Nanotechnology: hope or hype?

K. L. Chopra

Never in the history of science and technology has so much euphoria and hype been created – among scientists of varied disciplines, educationists, science policy makers, funding agencies and even politicians – as by the magical word 'nanotechnology'. Indeed, nanotechnology is being projected by some as the solution to all problems of humanity.

What is nanotechnology[1–4]? Any living or non-living matter having one/two/three dimensions of around nanometric (10^{-9} m) size is called nanomatter. The science associated with the properties of nanomatter is called nanoscience. Nanotechnology is the synthesis of nanomaterials of various dimensions, morphologies and shapes, and their utilization for creating a functionally useful material, device or system.

The word Nanotechnology was first used by Tanaguchi in 1974 for microelectronics having active electronic components of submicron dimensions. Today, this word applies loosely to any nanoscale process, product or components therefrom. Systematic scientific work on two-dimensional thin film nanomatter began during the 1960s with the availability of the electron microscope[5–7]. The *ab initio* growth of matter on a substrate by the condensation of its building blocks (e.g. atoms/molecules/ions) takes place by a vapour–solid (VS) nucleation and growth process. This, at its earliest stage of a critical size, yields nanomatter; the size, shape and topology depend on numerous molecular deposition parameters, associated surface and strain energies, and angle of contact with the substrate.

By controlling supersaturation and ambient conditions, any deposition process can also yield nano-powders of the feed material. A serendipitous observation showed that if the atoms of Si are condensed onto a suitable catalytic or eutectic-forming impurity material (e.g. gold), the vapour atoms undergo vapour–liquid–solid (VLS) transformation; under suitable conditions, they yield nano-size wires at the surface of the growing islands. This observation did not attract the attention of thin-film scientists, as the films appeared dirty and therefore were not considered useful. However, high-resolution electron microscopy of carbon films synthesized in VLS mode showed that the dirty-looking material contained a treasure of carbon nanotubes (CNTs). This discovery has set in motion a new scientific field of CNTs. Studies have shown that such suitable impurity-nucleated growth of almost any material can yield nanomatter in the form of thin films, powders, wires, tubes (in some cases), and a variety of nano-art morphologies of flowers. Synthesis of nanomatter provides much fodder for research publications today.

Myths and realities of nanotechnology

Myths have been created by many popular articles and reports. For example, the 2005 report entitled 'Innovation: applying knowledge in development' by the UN Millennium Project Task Force on Science, Technology and Innovation (http://www.unmillenniumproject.org/documents/Science-complete.pdf) stated: 'nanotechnology is likely to be particularly important in the developing world, because it involves little labour, land or maintenance; it is highly productive and inexpensive; and it requires only modest amounts of materials and energy.' Let us examine some realities.

Is nanotechnology new?

Certainly not. Though there was no way to see or measure nanometric sizes, chemists have been producing nanopowders of various materials for centuries. Historical records show that Indians were conversant (by the 9th century AD) with the amalgamation technique and the superior reactivity of fine silver powder thus produced. For centuries, Indian artisans have created ~200 nm thick silver and gold foils to decorate sweets simply by beating down thick foils of the materials. Indian 'bhasmas' containing nanometric powders of various mercury sulphides are well-known ayurvedic medicines. Millions of metric tonnes of nanosize silica, titania and zirconia nanopowders are being used in the rubber, cosmetics and toothpaste industries for several decades.

Thin films, which form the core of present-day nanotechnologies, have been created scientifically since the 1960s by numerous physical, chemical and electrochemical techniques[5–7]. Thin-film technologies have played a pivotal role in the development of modern optoelectronics, spintronics, very large-scale integration (VLSI) and ultra large-scale integration (ULSI) technologies, quantum metrology, surface technologies, thin-film solar cells and sensors, among others. The numerous, powerful, atomic-scale nano-analytical techniques that have been developed recently for imaging, analysing and manipulating nanomaterials and nano-devices owe a lot to these technologies.

Is nanotechnology cheap?

Of course not! Those who wrote the UN Millenium report are obviously either theoreticians or are not familiar with the required experimental facilities and cost of nano-analytical tools (each of which runs into several million dollars), leave alone the cost of clean rooms and ultra-pure feed materials for creating nanomaterials.

Numerous well-known physical, chemical, electrochemical, printing and mechanical synthesis techniques have now undergone sophistication and automation with extraordinary sensitivity, accuracy and controls on a nanoscale. However, manufacturable and economically viable nanomatter on a commercial scale is by no means simple and straightforward. Similarly, creation of commercially viable and useful devices from the given nanomatter beyond proof-of-concept is by no means a trivial exercise.

As an example, the nano-powder of an iron oxide is known to effectively remove arsenic from contaminated groundwater, which is present in some of our Indian states. But, on a commercial scale, this technology would be prohibitively expensive to provide drinkable water at a nominal cost for the public. Interestingly, a commercially viable solution for filters, to provide clean and potable water, has been developed by a private industry using some naturally available clays that are rich in nanosilica of different morphologies.

