Nanoscience and Nanotechnology: Perspectives and Overview

R. Ravichandran
Regional Institute of Education (NCERT)
Bhopal 462 013

P. Sasikala
Makhanlal Chaturvedi National University, 222 Zone-I, MP Nagar
Bhopal 462 011

Nanoscience is fast becoming one of the major areas of science. Its appeal lies in the long-dreamt-of ability to investigate and manipulate matter at the level of individual atoms and molecules. And while it is scientific curiosity that is currently driving research forward in this area, there is the tempting thought that discoveries could play key role in a future world of nano-devices and nano-computers. Hence, it becomes very much essential on the part of the science teachers to get the science students exposed, enriched and motivated on this interdisciplinary field which is going to rule this knowledge society. Also efforts should be made to include this thrust area in school science curriculum appropriately, for a successful exploitation of this upcoming area.

Introduction to Nanotechnology

Nanotechnology is defined as fabrication of devices with atomic or molecular scale precision. Devices with minimum feature sizes less than 100 nanometres (nm) are considered to be products of nanotechnology. A nanometre is one billionth of a metre (10^{-9} m) and is the unit of length that is generally most appropriate for describing the size of single molecules. The nanoscale marks the nebulous boundary between the classical and quantum mechanical worlds; thus, realisation of nano-technology promises to bring revolutionary capabilities. Fabrication of nanomachines, nanoelectronics and other nanodevices will undoubtedly solve an enormous amount of the problems faced by mankind today.

Nanotechnology is currently in a very infantile stage. However, we now have the ability to organise matter on the atomic scale and there are already numerous products available as a direct result of our rapidly increasing ability to fabricate and characterise feature sizes less than 100 nm. Mirrors that don’t fog, biomimetic paint with a contact angle near 180^{o}, gene chips and fat soluble vitamins in aqueous beverages are some of the first manifestations of nanotechnology. However, immenant breakthroughs in computer science and medicine will be where the real potential of nanotechnology will first be achieved.

Nanoscience is an interdisciplinary field that seeks to bring about mature nanotechnology. Focusing on the nanoscale intersection of fields such as physics, biology, engineering, chemistry, computer science and more, nanoscience is rapidly expanding. Nanotechnology centres are popping up around the world as more funding is provided and nanotechnology market share increases. The rapid progress is apparent by the increasing appearance of the prefix "nano" in scientific journals and the news. Thus, as we increase our ability to fabricate computer chips with smaller features and improve our ability to cure disease at the molecular level, nanotechnology is here.

A Brief History of Nanotechnology

The amount of space available to us for information storage (or other uses) is enormous. As first described in a lecture titled, 'There's Plenty of Room at the Bottom' in 1959 by Richard P. Feynman, there is nothing besides our clumsy size that keeps us from using this space. In his time, it was not possible for us to manipulate single atoms or molecules because they were far too small for our tools. Thus, his speech was completely theoretical and seemingly fantastic. He described how the laws of physics do not limit our ability to manipulate single atoms and molecules. Instead, it was our lack of the appropriate methods for doing so. However, he correctly predicted that the time would come in which atomically precise manipulation of matter would inevitably arrive.

Prof. Feynman described such atomic scale fabrication as a 'bottom-up' approach, as opposed to the 'top-down' approach that we are accustomed to. The current 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 is severely limited by our ability to cut, carve and mold.

Bottom-up manufacturing, on the other hand, 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.

Since that initial preview of nanotechnology, we have developed several methods which prove that Prof. Feynman was correct in his prophesy. The most notable methods are 'scanning probe microscopy' and the corresponding advancements in 'supramolecular chemistry'. Scanning probe microscopy gives us the ability to position single atoms and/or molecules in the desired place exactly as Prof. Feynman had predicted. Although the limitations of traditional chemistry were criticised in Prof. Feynman's lecture due to its seemingly tedious and random nature, recent advancements have improved its potential uses for nanotechnology.

Why Make Nanotechnology?

One might ask, 'what exactly are the potential uses of nanotechnology?' In the limited number of years that nanotechnology has been considered possible, a plethora of answers to this question have been presented. Possible answers include quantum computers, long term life preservation and virtually everything in between. It seems that nanotechnology could potentially solve just about any problem that we could think of; thus, a more interesting question is, 'what real problems will nanotechnology solve first?' As of now, it appears that the first revolutionary applications of nanotechnology will be in computer science and medicine. These two fields will most likely be affected first since they both call for molecular scale manipulation of matter in the near future.

