Nanoscience and nanotechnology initiatives in India

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General introduction

The prefix 'Nano' in the words nanoscience and nanotechnology means a billionth[1] (1×10^{-9}) and is derived from a Greek word meaning 'Dwarf' or extremely small. A nanometer (nm) is a billionth[1] of a metre or one-millionth of a millimetre. It is nearly 100 000th the diameter of a human hair and a single human hair is around 800 000 nm in width. The realm of nanotechnology, in general, lies between 1 and 100 nm. Nanotechnology literally means any technology performed on the nanoscale that has applications in the real world. There is no single definition of nanotechnology acceptable to everybody. Nanotechnology is based on the concept that particles less than about 100 nanometres (nm) impart to materials new and novel properties and behaviour. Particles of any material like metal, semiconductor or ceramic having a diameter below 100 nm constitute nanoscale clusters. A size comparison among commonly known objects are shown in Figure 1. The physico-chemical properties of such nanoparticles neither correspond to those of the free atoms or molecules making up the particles nor to those of bulk solids with identical chemical composition, but are controlled by phenomena that have critical dimensions on the nanoscale. Such nanoclusters are also characterized by a large value of the surface area to volume ratio, which signifies that a large fraction of the atoms resides at the grain boundary. In general, up to about 70% of atoms in nanoscale materials are exposed on the surface and thus can be involved in surface catalytic reactions, which compares to the very small percentage of atoms in bulk metal catalysis. Some nanoparticles are also known as *quantum dots* due to the quantum confinement of the electrons. In 1 nm there may be 3–5 atoms depending on the atomic radii, because the average size of an atom is of the order of 0.1–0.2 nm. All things are made from atoms and therefore the properties of materials depend on how their atoms are arranged at the nanoscale. Presently, scientists are merely able to arrange atoms and molecules in a mass at the nanoscale with considerable success, but eventually it is likely that nanotechnology will allow us to design all the objects we require. Nanotechnology has highly promising prospects for turning fundamental research into innovative results, and is likely to make positive changes in the lives of mankind in many different fields such as medicine, environment, electronics etc.

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[1] This is standard terminology in the USA. In Europe, 'billionth' is 1×10^{-12}, and 'milliardth' refers to 1×10^{-9}.

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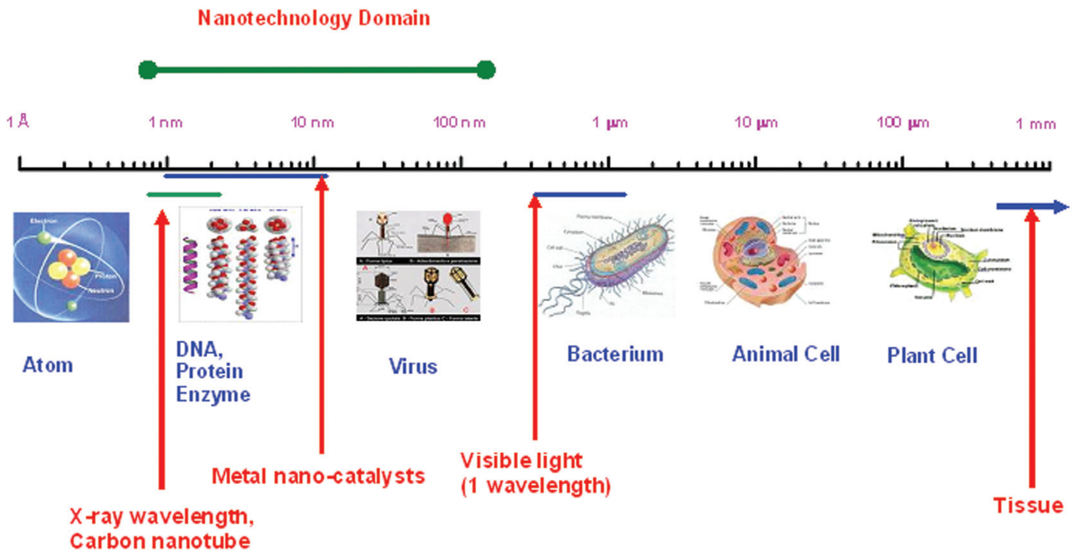

Figure 1. Comparison of the sizes of commonly known objects. The nanoscale (nanotechnology domain) lies in the 1–100 nm range (approximately). Biological catalysts (enzymes etc.), heterogeneous metal/metal oxide catalysts (surface active) and the wavelength of X-rays all lie in the nanoscale domain.

