Heralding a new future – Nanotechnology?

Jyoti S. A. Bhat

Nanotechnology is being heralded as the next enabling technology that will redesign the future of several technologies, products and markets. Nations are focusing on this emerging technology in particular and serious research as well as industry efforts are being made. Recent developments, current trends and industry progress in this field are discussed here. This paper also examines research efforts in this field and whether this technology could have serious implications for a nation like India.

NANOTECHNOLOGY has become one of the important sectors which is drawing intense interest and it will replace most of the existing technology in use today. It is widely publicized to be an important technology that is going to change every aspect of our lives and lead to generation of new capabilities, new products and new markets. It is thus described as an *enabling technology* that will pave the way for novelty in every stream of technology. Another important aspect associated with nanotechnology is its multi-disciplinary nature which makes it difficult to pin down and prophesize the future impact in any specific sector appropriately. Its impact on society is expected to be widespread and all-pervasive. Critical research in this field is being carried out all over the world. World over, interest in nanotechnology has grown over the years and funding statistics has grown both very impressively and substantially in the last couple of years. A number of new firms have been established in recent years with the specific objective of exploiting one or more of the several avenues that this new technology provides.

Nanotechnology, the term

Nanotechnology has come to mean a range of highly promising disciplines in science and technology. A nanometer is one thousandth of a micron or one millionth of a millimeter or 10^{-9} of a meter and is roughly the length occupied by five to ten atoms stacked in a straight line.

To give an idea of the length of the nanometer, the hydrogen atom is about 0.1 nanometer, while a virus may be about 100 nanometers and a red blood corpuscle approximately 10,000 nanometers in diameter. Looking further at whole systems at these scales, it has been known that living cells that first emerged over 3.5 billion years ago are the best specimens of machines that operate at the nano-scale that perform a host of jobs ranging from generation of energy to extraction of targeted materials at very high orders of efficiency. Even today it is well known that there is no process that has yet been engineered by mankind – be it mechanical, chemical, biotechnology or any other – that has been able to reach anywhere near the levels of perfection observed in living cells.

While the word 'atom' was coined by Democritus as early as 400 BC to denote the smallest particle 'not cleavable' any further, and the entire world of science devoted itself to studying physical, chemical and natural phenomena and deriving useful applications, until 1959, nobody dreamt of using atoms and molecules for fabricating devices and everyday apparatus. It was then that the Nobel Laureate Richard Feynman urged mankind to think tiny at the scale of the atom itself. It was much later in 1974 that Noria Taniguchi used the term nanotechnology while measuring precise machining tolerances. It is this name that has stuck and has now grown to mean a whole range of tiny technologies that are from anywhere in metallurgy and material sciences where new materials for a host of varied applications are concerned; to electronics where memories, computers, components and semi-conductors are concerned; to biotechnology where diagnostics and new drug delivery systems are concerned.

Definitions

The term nanotechnology itself has been variously defined. By one definition, it is the ability to do many things: measure, see, predict and make – on the scale of atoms and molecules. Nanotechnology has also been defined to be dealing with materials in the range of 0.1 to 100 nanometers[1]. It is also referred to as the term for the construction and utilization of functional structures with at least one characteristic dimension measured in nanometers[2].

Jyoti S. A. Bhat is in the Department of Scientific and Industrial Research, Government of India, Technology Bhawan, New Mehrauli Road, New Delhi 110 016, India
The views expressed in this article are those of the author and do not represent the Department's opinion.
e-mail: jsabhat@alpha.nic.in

While these may sound like slightly restrictive definitions, in actual practice, nanotechnology is being used to represent a far broader arena. In fact, it is accepted that all that is referred to as nanotechnology may not be really nano, as one may be dealing instead with structures on the micron scale (millionths of a meter), which is at a scale of a thousand times or more larger than a nanometer. What really matters is that this technology involves dealing with structures having at least one dimension that is sufficiently small, of the order of about one to several hundred nanometers.

It is concerned with materials and systems whose structures and components exhibit novel and significantly improved physical, chemical, and biological properties – and that enable the exploitation of novel phenomena and processes due to their nanoscale size. All nations share a similar understanding of this broad definition of nanotechnology, though many have more specifically delineated the areas that are covered.

This explains why the arena of nanotechnology is quite broad. It is also clear that it is not mere nano-sizing of known or existing matter or devices, but the study and development of something new that is as yet unknown but characteristic of matter at those sizes that is really being sought to be covered under the realm of nanotechnology. Significant developments in the field have been indicated in Table 1.