Nanomaterials. Nanodevices and Applications of Nanomaterials

Nanomaterials are single-phase or multi-phase polycrystals with a typical crystal size of 1 to 100 nm in at least one dimension. Depending on the dimensions they can be classified into (a) nanoparticles; (b) layered or lamellar structures; (c) filamentary structures; and (d) bulk nanostructured materials. The properties of nanomaterials mainly depend on four features, namely (a) grain size and size distribution; (b) chemical composition; (c) presence of interfaces (grain boundaries, free surface); and (d) interactions between the constituent domains. Due to the large surface/interface to volume ratio in nanophase materials, a wide variety of size-related effects can be introduced by controlling the size of the particles:

- The density of dislocation, interface to volume ratio and the grain size strongly influence the mechanical properties.
- Quantum confinement, i.e., quantisation of the energy levels of the electrons due to confined grain size, has applications in semiconductors, optoelectronics, and nonlinear optics. Nanoclusters, so-called quantum dots for example can be developed to emit and absorb a specific wavelength of light by changing the particle diameters.
- The large amount of surface atoms increases the activity for catalytical applications.
- The magnetic properties of nano-sized particles depend on the large surface to volume ratio. Unlike bulk materials consisting usually of multiple magnetic domains, several small ferromagnetic particles can form only a single magnetic domain, giving rise to superparamagnetism. This behaviour opens the possibility for applications in information storage.

Nanodevices may be defined as structurally organised and functionally integrated chemical systems in the dimension of nanometres. The components may be photo-, electro-, iono-, magneto-, thermo-, mechano-, or chemoactive, depending on whether they handle photons, electrons, or ions, respond to magnetic fields or to heat, undergo changes in mechanical properties, or perform a chemical reaction.

Areas of application that can be foreseen to benefit from the small size and organisation of nanoscale objects include quantum electronics, nonlinear optics, photonics, chemoselective sensing, and information storage and processing, adsorbents, catalysis, solar cells, magnetic recording devices, superplastic ceramics, superhard metals, metastable alloys.

Semiconductor Fabrication

Moore's law, optical lithography and the search for alternatives

Computer chips (and the silicon based transistors within them) are rapidly shrinking according to a predictable formula (by a factor of 4 every 3 years – Moore's Law). According to the Semiconductor Industry Association's extrapolation of formulas such as this one (SIA road map) it is expected that the sizes of circuits within our chips will reach the size of only a few atoms in about 20 years.

Since almost all of our modern computers are made from silicon 'semiconductor' transistors patterned and carved by light (photolithography), the shrinking of circuits predicted by the SIA may not be the most economical method for the future. An enormous amount of money has been invested in the semiconductor industry in order to consistently shrink and improve our semiconductor electronics. Smaller circuits require less energy, operate more quickly and, of course, take up less space. Thus, Moore's law has been adhered to since computers first became commercially available. However, this simple shrinking of components can not continue for much longer.

As transistors such as the Metal-Oxide Semiconductor Field Effect Transistor (MOSFET - one of the primary components used in integrated circuits) is made smaller, both its properties and manufacturing expense change with the scale. Currently, Ultraviolet light is used to create the silicon circuits with a lateral resolution around 200 nm (the wavelength of ultraviolet light). As the circuits shrink below 100 nm new fabrication methods must be created, resulting in increasing costs. Furthermore, once the circuit size reaches only a few nanometres, quantum effects such as tunneling begin to become important, which drastically changes the ability for the computers to function normally. Thus, novel methods for computer chip fabrication have been and are being intensely sought by microchip manufacturers.

Molecular and Quantum Computing

Alternative architectures for nanocomputing

In addition to single electron transistors, two promising alternatives to traditional computers are molecular computing and quantum computing. These two methods are intimately related, yet deal with information on two different levels. Much progress has been made in these areas during the last few years and both have been shown to be feasible replacements for semiconductor chips.

Quantum computing seeks to write, process and read information on the quantum level. It is at the nanoscale that quantum mechanical effects such as (the wave particle duality) begin to become apparent. Numerous scientists are seeking ways to store information within the 'quantum mechanical' realm. This is not a simple task because of the delicate nature of quantum mechanical systems. However, since the laws of quantum mechanics involves unintuitive principles such as superposition and entanglement, a quantum computer would be able to violate some rules that limit our classical computers. For instance, taking advantage of superposition would mean that a quantum bit of information, termed a 'qubit' would be able to be used in several computations at the same time. Taking advantage of entanglement would mean that the information could be processed over 'long distances' without the classical requirement of wires.

Molecular computation is another method complimentary to quantum computing that seeks to write, process and read information within single molecules. One molecule that has proved most promising for molecular computation is Deoxyribonucleic acid (DNA). DNA is a long polymer made of 4 different nucleotides that can be represented by the letters A, T, C and G. The order or sequence of these nucleotides within DNA provides the information for making protein, the main components of the molecular scale machinery used by living organisms to carry out life sustaining functions.

Mathematicians have figured out numerous ways to use DNA as the various proteins that come with it to carry out numerical computations that are notoriously difficult for silicon computers, namely 'NP-complete' problems. The advantage that molecular computing using DNA has over conventional computing is that it is massively parallel. This means that each DNA molecule can function as a single processor, which greatly improves the speed of computation for complex problems.