A similar problem of cost arises in cases of large-area applications of nanotechnology, such as solar cells and surface engineering. Major R&D efforts are being made to develop cheaper processes, such as stamping or printing of the relevant nano-materials without major changes in their properties. A lot of transformational and translational research would be required before such exciting materials can possibly be exploited for large-area applications. However, the economics of nanotechnology is hardly appreciated or discussed by either the scientists/engineers or the funding agencies, particularly in India.

There are, of course, some areas such as sensors, actuators, biomarkers and biosensors, nano-electronics and nanophotonics where nanotechnology makes a lot of economic sense because the smaller the device, the faster, more effective, smarter, cheaper, integratable and densely packageable it is. Unfortunately, these are the areas in which we have very little ongoing research, competence or even aptitude in Indian academia or industry. A NanoFab is a distant dream in India, when we have yet to establish even a decent microfab in our premier academic institutions.

Is nanotechnology durable and safe?

Durability and safety are determined by the characteristically high activity and reactivity of nano-materials, arising from the high surface–volume ratio of atoms. Consequently the shape, size, morphology and dimensionality of the material, its internal physical microstructure and the associated electronic and chemical structure dominate the exotic properties of such materials. Generally speaking, the nano-powder of any material is not completely stable and requires a protective, passivating or functionalizing coating.

The 'nanoscare' bugle has been sounded globally by several scientists[8]. Nano-particles of silver and gold, and CNTs are now known to penetrate human skin rather easily. The nano-particles of both metals and non-metals have been found to be toxic in varying degrees. Their toxicity cannot be predicted from that of the corresponding bulk materials. These particles have the potential to accumulate in the environment. They could accumulate in the food chain. Because of their invisibility, they could pose safety concerns in military applications. Their use in areas such as biomedicine and bio-agriculture have raised serious ethical issues for society.

Is there any academic hype?

Nanoscience and nanotechnology require a good working knowledge of postgraduate-level physics, chemistry, materials science, biosciences and sophisticated nano-analytical instruments, among other technical skills. Any academic who is familiar with the level of science taught in our high schools and B Sc courses will be shocked to know that numerous engineering colleges are offering a 4-year B Tech degree in nanotechnology and that ~20 universities are doling out M Sc degrees in nanotechnology. Just imagine the discomfort of the faculty in these institutions, who are still learning what and how to teach nanotechnology.

Along with the institutions concerned, both the University Grants Commission and the All India Council for Technical Education are clearly guilty of misleading young minds. Unfortunately, the generous Department of Science and Technology (DST) has incentivized this process by providing liberal grants to the concerned universities for hiring faculty and for providing some rudimentary facilities for the synthesis of nano-materials. Nobody has yet bothered to get a feedback from the angry and confused students, to assess what they have learnt and where they will fit in the academic scheme.

As knowledgeable academics would certainly agree – for fruitful learning and knowledge creation – only Ph D or M Tech students should be engaged in learning and conducting R&D in the field. Even here, an institution requires competent faculty to teach and supervise such students. But such faculty members are few and far between. No wonder, I have yet to meet a student who has been made aware by any faculty that nanomatter is created by a nucleation process.

Is nanotechnology a research fodder?

In order to nurture nanotechnology, DST has already invested over Rs 1000 crores in setting up several nanocentres and nationally coordinated R&D programmes. Admittedly, some academics in a few select centres are doing globally competitive fundamental research work. However, a large number of publications from such generously sponsored projects are pedestrian and provide nano-incremental contributions to the field of synthesizing well-known nano-materials. In most cases, the changes in shape, morphology, microstructure of nano-powders, wires and tubes are reported. Most publications claim potentially important applications without understanding what is required for a viable application.

Despite a lot of research activity, nanotechnology has yet to reach our Indian industries. Our rubber, cosmetic and toothpaste industries continue to import large quantities of silica, titania and zirconia nano-powders. There is no question that we have the capability to produce these materials and even to set up industries to replace imports. But many researchers do not even attempt to synthesize nano-materials for their own research; they import nano-powders of various materials, transparent conducting glass slides, CNTs and nano-templates at exorbitant prices. But alas, we do not yet have liberal administrative and financial policies to nurture our entrepreneurial scientists. So far, nurturing nanotechnology in India has only provided fodder for more pedestrian research publications and Ph Ds of questionable quality.

Is there a future for nanotechnology[1,4]?

Undoubtedly, and indeed a bright one too for both nanoscience and nanotechnology. Today's nanotechnology is the creation of yesterday's nanotechnology, which has already crossed several new and unforeseen frontiers. Thanks to extraordinary developments in integrated electronic circuits, sensors, data and image-processing techniques, and nano-analytical instrumentation, it is now possible for scientists to literally play with and manipulate single electrons/photons/atoms/molecules/living cells. As a result, single-electron transistor, single-electron spin memory, single-molecule switch and single-atom laser have now been demonstrated as proof-of-concept. A single atom can now be removed from matter and replaced with any other atom.