It must be appreciated that research in this vast area has been possible only because of the development of tools and instruments that are effective at these levels. While the electron microscope and much later molecular beam epitaxy did offer some scope for work, more effective tools are of fairly recent origin, as can be seen in the table. The Scanning Tunneling Microscope (STM) that was invented in 1981 was the first instrument that permitted human beings to see atoms. The Atomic Force Microscope (AFM) followed this and these instruments are referred to as Scanning Probe Microscopes. Currently, optical techniques, lithographic tools, nuclear magnetic resonance and laser equipment, as well as computer modelling techniques are used for permitting work at the scale of nanometers. Realizing the importance of these tools and instruments to enable faster development of the technology, newer tools and techniques are being developed for the purpose of dealing with 'nano-sizes'.

Table 1. Nanotechnology: some major breakthroughs

1931: Electron microscope	Sub-nm imaging
1959: Dr Feynman's lecture	Thinking at nano-scale
1968: Molecular beam epitaxy	Deposit single atomic layers on a surface
1974: 'Nanotechnology' use	(Nori Taniguchi, Japan)
1981: Scanning Tunnel Microscope	Image atoms
1985: Buckminsterfullerenes cages of 60 C atoms	(Richard Smalley, Rice University, US)
1986: Atomic Force Microscope	Indenting surfaces
1989: Use of individual atoms	(D M Eigler, IBM, US)
1991: Carbon nanotubes special strength, electrical properties	(Sumio Iljima, NEC, Japan)
1993: Virtual reality system	(W Robinett, University of North Carolina, US)
1997: Nanomech device using DNA	(Seeman, NYU, US)
1998: Nanotech transistor	(C Dekker, Delft University, The Netherlands)
1999: Single molecule organic switch	(James Tour. Rice University, US)
2001: CN-based devices, Logic gates	(IBM, US)

Source: Culled from refs 6, 7.

Importance of nano: Unique properties

The special significance of this technology and the dealing with such nano sizes is that the behaviour of matter is very different from what is familiar, generally understood and commonly accepted. Laws relating to physical, chemical, biological, electrical, magnetic and other properties at the nano-scale are different from those that apply to macro matter; as it is laws of quantum mechanics that apply at that scale, as can be seen in Table 2.

Quite understandably, research in this technology began with developing an understanding of materials with novel characteristics at the nano-scale. Attempts to achieve control over conductivity, opacity, strength, ductility, reactivity, etc. in different combinations of matter, are among the earliest of research forays in this field. This has led to radical changes and departures in the fundamental understanding of matter. For instance, it is now clear that metals could become harder, ceramics could become softer, alloys could be engineered to become either harder or softer, and mixtures with specifically designed properties can be fashioned. As a result, a whole new world is opening up, in which things that are made are not only just smaller, but stronger, or faster or cheaper or better in terms of so many features that were unthinkable, leading to the creation of whole new capabilities, new products and new markets and not merely the extension of existing capabilities, products or markets.

Table 2. Nanotechnology: properties

- Not only miniaturization but change in physical properties
- Laws of quantum physics
- Surface behaviour dominates bulk material behaviour
- Metals become harder
- Ceramics become softer
- Composites and alloys of a whole variety possible
- Thin polymers less permeable
- Stronger, more heat resistant, transparent
- Increased chemical resistance, reduced weight
- Different interactions with light/other radiation
- New electrical properties
- Novel biological properties

Another important dimension is that the domain of nanotechnology is not restricted to only the realm of materials and applications but extends even to life sciences. It is now plausible to replicate living organisms to perform engineered tasks. Besides, as a number of technological strides are being made in information technology, biotechnology, semiconductors, and other technologies, they are all impacted by and are in turn being impacted by developments in nanotechnology, which makes the technology multi-disciplinary, as it is becoming increasingly difficult to demarcate between the different disciplines at the nano-scale when the definition of nanotechnology itself is broad enough to permit their inclusion within its realm.

Applications

Nanomaterials

It is notable that at the nano-scales, forces such as gravity, or inertia do not play much of a role. Van der Waal's forces, electron resistance and magnetism are the more important governing forces. It is comprehending these issues that has led to the first major area of application of nanotechnology to be nanomaterials. Nanomaterials in the form of particulates as well as layers – both mono as well as composite – have been found to improve the characteristics of products. The unique chemical, electronic, magnetic, optical, and other properties of nanoscale particles have already led to their evaluation and use in a broad range of industries, including biotechnology, catalysis, data storage, energy storage, microelectronics, and others.