Medical Applications

Molecular medicine, bioinformatics and biomolecular nanotechnology are rapidly increasing our ability to heal and stay healthy

The other field in which molecular scale manipulation of matter is receiving abundant attention is medicine. Since all living organisms are composed of molecules, molecular biology has become the primary focus of biotechnology. Countless diseases have been cured by our ability to synthesise small molecules commonly known as 'drugs' that interact with the protein molecules that make up the molecular machinery that keeps us alive. Our understanding of how proteins interact with DNA, phospholipids and other biological molecules is what allows such progress.

Living systems are able to live because of the vast amount of highly ordered molecular machinery from which they are built. The central dogma of molecular biology states that the information required to build a living cell or organism is stored in the DNA (which was described above for its use in molecular computation). This information is transferred from "M the DNA to the proteins by the processes called 'transcription' and 'translation'. These processes are all executed by various biomolecular components, mostly protein and nucleic acids.

Molecular biology is a field in which the study of these interactions has led to the discovery of numerous pharmaceuticals that have been enormously effective in curing disease. Understanding of molecular mechanisms, including substrate recognition, energy expenditure, electron transport, membrane activity and much more have greatly improved our medical technology.

So, what does this have to do with nanotechnology? First of all it shows the abilities of molecular scale machinery. Since the goal of nanotechnology is molecular and atomic precision, nanotechnology has much (if not everything) to learn from nature. Copying, borrowing and learning tricks from nature is one of the primary techniques used by nanotechnology and has been termed 'biomimetics'. Secondly, our ability to design synthetic, semi-synthetic and natural molecular machinery gives us an enormous potential for curing disease and preserving life. An extensive textbook titled 'Nanomedicine' has been written and does an excellent job of summarising how nanotechnology is changing medicine.

Molecular Simulation

Computer models of atoms, molecules and nanostructures provide the theory behind nanoscience

Finally, a branch of computer science that is allowing rapid progress to be made in nanotechnology is the computer simulation of molecular scale events. Molecular simulation is able to provide and predict data about molecular systems that would normally require enormous effort to obtain physically. By organising virtual atoms in a molecular simulation environment, one can effectively model nanoscale systems. Deepak Srivastava, one of the world's leading experts in molecular simulation and computational nanotechnology, has described the situation with the following quote, *Theory, modeling and simulations have provided and will continue to provide insights into what to expect next and verification/explanation* of *what has been done or observed experimentally. For nanoscale systems, simulations and theory in fact have provided novel properties that has led to new designs, materials and systems for nanotechnology applications. For example carbon nanotubes applications in molecular electronics or computers were predicted first by theory and simulations, the experiments are now following up to fabricate and conceptualise new devices based on those simulations.*

Current limitations of molecular simulation techniques are the molecular simulation algorithm and computation time for complex systems. Force field algorithms are currently quite efficient and are often used today. However, such models neglect electronic properties of the system. In order to calculate electron density, quantum mechanical models are required. However, as the number of atoms and electrons is increased, the computational complexity of the model quickly reaches the limits of our most modern supercomputers. Thus, as the computational abilities of our computers are improved (often with help from nanoscience), increasingly complex systems will be within the reach of molecular simulation.

The Future

Nanotechnology has arrived, but it has yet to realise its full potential

Our computers are quite fast and small, but no revolutionary breakthrough in computing has happened since the transistor was invented. The human genome project has reached completion, yet limits in our ability to cure disease on a molecular basis remain. While it is often difficult to predict the future, some things seem inevitable. Just as a ball thrown into the air can be expected to fall to the ground, so can we expect our technology to reach the molecular scale. We must keep a very close pace with this new technology to harvest the best potentials at the right time or else we will perish.

Useful links on the NET

www.nano.ku.dk/research/nanochemistry/
www.nanoindustries.com
www.cordis.lu/nanotechnology/
www.nanonet.de
www.ieee.org/portal/index
www.nanotechweb.org
http://home.pusan.ac.kr/~nanobio//
http://nano.gov/
www.nanoapex. com
www.nd.edu/~ndnano/index.html
www.nanobio.com
www.nsti.org/
www.nanobionet.de/
www.nanoword.net/pages/quiz.htm
www.mitre.org/tech/nanotech/
www.nanoword.net/pages/busquiz.ht

REFERENCES

Smalley, R.E. 1999. Nanotechnology — A Revolution in the Making — Vision for R&D in the Next Decade, Interagency Working Group on Nanoscience, Engineering, and Technology, USA.

Gonsalves, K.E., Rangarajan, S.P., Wang, J. 2000. *Handbook of Nanostructured Materials and Nanotechnology*, Vol. I, Synthesis and Processing, Academic Press.

Srinivasan, S. 2004. *Nanotechnology: the next revolution*, National Book Trust, New Delhi.

MHRD, Govt. of India. 2004. *Nanoscience & technology base and vision for R&D in India*, New Delhi.