The effect of particles size on the characteristics of materials can be demonstrated with the simple example of elemental gold: the melting point of bulk gold is 1064 °C, whereas 1.5 nm-sized gold particles melt at about 500–600 °C. Similarly, gold is inert in its bulk form, but if the diameter of the particles is reduced to a few nanometres, it acquires catalytic properties and can convert carbon monoxide to carbon dioxide efficiently. Even the colour of gold changes from yellow (in the bulk) to other colours like blue, green etc. depending on its size.

Nanotechnology is a new word, but is not an entirely new field. There are many objects and processes in nature that function on a macro- to nanoscale,[2] and which may pave the way through guidance and imitation for producing nanodevices. For example chlorophyll, arranged within plant cells on nanometre to micrometre scales, can capture light energy and convert it into chemical energy. The bacterial flagellum rotates at over 10 000 rpm and is an excellent example of a biological molecular machine. It is not known exactly when humans started to apply the advantages of nanosized materials, but during the fourth century A.D., Roman glassmakers were already fabricating glasses containing nanosized metals like gold (red glass) and silver (yellow glass). The beautiful colours of the windows of medieval cathedrals are due to the presence of metal nanoparticles in the glass.[3] Another important (eighteenth and nineteenth century) application of such nanosized particles is in photography, where silver nanoparticles sensitive to light were developed.

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[2] B. Bhushan, Introduction to Nanotechnology, in: B. Bhushan (ed.) Springer *Handbook of Nanotechnology*, Berlin: Springer-Verlag (2004).

[3] C.P. Poole, Jr. and F.J. Owens, *Introduction to Nanotechnology*, New Jersey and Canada: Wiley-Interscience (2003).

Although widespread interest in nanomaterials is very recent, the concept was raised over 45 years ago by the physicist Richard P. Feynman at the Annual Meeting of the American Physical Society on the 31st December 1959. One important vision was put forward in his lecture "*There's Plenty of Room at the Bottom*": he speculated on the possibility of nanosized devices and related technology. In 1974, the word 'Nanotechnology' was introduced by Prof. Nori Taniguchi in Japan, and in 1981, Dr K. Eric Drexler, a young student at Massachusetts Institute of Technology (MIT), published the first technical paper on 'molecular nanotechnology'; in which he described something unconventional. Fractional nanoscience and nanotechnology started in the early 1980s after the two major developments, i.e. cluster science and the invention of the scanning tunnelling microscope (STM), which led to the discovery of fullerenes (in 1986), and have been important tools for the characterization of carbon nanotubes and semiconductor nanocrystals (quantum dots).[4]

The nanoscience and nanotechnology scenario in India

In 2005, India ranked 11th in the world, between Taiwan (10) and Spain (12) in terms of the number of nanoscience/nanotechnology papers published.[5] NanoIndia.com, the first Indian nanotechnology research news portal, has however recorded significant growth in its web traffic. Great interest in nanoscience and nanotechnology among the Indian people indicates that India is marching towards achieving the goal of excellence in nanoscience and nanotechnology. This public interest has been further enhanced by the support of the Department of Science and Technology (DST), Government of India, based in New Delhi, which promulgated (in 2003) a 'Nano Science and Technology Initiative' (NSTI) aimed at developing up-to-date technology in comparison to other countries. The DST has already allocated Rs. 100 crore for R&D under the scheme, though this amount is very small compared to the investments made by other countries like the USA, Japan, in Europe, etc. Several "*Units of Nano Science & Technology*" (UNANST–DST) have been opened with the aid of the DST at different Institutions and Universities of India such as the Indian Institutes of Technology (IIT) at Madras, Kanpur and Delhi; the University of Poona (Pune); Banaras Hindu University; the Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore; the Indian Institute of Science (IISc), Bangalore; the Indian Association for the Cultivation of Science; the S.N. Bose National Centre for Basic Science; and the Saha Institute of Nuclear Physics, Kolkata. Besides these institutes, research in nanoscience and nanotechnology is being carried out in many of the existing academic and scientific institutions in India, such as the University of Delhi, IIT in Mumbai, Kharagpur, Guwahati etc., other parts of the IISc in Bangalore, DRDO (Gwalior), NIPER (Chandigarh), CSIR Laboratories (the National Chemical Laboratory, Pune; IICT, Hyderabad; CCMB, Hyderabad; RRL-Trivandrum; RRL-Jorhat etc.), Jadavpur University (Kolkata), etc.

