Why Nanoscience and Nanotechnology? What is there for us?

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Abstract

Nanotechnology is about to affect almost every field of human life. It is an enabling technology that will impact electronics and computing, medicine, materials and manufacturing, catalysis, energy and transportation. It will revolutionize future world by changing the current using materials in durability and reactivity. We have great opportunities to make things smaller in size, lighter in weight and stronger. Therefore scientists and engineers have great interest in this emerging field. From the present activities going on in the world particular by no. of conferences, seminars and the money injected in this field we can say that this rapidly expanding field is going to bring about an innovative transformation in upcoming years.

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Introduction to Nanoscience

Nanoscience is an emerging area of science which concerns itself with the study of materials that have very small dimensions, in the range of nano scale. The word itself is a combination of nano, from the Greek “nanos” (or Latin “nanus”), meaning “Dwarf”, and the word "Science” meaning knowledge [1]. It is an interdisciplinary field that seeks to bring about mature nanotechnology, focusing on the nano scale intersection of fields such as physics, biology, engineering, chemistry, computer science and more.

Nanoscience is the study of phenomena on a nanometer scale. Atoms are a few tenths of a nanometer in diameter and molecules are typically a few nanometers in size. Nanometer is a magical point on the length scale, for this is the point where the smallest man-made devices meet the atoms and molecules of the natural world. Typically nano means $10^{-9}$. So, a nanometer is one billionth of a meter and is the unit of length that is generally most appropriate for describing the size of single molecule. Nanometer objects are too small to be seen with naked eye. Infect, if one wanted to see a 10 nm sized marble in his hand, his eye would have to be smaller than a human hair. Anyhow the rough definition of Nanoscience could be anything which has at least one dimension less than 100 nanometer. How big a nanometer is, the idea has been elaborated in Fig.1 [2].

Classification of Nanomaterials

Nanomaterials can be classified dimension wise into following categories.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 dimension &lt; 100nm</td>
<td>nanorods, nanowires etc.</td>
</tr>
<tr>
<td>2 dimensions &lt; 100nm</td>
<td>Tubes, fibers, platelets, etc.</td>
</tr>
<tr>
<td>Zero or 3 dimensions &lt; 100nm</td>
<td>Particles, quantum dots, hollow Spheres, etc.</td>
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On the basis of phase composition, nanomaterials in different phases can be classified as,

Single phase solids include crystalline, amorphous particles and layers, etc.
Multi phase solids include matrix composites, coated particles, etc.
Multi phase systems include colloids, aero gels, Ferro fluids, etc.
Nanoscience and Physics

Physics is the mother of natural sciences. In principle, physics can be used to explain everything that goes on at the nano scale. There is active physics research going on in nanomechanics, quantum computation, quantum teleportation, artificial atoms etc. At nanometer scale physics is different. Properties not seen on a macroscopic scale now become important - such as quantum mechanical and thermodynamic properties. Rather than working with bulk materials, one works with individual atoms and molecules. By learning about an individual molecule’s properties, we can put them together in very well-defined ways to produce new materials with new and amazing characteristics.

Some Physical Properties of Nanomaterials

Materials reduced to nano scale can suddenly show very different properties compared to what they exhibit on a macro scale, enabling unique applications.

For instance:

Copper which is an opaque substance become transparent.
Platinum which is an inert material become catalyst.
Aluminum which is a stable material turns combustible.
Silicon insulators become conductors.

Gold which is solid, inert and yellow on room temperature at micro scale becomes liquid and red in color at nano scale on room temperature. It also gets unusual catalytic properties not seen at macro scale. Figure2 [3] shows dependence of melting point on the particle size.
Nanotechnology

The nanoworld provides scientists with a rich set of materials useful for probing the fundamental nature of matter. These materials have unique structures and tunable properties. This makes them valuable for many different real world applications.