Scientists are moving ahead to create a living cell. The bonding of a variety of biomolecules with metallic nanoparticles/quantum dots has opened up a new frontier in biomedical sciences. Self-assembly techniques through controlled nucleation and growth, pen and rubber stamp lithography of nano-materials, and bioprinting of cells are some exciting developments for creating new and functionalized living and non-living materials.

Nanotechnology will continue to be pursued vigorously for discovering new phenomena, for developing new/tailored/functionalized high-performance materials and for economy-driven applications in the more practical and useful form of thin films. Nano-electronics and nanophotonics will continue to lead the pack by creating new frontiers driven by the economic forces of the information technology industry. Perhaps the most significant and singular contribution of nanotechnology is the convergence between the various sciences and engineering disciplines. Thus, life scientists are now happily shaking collaborative hands with physicists, chemists, materials scientists and engineers in developing new inter-disciplinary areas of medical science and technology, bio-fuels and bio-agri technologies that are expected to have an impact on the health and welfare, energy and food security of mankind.

Concluding remarks

Hype creates mirages. Hope leads to reality. Any realistic and significant research and development in these new frontiers can only be achieved by well-endowed, critically sized groups of dedicated scientists and engineers working in an ecosystem that ensures autonomy with accountability for outcomes, competitiveness and a liberal academia–industry interface for entrepreneurship. If we fail this time in India, as we have done in some other nationally coordinated projects, our nanotechnology will become 'na-no technology'.

1. Foster, E. L., *Nanotechnology: Science. Innovation and Opportunity*, Pearson Publication, Singapore, 2008.
2. Ratner, M. and Ratner, D., *Nanotechnology: A Gentle Introduction to the Next Big Idea*, Pearson Education, Singapore, 2003.
3. Wolf, E. L., *Nanophysics and Nanotechnology: An Introduction to Modern Concepts in Nanoscience*, John Wiley, New York, 2004.
4. http://www.nanotec.org.uk/finalReport.htm
5. Chopra, K. L., *Thin Film Phenomena*, McGraw Hill, New York, 1969.
6. Chopra, K. L., *Bull. Mater. Sci.*, 1998, **18**, 639–662.
7. Chopra, K. L. and Kaur, I. J., *Thin Film Device Applications*, Plenum Press, New York, 1983.
8. Allhoff, F., Lin, P. and Moore, D., What is Nanotechnology and Why Does it Matter? From Science to Ethics, Wiley-Blackwell, Oxford, 2010.

K. L. Chopra lives at M-70, Kirti Nagar, New Delhi 110 015, India.
e-mail: choprakl@gmail.com

Plant biodiversity conservation and role of botanists

V. A. Bapat, G. B. Dixit and S. R. Yadav

It is a well-known fact, that worldwide thousands of plant species are endangered and facing extinction with the current trend of their exploitation and destruction[1,2]. In recent years, there is a growing awareness concerning the impact of temperature rise, industrialization, desertification and shift in the growing seasons of plants, loss of pollinators, seed dispersers and increasing frequency of intense weather events such as drought, storms and floods making several valuable plants extinct[3,4]. According to the International Union of Conservation of Nature (IUCN), it is estimated that the current species extinction rate is between 1000 and 10,000 times higher than it would naturally be. It is acknowledged that the future survival of humanity depends on the conservation and protection of natural wealth, and destruction of a species or a genetic line symbolizes the loss of a unique resource. This type of genetic and environmental impoverishment is irreversible. Changes in the structure in the multiplicity of resources lessen the society's scope to respond to new problems and opportunities, and there is the danger of new plant diseases or pests, climatic change due to the greenhouse effect and other setbacks. To overcome these hurdles, there is a need of coordinated efforts of scientists, government departments and nongovernmental organizations to undertake effective measures for conservation of plants (Figure 1). Methods to support conservation consisting of education, providing enticements and adding capacity building need to be adopted at the earliest. To avoid the loss of biodiversity the government authorities have formulated stringent rules to safeguard and protect the existing biodiversity, ensuing protection of the present natural assets. This guided enactment of the Biological Diversity Act for India controls access to all genetic resources of the country and includes provision for equitable profit-sharing. The detailed specific rules are available on the webpage of the Ministry of Environment and Forests, Government of India, and the National Biodiversity Authority, a statutory and regulatory body established under Biological Diversity Act, 2002 (www.nbaindia.org). IUCN and other organizations undertake wide ranging research projects on the status of biodiversity to protect specific species, manage and restore national parks, botanical gardens[5] and other protected areas, and promote the sustainable uses of natural resources[6,7]. The modus operandi of biodiversity conservation, however, has to be implemented considering not only protection of any plant life in its natural status but its further multiplication and subsequent plantation followed by utilization which have other economic reflections[8]. Considering the new concept of bio-power applied to numerous crops, fruit and plantation crops as well as forest trees, saving of endangered plants has to focus on their further utility, if any, for various benefits to civilization. In this context, the role of a botanist assumes prime significance to undertake a particular project on