Some of the applications where nanomaterials already find use are mainly in reinforcing currently-existing material and increasing the strength as in the case of stronger and thinner bumpers for vehicles. Many newer applications in this category are being developed that are likely to impact several industries. Nanoparticles are used in a variety of commercial products, ranging from magnetic recording films and chemical-mechanical planarization slurries to sunscreen products and wear-resistant coatings.

Another area of concentration is in making new improved nanomaterials that can be added to paints to make them scratch resistant. There are others who are making nanomaterials for photo resist and silicon used slurries for use in semiconductor manufacture. New LCD panels and improved automobile materials are at the same time being attempted.

Nanomaterials research is now concentrating on the development of materials that can be designed to have desired properties by manipulating and attaching atoms in different ways. Among the important materials, a major breakthrough is the development of buckminsterfullerenes or buckyballs. These are particular formations of 60 carbon atoms that are joined together by linking hexagons and pentagons. The resultant hollow spherical structure, which somewhat resembles a football, has been seen to exhibit very rare properties. What is most special about these formations is that they can withstand very high amounts of heat and pressure. Equally important have been nanotubes which are really strings of carbon atoms that are formed by exposing graphite to extreme heat. Both single-walled and multi-walled tubes are possible. What is special about nanotubes is their high strength coupled with special electrical conductivity properties. It has been found that carbon nanotubes have a tensile strength six times that of steel. Various applications putting these special materials to use are even now being developed as their potential in different kinds of applications is being explored.

Nano-electronics

The second major implication of nanotechnology is in electronics. Nano and quantum computing, nano-formed components and nano-based wiring have been some of the focus areas. Research has led to some important developments: demonstration of Coulomb blockade, quantum effect, single electron memory and logic gates that operate at room temperature; integration of scanning probe tips into sizable arrays for lithographic and mechanical information storage applications; and fabrication of photonic band-gap structures[3]. In addition, biological computing is becoming a possibility.

Novel nano-electronic components are now being formed by hybridization of silicon components that are currently in use. Single logic circuits are being made out of self-assembled single molecule transistors. Nanowires that can conduct electricity have become feasible. Different methods of using nano-electronics to make new forms of memories and storage devices are under development.

The feasibility of using carbon nanotubes as basic electronic components is being worked out and techniques ranging from self-assembly to soft lithography are being attempted for arriving at viable continuous mass manufacturing methods. In the area of memory, immense possibilities to improve basic features through the use of nanotechnology, by way of better access speed and storage density at lower costs by several orders of magnitude, are being worked out. Other new forms of storage like magnetic memory (MRAM), and also for improving existing forms of traditional magnetic storage are being thought of.

With these developments, it is thought that conventional electronic device manufacture, with its attendant heat dissipation problems, would change radically in the years ahead.

Nanobiotechnology

The third area where nanotechnology has led to major developments is in health and medicine. This has come about because of the integration of biotechnology and nanotechnology. In fact, this confluence has led to among the most exciting of developments and new possibilities. Nano-devices having bio-capabilities are the outcome of such research. New kinds of drug delivery systems that can pervade the blood stream, target contaminated cells and even deliver the desired medication in programmable quantities at desired intervals have become a reality. Artificial replacements and placebos at the nanoscale have been other major developments.

It is even thought likely that macroscopic 'living-like' organisms that are actually synthetic and made of nano-materials, but that would perform natural processes of healing and replication exactly like living organisms would soon be quite commonly used. Rapid advancements in biotechnology and information technology have further boosted medical diagnostics, biomedical research, genomics, genetic testing and new drug discovery. Attempts are being made to develop nano-thick particulate coatings onto macroscopic and microscopic structures using a novel pulse laser deposition technique. There have been other concerted efforts at integrating microelectronics and molecular biology into a platform technology with a number of potential commercial applications ranging from diagnostics and treatment to novel drug discovery.