Nanotechnology is currently in a very infantile stage. It is basically the creation of Useful/Functional materials, devices and systems through control of matter on the nanometer length scale and exploitation of novel phenomena and properties (physical, chemical, biological) at that length scale.

History

The first mention of nanotechnology (not yet using that name) was in a talk given by Richard Feynman in 1959, entitled there’s plenty of Room at the Bottom. Feynman suggested a means to develop the ability to manipulate atoms and molecules directly, by developing a set of one-tenth-scale machine tools analogous to those found in any machine shop. These small tools would be used to develop and operate a next generation of one-hundredth-scale machine tools, and so forth. As the sizes get smaller, it would be necessary to redesign some tools because the relative strength of various forces would change. Gravity would become less important, surface tension would become more important, van der Waals attraction would become important, etc. Feynman mentioned these scaling issues during his talk. The feasibility of his proposal has never been effectively refuted.

Manufacturing Approaches

There are mainly two major approaches to get nanomaterials. One is the bottom up and the other is top down approach.

Fig. 2: Dependence of melting point of gold on particles size.
Bottom up manufacturing would provide components made of single molecules, which are held together by covalent forces that are far stronger than the forces that hold together macro-scale components. Furthermore, the amount of information that could be stored in devices built from the bottom up would be enormous. For example, use of AFM, liquid phase techniques based on inverse micelles, sol-gel processing, chemical vapor deposition (CVD), laser pyrolysis and molecular self assembly use bottom up approach for nano scale material manufacturing.

Top down method for manufacturing involves the construction of parts through methods such as cutting, carving and molding. Using these methods, we have been able to fabricate a remarkable variety of machinery and electronics devices. However, the sizes at which we can make these devices are severely limited by our ability to cut, carve and mold. Milling, Nano-lithography, hydrothermal technique (for some materials), laser ablation, physical vapor deposition, electrochemical method (electroplating) uses top down approach for nano-scale material manufacturing.

Nano science can use every element of periodic table depending upon the target material which someone is going to fabricate. The range of nano materials starts from nano medicine and goes up to nano concrete via nano electronics. Nanotechnology provides us the opportunity to synthesize nano scale building blocks with control on size, composition etc. Further assembling into larger structures with designed properties will revolutionize materials manufacturing. Metals, polymers, ceramics etc can be manufactured at exact shape without machining.

Chemical catalysis benefits especially from nanoparticles, due to the extremely large surface to volume ratio. The application potential of nanoparticles in catalysis ranges from fuel cell to catalytic converters and photocatalytic devices. Catalysis is also important for the production of chemicals. Catalysis represents a major success story, both in the use of oxide-supported, highly dispersed metal (nanoscale active sites) catalysts and in the use of crystalline materials (zeolites) as highly selective catalysts. The availability of unlimited commercial quantities of zeolites has led to a modern revolution in catalysis [4].

**Applications of Nanotechnology**

The potential applications of nanotechnology in different fields are the following:

I. Electronics  
II. Health and Medicine  
III. Transportation  
IV. Energy and Environment  
V. Space exploration

**Nanotechnology in Electronics**

Nanotechnology has already reached the electronics industry with features in microprocessors now less than 100 nanometres (nm) in size. Smaller sizes allow faster processing times and also more processing power to be packed into a given area. However, these advances are really only a continuation of existing microelectronics, and will reach their limit sometime around the end of the next decade when it will be both physically impossible to “write” or “etch” smaller features in silicon, and also because at extremely small sizes (less than 20 nm) silicon becomes electrically “leaky” causing short circuits.
Some of the areas under development include:

- Improving display screens on electronics devices. This involves reducing power consumption while decreasing the weight and thickness of the screens. This can be achieved using carbon nanotubes (CNT). They can be used as field emitters with extremely high efficiency for field emission displays (FED).

- Increasing the density of memory chips. Researchers are developing a type of memory chip with a projected density of one terabyte of memory per square inch or greater. Integrated nanosensors are used for collecting, processing and communicating massive amounts of data with minimal size, weight, and power consumption.

