according to a United Nations study is increasingly becoming global as it spreads rapidly to Eastern Europe and Asia.

Cancer kills over 500,000 people and 1.5 million are diagnosed annually in the United States. According to the World Cancer Report, there could be a 50% increase to 15 million new cases in the year 2020 primarily attributed to an aging population worldwide.

Nanotechnology Solutions
Recent nanotechnology research is making tremendous progress in the medical field. Some of the nanotechnology applications in the arena will be inexpensive and rapid diagnostics, new methods of drug delivery, and faster development of new drugs. Some longer term and even more powerful nanotechnology solutions will repair DNA and cellular damage and customize drug therapy.

In the Expert Opinion essays below, longer-term applications of advanced nanotechnology to health and longevity are explored.

4. Healing and Preserving the Environment
As a set of fundamental technologies that cuts across all industries, nanotech can benefit the environment in a wide variety of ways. Stronger, lighter-weight materials in transportation can reduce fuel use, nano-structured fibers reduce staining and therefore laundering, and low-cost nanosensors will make pollution monitoring affordable. In the longer term, manufacturing processes using productive nanosystems should be able to build our products with little if any waste.

Challenge and Problem
There is an ever-increasing demand for natural resources and living space for humans, while toxics continue to build up in our water and soil. Biodiversity is being destroyed worldwide with 7 million hectares of forest being lost annually. Half of our world’s forests and a quarter of our coral reefs are gone.

Biodiversity decreases each year, with increasing threats especially to the oceans. Damage to the atmosphere’s ozone layer has slowed but a hole still remains. Many believe that man-made greenhouse gases are causing disruption to the planet’s climate, a process popularly termed ‘global warming.’ Proposals to correct this are expensive and unlikely to be followed by developing nations who see economic advance as more urgent.

Nanotechnology Solutions
Nanotechnology will provide solutions through precision pollution monitoring using nanosensors, lower energy needs due to lightweight strong materials, and reducing the use of harsh cleansers through the applications of nanocoatings to surfaces. A more advanced nanotechnology solution will be building our products with molecular-level precision through the use of productive nanosystems, resulting in virtually no chemical waste.  

Through May of 2006, Challenge 4 was "Maximizing Productivity of Agriculture"

Pressure on the world's food sources is ever increasing while harvests have fallen short in recent years. It is anticipated that our world population will swell to 8.9 billion by the year 2050 putting even greater demands on agriculture. Precision farming, targeted pest management and the creation of high yield crops are a few nanotech solutions.  

5. Making Information Technology Available To All

Humanity will need to cooperate as we respond to disasters and critical threats to our survival. A "planetary nervous system" fostering rapid communication and cross-cultural relationships is needed. Nanotechnology applications in electronics will increase access through reduced cost and higher performance of memory, networks, processors and components.  

Challenge and Problem

In 2005 an estimated 13.9% of the world’s population has Internet access with the greatest saturation in North America and the least in Africa. The recent tsunami disaster illustrates how rapidly the world can be informed about and respond to crises. A "planetary nervous system" would enable humanity to work collectively to make a better world for all of us. There are currently many who lack widespread access to communications, information, services and resources. This lack of access creates insurmountable barriers to education, democratization, and economic growth.  

Nanotechnology Solutions

Electronics is an area where nanotechnology is making great gains. The use of nanotechnology applications will drastically reduce the cost and increase the performance of memory, displays, processors, solar powered components, and embedded intelligence systems. It will also enable networks to be self-configuring. These improvements would create a pervasive computing environment that would promote greater global communication, cross-cultural understanding and cooperation.  

6. Enabling Space Development

Heavy demands on resources and raw materials are creating challenges on earth, whereas these items are plentiful in space. Current obstacles to developing space are cost, reliability, safety, and performance. Nanotechnology will solve these through improved fuels, smart materials, uniforms and environments.  

Challenge and Problem

The earthly challenges facing humanity are the result of our heavy demand on resources and raw materials. Many of these materials can be found in space but the expense to extract them is a major barrier. In addition to cost, other obstacles to developing space are safety, reliability, and performance. According to the National Space Society there are four reasons why we need to pursue space exploration and colonization. These reasons—survival, growth, prosperity and curiosity—all point to the fact that we, as a species, want more room. Space exploration will give us a means to monitor the health of our planet, a source of resources and an outlet for our imagination.  

Nanotechnology Solutions
Nanotechnology will create the ability for humans to operate in space more safely. Applications where nanotechnology will impact space exploration are propulsion fuels, coatings, structural materials, smart uniforms, and electronics and life support environments. These will be more efficient, stronger, self-healing and lighter than what is currently available.

**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.