Other developments

There are a group of devices called microelectro-mechanical devices or MEMS that consist of tiny elements generally manufactured using lithographic techniques to achieve microdimensions that function like traditional larger devices. It is interesting to note that MEMS have been under development and trial use for some years now. But, again it is the integration of nanotechnology, biotechnology and information technology that has had a very large impact on MEMS. In fact the term NEMS has also been coined to represent nanoelectromechanical devices which are nothing but tinier MEMS. These devices find applications in a host of areas and more recently in medicine. Sensors of various kinds have become possible as a result of application of these devices in different areas. These MEMS and NEMS are also embraced within nanotechnology.

The various applications which nanotechnology has been impacting are indicated in Figure 1. A cursory examination of the categories indicated makes it clear that the reference to naotechnology is quite broad. Not only are micro-instruments and materials referred to as nanotechnology, but also recent technologies in the realm of essentially biotechnology and chemical technologies are also referred to as nanobiotechnology and are being categorized broadly under nanotechnology. Eventually as individual technologies continue to develop and more and more of the traditional boundaries between different disciplines begin to meld, clear distinctions are likely to become very difficult.

Nanotechnology development: The real picture

There is indeed a large amount of hype associated with this technology, which has been fuelled by Government interest and media projections. But that does not denigrate the importance of this technology which is undoubtedly one of the most important of technological discoveries in the existence of mankind that is likely to have enormous implications to the way life will be lived in the future.

The kind of focus on nanotechnology in a spectrum of regions is indicated in Tables 3 to 5.

It may also be mentioned that in most countries the level of proposed funding during 2003 is being greatly enhanced. For instance, in Japan, it is likely to be 1000 million dollars as against 750 million dollars during 2002. In Europe, funding for the period 2002 to 2006 is estimated to be a staggering 7000 million euros. Thus, it can be seen that the long term potential of a strong nanotechnology base is not being overlooked.

Looking at general interest articles in recent years, it can be seen that media projections of nanotechnology have definitely been on the rise, as depicted in Figure 2. Over the same period, the number of patents and research articles is also indicated. It is immediately seen that while the number of general articles has increased substantially, the same is not the case with research articles and patents. That the number of media articles and general readership publications do indicate a measure of the hype associated with the technology cannot be denied. However, it cannot be surmised on this basis that the technology has been sustained only by hype and that the developments so far do not amount to anything substantial. A deeper analysis of the situation as attempted in ref. 4 indicates that protection of technology in the case of nanotechnology is not very easy. This explains to an extent, the scenario in respect of patents and research articles. Any research article that is linked to the technology's secrecy and could result in divulging of crucial information is not being published, without taking due precautions. So also patenting in this field has not been very easy for a number of reasons: difficulty in demarcating the claims, reluctance in assigning rights and hesitation in revealing trade secrets.

It must also be noted that it is not only Governmental attention that is supporting the development efforts. Venture funding is playing a very major role in supporting a