- Reducing the size of transistors used in integrated circuits. One researcher believes it may be possible to "put the power of all of today's present computers in the palm of your hand". Processors with declining energy use and cost per gate, thus increasing efficiency of computer by $10^6$.

- Allowing the refrigeration without the need of refrigeration fluids. This can be done if nanoparticles with large magnetic moments and adequate coercivity can be obtained then the magnetocaloric effect may allow refrigeration on a practical scale [5].

**Nanotechnology in Health and Medicine**

Mankind is still fighting against a high number of serious and complex illnesses like cancer, cardiovascular diseases, multiple sclerosis, Alzheimer’s and Parkinson’s disease, and diabetes as well as different kinds of serious inflammatory or infectious diseases (e.g. HIV). Nanotechnology has also its applications in field of health and medicine called nanomedicine. The approaches to nanomedicine range from the medical use of nanomaterials, to nanoelectronic biosensors, and even possible future applications of molecular nanotechnology [6]. The medical area of nanoscience application is one of the most potentially valuable, with many projected benefits to humanity.

- Nanomedicine has the potential to enable early detection and prevention, and to essentially improve diagnosis, treatment and follow-up of diseases.
- Biological tests measuring the presence or activity of selected substances become quicker, more sensitive and more flexible when certain nano scale particles are put to work as tags and labels.
- Nanodevices can make gene sequencing more efficient. Gold nanoparticles tagged with short segments of DNA can be used for detection of genetic sequence in a sample.
- Nanotechnology can help to reproduce or to repair damaged tissue. This so called tissue engineering makes use of artificially stimulated cell. It might replace today’s conventional treatments, e.g. transplantation of organs or artificial implants.

Carbon nanotubes have recently become promising functional materials for the development of advanced biosensors with novel features. These sensors are being used for astrobiology to study origins of life. The technology is also being used to develop sensors for cancer diagnostics. CNT, though inert, can be functionalized at the tip with a probe molecule. Their study uses AFM as an experimental platform.

i. Probe molecule to serve as signature of leukemia cells identified
ii. Current flow due to hybridization will be through CNT electrode to an IC chip.
iii. Prototype biosensors catheter development
Nanotechnology in Transportation

The transportation industry will experience many enhancements from nanotechnology. It will allow cars and planes to become safer and cheaper. Nano materials and new fuel sources will permit travel to become farther and more financially feasible, by reducing the weight of heavy structural materials. It may be possible to make carbon based fibers which are 100x stronger than steel and only one sixth of weight [7].

- Nanotechnology will enhance aerospace application and space flight as new materials will allow space shuttles to become lighter and tougher.
- Emissions from cars contain many different noxious gases, including several known human carcinogens. But now it looks as though nanotechnology may be able to reduce health risks. NanoTwin Technologies has recently released an air filter, which uses nanotechnology principles, to remove hazardous chemicals from the air in car cabins.
- Improved catalysts could reduce or eliminate the emission of pollutants from engines.
- Nanocoating of metallic surfaces to achieve super-hardening, low friction, and enhanced corrosion protection; ‘tailored’ materials for infrastructure and vehicles; and “smart” materials that monitor and assess their own status and repair any defects resulting from fatigue, fire, etc.
- Cerium oxide nanoparticles are used in diesel fuel to greatly increase fuel efficiency. Introducing the nanoparticles reduces fuel deposits on pistons and cylinders, increasing fuel efficiency by about 10% [8].
- Nanoparticles of inorganic clays and polymers will replace carbon black tires and therefore we will have environmental friendly, wear resistant tires.
- Iran Polymer and Petrochemical Institute have designed car and aircraft tires with high frictional resistance using Nanotechnology. Mohammad Karrabi, a researcher at the Institute says “In this method, the frictional resistance of tires has been increased through calculating the mechanical characteristics of them. Also, Lower rolling resistance and higher frictional resistance will lead to less fuel consumption.” Fig 3 [9] gives good illustration of how nanotechnology will effect transportation in future.
Nanotechnology will affect every aspect of transportation.