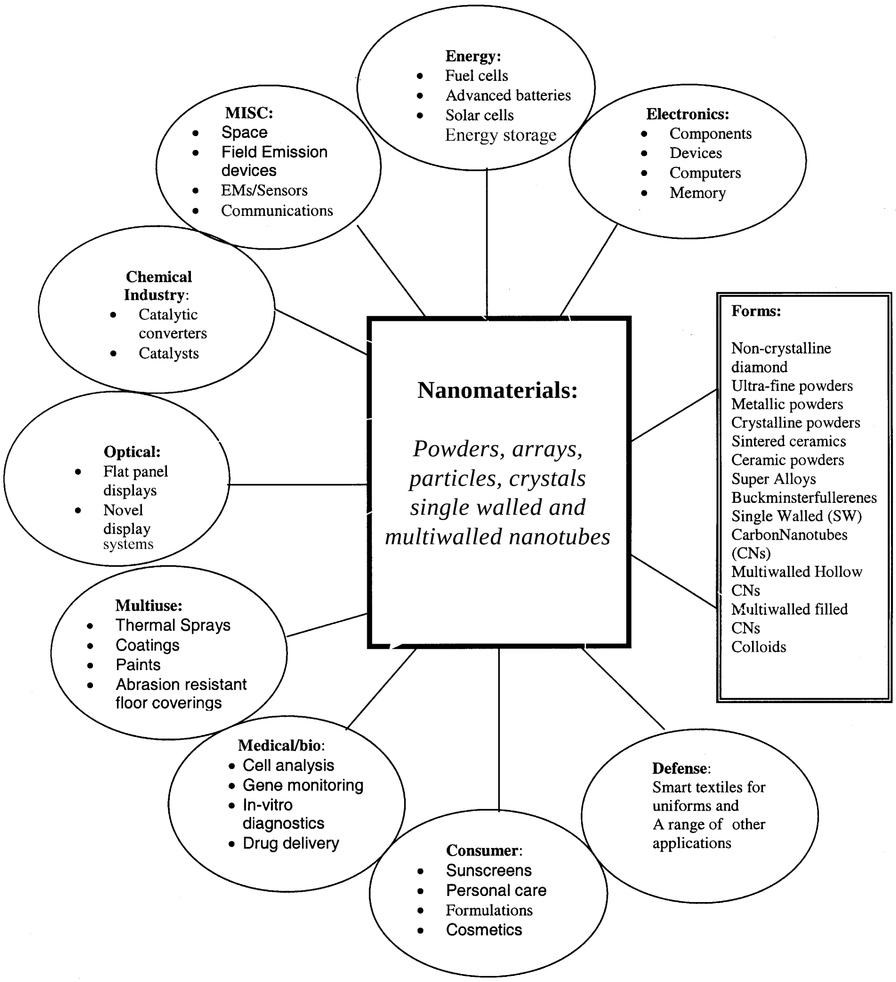

Figure 1. Nanotechnology applications.

Table 3. Government spending on nanotechnology in the East, 2002

Country	Amount (millions of US dollars)
Japan	750
China	200
Taiwan	111
Korea	150
Singapore	40

Source: Ref. 8.

growing industry. The implications of this could be many but two major aspects need highlighting. The first is that despite the kind of shakedown high technology industries have been facing, the kind of venture funding that is being made available to nanotechnology-based industries in particular is a clear indication of the kind of faith that is being placed on the technology. The second important implication is that commercialization of research efforts would take place faster than in the case of other emerging technologies; spurred on by ease of venture funding together with Government funding.

The industry

The nanotechnology industry has been given a lot of attention by governments, industries and nations. The feasibility of developing a vast range of fastidiously and exquisitely 'custom-designed' materials for specific uses, addressing the needs of varied industries has become a reality because of the pace at which research in nanomaterials has been stepped up in recent years. More precisely, it looks increasingly possible to engineer hitherto impossible applications to accurately honed requirements by hurtling above normally understood boundaries of inherent physical characteristics of existing materials. It thus is entirely probable now to achieve unprecedented levels of efficiency, hardness, ductility and conductivity, beckoning opportunities in a host of areas that would most certainly rewrite the histories of several industries.

As a result, the intense interest in nanotechnology by industry is being driven by visions of a range of new nanotechnology-related commercial applications in a host of areas. As mentioned, the introduction of new nanomaterials is leading this revolution. New nanomaterials to address specific needs of different industries are being created rapidly and these new materials promise a cornucopia of new products with superior performance characteristics that are likely to dramatically transform the markets in a number of key industries. The point to note is that such products are not in the realm of science alone anymore, as real products incorporating new nanomaterials are being introduced into the market.

Table 4. European countries spending on nanotechnology: millions of euros

Country	1997	1998	1999	2000
Austria	1.9	2.0	2.2	2.5
Belgium	0.9	1.0	1.1	1.2
Denmark	NA	1.9	2.0	2.0
Finland	2.5	4.1	3.7	4.6
France	10.0	12.0	18.0	19.0
Germany	47.0	49.0	58.0	63.0
Greece	0.2	0.2	0.3	0.4
Ireland	0.4	0.4	0.5	3.5
Italy	1.7	2.6	4.4	6.3
The Netherlands	4.3	4.7	6.2	6.9
Portugal	0.2	0.2	0.3	0.4
Spain	0.3	0.3	0.4	0.4
Sweden	2.2	3.4	5.6	5.8
UK	32.0	32.0	35.0	39.0
European Commission	23.0	26.0	27.0	29.0

Source: Ref. 1.

Table 5. US government focus areas in nanotechnology

Area	2000	2001	2002	2003 (est)
Research and development	97	150	199	221
Defence	70	125	180	201
Energy	58	88	91	139
Standards	8	33	38	44
Health	32	40	41	43
Space	5	22	46	51
Others	0	8	10	11
Total	270	466	604	710

Source: Ref. 9.

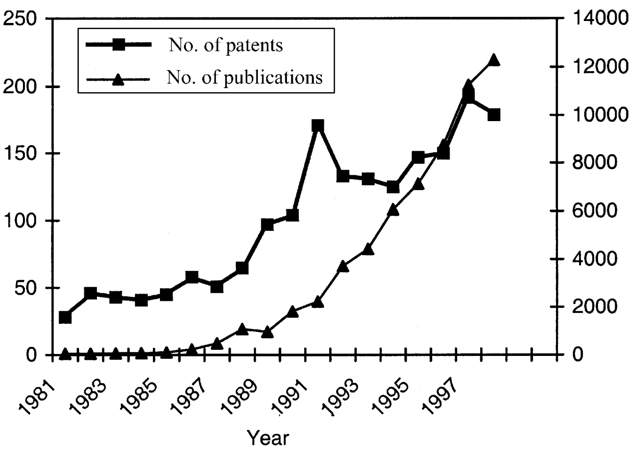

Figure 2. Number of publications/patents in nanotechnology. Source: Ref. 10.

As technology is developing, it is becoming increasingly evident that it does not relate to any particular sector but is more a kind of an avant-garde technology that is opening up several possibilities in different industries that are daring to explore atomic and molecular structures. The reason being all industries are based on specific materials and nanotechnology offers an exciting range of solutions. Specifically electronics and medicine have made the largest forays so far in exploring new avenues and achieving breakthroughs, but other sectors are not far behind in opening up to rewarding experiments.

While nanomaterials may create a wealth of new business opportunities with the potential to radically and abruptly impact a company's market position, they may also pose tremendous business risks. Clearly, the nanomaterials revolution has launched a new high stakes game, and companies are attempting to successfully position themselves to be nanotechnology leaders.

Overall, there is a general consensus that nanotechnology will be a very big and dominant industry not far into the future. It has been estimated that the market will grow to over USD 1 trillion in little over 10 years by 2015 from around USD15 billion predicted for the year 2002. Currently, a large part of the revenue is from MEMs, used largely in automobiles, but the scenario is changing with many new applications getting developed.

There have been different kinds of estimates of industrial concerns devoted to nanotechnology. The best estimate for number of firms focusing on nanotechnology-related work worldwide is around 550 (as of 2002 end), includ-

Table 6. Common traits of nanotechnology startups

Previous experience with startups
Strategic technology availability
Access to financial support
Information availability
Notion of viability
Risk-taking ability
Capital investments
Confidence level
Linkages
Networking
Areas of pursuit
Location influence
Predominant government funding

Source: Culled from ref. 4.

ing large firms that have opened up units devoted to nanotechnology, startups and firms that have gone public. Out of these firms, around 100 are public firms or large multinationals and the remaining are private firms. Companies such as Dupont, Dow and BASF are among the large companies that are focusing on nanomaterials research for specific applications related to semiconductor chemicals, LCD panels and automobile parts, generally focusing on new nanomaterials. Other large companies such as IBM, Hewlett Packard and Bell Labs are focusing on electronic components and memory. Several leading biotechnology companies including Amgen, Genentech, Pharmacopea and others are turning their focus towards health-related nanotechnology applications.

On studying the companies focusing on nanotechnology worldwide, one interesting feature is that in almost each category there are some established companies with large interests in competing staple products, which are also into development of the new technology together with other new entrants. But a majority of the companies are startups. As seen in Table 6, almost all the companies have strong linkages with scientists who are either currently attached to universities or research institutions and are researching nanomaterials or were actively involved in nanotechnology research before joining the companies.

As in the case of most evolving technologies, largely government funding supports development, but other forms of funding has also played a very prominent role. Seed funding, angel funding and organized venture capital funding have been all contributed. In addition, large companies have patronized startups in many cases. These are healthy trends that indicate commercialization efforts of some of the more promising technologies are already underway, while development of other technologies is taking place simultaneously.

As noted, there are many established companies, which have set up specific outfits focused on nanotechnology applications. These include IBM, DuPont, Intel, Bell Labs, Proctor & Gamble, BASF, Bayer, Merck, Henkel and Samsung. Many of them are actively partnering with small firms for the development of new nanotechnology products. Whether these companies have a leadership in the days ahead in the nanotechnology-based products as compared to the tinier enterprises that have mushroomed in this industry is to be watched. Some recent partnerships have been indicated as an illustration in Table 7.

Is it still too early for India?