Nanotechnology, Energy and Environment

Nanotechnology is fundamental over the next 50 years to providing sufficient energy for a growing world and to protecting the environment in which we live. There is an energy/environmental storm gathering and we must pay attention. Under all practical solutions nanotechnology will play a critical role in any successful outcome. The most advanced nanotechnology projects related to energy are: storage, conversion, manufacturing improvements by reducing materials and process rates, energy saving e.g. by better thermal insulation and enhanced renewable energy sources.

- Nanotechnology is having on renewable energies, from solar technology, to nano-catalysis, fuel cells and hydrogen technology. Thus using nanotechnology more clean and less expensive ways for energy production have been found.
- Carbon nanotube fuel cells are being used to store hydrogen. These are the environmentally friendly form of energy. Researchers are trying to increase effectiveness of carbon nanotube at storing hydrogen. This has the potential to power cars.
- Research on photovoltaics is being done to make them cheap, light weight and more efficient.
- Nanotechnology can contribute to the further reduction of combustion engine pollutants by nanoporous filters, which can clean the exhaust mechanically, by catalytic converters based on nanoscale noble metal particles or by catalytic coatings on cylinder walls and catalytic nanoparticles as additive for fuels.
- Nanotechnology can help in developing new environmental safe and green technologies that can minimize the formation of undesirable byproducts or effluents.
- Solid state lightening can reduce total electricity consumption by 10% and cut carbon emission by the equivalent of 28 million tons/year.
A reduction of energy consumption can be reached by better insulation systems, by the use of more efficient lighting or combustion systems, and by use of lighter and stronger materials in the transportation sector. Currently used light bulbs only convert approximately 5% of the electrical energy into light. Nanotechnological approaches like LEDs (Light-emitting diodes) or QCAs (Quantum Caged Atoms) could lead to a strong reduction of energy consumption for illumination.

**Nanotechnology in Space Exploration**

Most of today's rocket engines rely on chemical propulsion. Real rocket scientists though are actively researching new forms of space propulsion systems. One heavily researched area is electric propulsion (EP) that includes field emission electric propulsion (FEEP), colloid thrusters and other versions of field emission thrusters (FETs). EP systems significantly reduce the required propellant mass compared to conventional chemical rockets, allowing increasing the payload capacity or decrease the launch mass. A new EP concept proposes to utilize electrostatically charged and accelerated nanoparticles as propellant. Millions of micron-sized nanoparticle thrusters would fit on one square centimeter, allowing the fabrication of highly scaleable thruster arrays [10].

The greatest challenges in the space craft are

1. performance
2. reliability and safety
3. cost

Nanotechnology can improve the situation. Some specific benefits nanotechnology can bring are [11]

- Nanotechnology can make the structure of space planes much lighter thus can greatly improve their viability.
- Nanotechnology can improve the performance of laser sails. Using nanotechnology sails with 20 nm thickness can be constructed making them light and more durable.
- Performance can also be increased using solar powered ion engines with nanotechnology.
- Using a combination of AI and nanorobotics, computer controlled manufacturing systems will reduce the time and cost of developing new technologies.
- Making exterior of crafts using nanosensors and nanorobots will increase mission rates at lower cost.

**Conclusion**

In this way we see that nanotechnology is about to affect almost every field of human life. It is an enabling technology that will impact electronics and computing, medicine, materials and manufacturing, catalysis, energy and transportation. It will revolutionize future world by changing the current using materials in durability and reactivity. We have great opportunities to make things smaller in size, lighter in weight and stronger in strength. Therefore scientists and engineers have great interest in this emerging field. From the present activities going on in the world particular by no. of conferences, seminars and the money injected in this field we can say that this rapidly expanding field is going to bring about an innovative transformation in upcoming years.
References:

[4] Nanotechnology research directions: IWGN workshop report