Ultimately, does this technology make sense for a country like India? It is no more arguable whether we need to also take conscious steps to develop capability in nanotechnology. It is seen that countries, both large and small, have been serious about consciously developing a strong knowledge base in this area. Two kinds of efforts are discernible. Realizing the nature of growth and development in the field of nanotechnology, there has been increased emphasis on multidisciplinary endeavours in the last couple of years. Countries have also been framing funding decisions based on high level goals, which would no doubt be reviewed from time to time to ascertain relevance and progress. To illustrate the kind of importance, for instance, in Europe, nanotechnology funding constitutes between 4% and 20% of total European research funding alone. US funding statistics over the years have been substantial as illustrated in Table 5.

It cannot be pondered any further whether this technology is crucial enough as it is being stressed that emerging developments are likely to be fundamental to economic performance than any other previous technology revolution. This would profoundly affect even a predominantly agrarian economy such as ours. A number of specific focus areas need be implemented as early as possible to prevent setbacks due to past complacency.

Apart from developing a strong science and technology base in this field through concentrated research efforts, an appropriate environment for allowing fledgling industry based on this technology to flourish must be provided. Technology developed in laboratories and research insti-

Table 7. Illustrative list of innovative products made using new developments in nanotechnology

BASF	Clear and clean sunscreen based on ZCOTE nanodispersed zinc oxide	Material source: Nanophase Technologies, Illinois US
Babolat, France	VS nanotube power racquets for tennis using high modulus graphite with carbon nanotubes	Material source: Nanoledge, France
Wilson	Double core tennis balls with Aor D-Fense nanocomposite products	Material source: InMat, New Jersey US
Hornberg, Germany	Easy cleaning tile based on nanoparticle coating	Material source: Nanogate, Germany
Eddie Bauer	Stain and wrinkle-free clothes, jeans using molecular structures added to cotton fibers	Material source: Nano-Tex, California US
Maui Jim	Eye glasses with protective and anti-reflective scratch-resistant glass coating made using novel chemical self assembly	Material source: Nanofilm, Ohio US
GM	GMC Safari's 2002 model uses thermoplastic olefin nanocomposite step assist	Material source: Southern Clay, Texas US
Samsung	HDTV using carbon nanotubes for display leading to better resolution	Material source: Samsung

Source: Culled from the company sources.

tutions must be transferred most effectively to industry and suitable mechanisms must be put in place to ensure successful commercialization. At the same time, media efforts to dispel the notion that nanotechnology is mere science fiction and to inform the general lay public of the immense potential and future possibilities of this technology must also be organized. Mechanisms to specifically teach courses and encourage research opportunities for young scientists and technologists in this field must be instituted.

An implementation plan can be drawn up in tune with the objectives and strategy outlined in the new Science and Technology Policy[5].

Conclusions

The nanotechnology industry is heralding a new world order. The number of sectors that are involved are many, due to the multi-disciplinary nature of the technology, offering scope for numerous opportunities. Nanotechnology is heavily intertwined with biotechnology and information technology, making its scope very wide. Generous funding from governments and venture funds is helping initiate new ventures. Looking at worldwide developments in recent years, it is time India forges a nanotechnology policy in tune with the specific needs of the country and its existing strengths.

1. *CMP Cientifica*, CMP Cientifica, Madrid, July 2002.
2. *National Nanotechnology Initiative, The Initiative and its Implementation Plan*, National Science and Technology Council, Committee on Technology, Subcommittee on Nanoscale, Science and Engineering, NSET, 2000.
3. *Nanotechnology Research Directions: Vision for Nanotechnology R&D in the Next Decade*, National Science and Technology Council, Interagency Working Group on Nanoscience, Engineering and Technology, NIST, 1999.
4. Bhat Jyoti, S. A., *Issues and Concerns of New Technology Based Industries – Advances in Nanotechnology*, ICMARD, 2003.
5. Science and Technology Policy 2003, Ministry of Science and Technology, Government of India, 2003.
6. Josh Wolfe, *The Nanotechnology Report*, Lux Capital, 2001.
7. *Sci. Am.*, September 2001.
8. European Nanobusiness Association, October 2002.
9. Budget FY 2003, Report, NSTC/NSET, 2002.
10. Internationaler Wissenstransfer und technischer Wandel, Heidelberg, 2001.

ACKNOWLEDGEMENTS. The support and encouragement of Dr R. A. Mashelkar, Department of Scientific & Industrial Research is gratefully acknowledged. This article is based on research carried out by me while at Sloan School of Management, MIT, USA on a Fulbright Fellowship.

Received 21 May 2003; revised accepted 3 June 2003