The Indian President, Dr A.P.J. Kalam, believes that nanotechnology research, development and commercialization will be important for India to become a developed nation

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[4] J.J. Ramsden and M. Grätzel, The photoluminescence of small CdS particles, *Journal of the Chemical Society, Faraday Transactions* 1, 80 (1984) 919–933.

[5] R.N. Kostoff, R.G. Koytcheff and C.G.Y. Lau, *Nanotechnology Perceptions,* 2 (2006) 229.

by 2020. Dr Kalam has emphasized that India should utilize the opportunity, as nanotechnology has tremendous applications in the fields of medicine, electronics, and materials science. The eminent scientist, Prof. C.N.R. Rao, has noted, "India cannot afford to miss the revolution in nanotechnology and must make investments in the area carefully. We shall not be able to do it later in those areas of nanotechnology that may become big in the next five to six years."

Nanotechnology may offer cheaper and faster medical diagnosis, new therapeutics and novel methods of drug delivery. India has a huge potential to market nanotech products. Carefully selected investments in nanotechnology can enhance economic development and pave the way for becoming a developed nation by 2020. Prof. Jayesh Ballare, Head of the Nanobioscience Project at IIT Bombay and his team are pursuing the development of soft nanomaterials, nano-bio-engineering materials, nano-biomedical devices, nano-bio-optics, drug delivery materials etc. Several industries are exploring opportunities in nanotechnology. There are about 100 pharmaceuticals, biotechnology and biomedical companies in India working on nano-based technologies. As of now, the major funding for nanotech R&D is sourced from Government agencies. The private sector is also spending on nanotech, but relatively little. Considering the huge market potential for nanoparticles in India, companies from China, Japan and Iran are entering the domestic market through tie-ups. An Iranian company called Tide Waters has entered into a tie-up with Mumbai-based SSB Technology to market its range of products under the brand name Nanocid in India. Besides public sector R&D institutions, there are companies like Cranes Software International Limited, Monad Nanotech, Naga Nanotech India, Velbionanotech etc. in India that are working on nanotechnology.

According to Mr Anurag Gupta, CEO of Yash Nanotech, leading companies like Reliance, Tata Group etc. are also making investments in nanotechnology development. Cranes Software International Limited has set up research into NEMS and Nanotechnology at India's leading institutions like IISc Bangalore. Velbionanotech, ranked in Asia's top 100 bionanotechnology companies is designing drugs for various ailments such as heart disease, kidney stones, AIDS, cancer etc. Monad Nanotech is another company producing carbon nanomaterials (CNM) commercially using low cost production technology developed by Prof. Maheswar Sharon's group at IIT Bombay. Besides carrying out research and development and producing nanomaterials, Monad Nanotech has taken up the agency for China's Shenzhen Nanotech Port Co. Ltd (NTP) for sales in India and Canada.

There are non-government organizations working to act as a bridge between academia and industry in technology. The Nanotechnology Research and Innovative Foundation (IndiaNano) is one such non-profit organization supported by academic and industry experts aimed at developing a platform for real-time strategic collaboration between diverse groups in order to harness the benefits of progress in advanced technologies, including nanotechnology. The IndiaNano has an "Innovation Acceleration Network" (IAN) designed to bridge the gap between invention and commercial reality by providing pragmatic support for technology entrepreneurs in global markets. To give an example of such support, in January 2006 the Nanotechnology Research and Innovation Foundation (USA) and the Regional Research Laboratory (RRL-T) have collaborated to form a strategic partnership that will allow the pooling of their respective expertise and thereby facilitate the commercialization of technologies in India and around the globe.

The Nano Science and Technology Consortium is another non-governmental, industry-managed and -promoted organization to facilitate the processes of nano-development. An Indo-UK collaboration programme in nanoscience and technology is beginning to take a shape with participating scientists from both countries. Veeco Instruments Inc., New York, a leading manufacturer and supplier of instrumentation to the nanoscience community, has been establishing a nanotechnology centre at Bangalore, India. The centre will be equipped with the latest sophisticated metrology equipment, e.g. AFM (atomic force microscope), STM etc., and the Veeco-India Nanotechnology Laboratory will be jointly operated with JNCASR, Bangalore, for promoting interdisciplinary areas of the science and technology.

Opportunities in India

Realising the huge potential of nanotechnology, the Government of India has started supporting various research and commercialization activities in India. The technology is still in its infancy in our country. Scientists are trying to establish interdisciplinary centres for nanotechnology research. There is, perhaps, a gap in understanding about nanotechnology between the bureaucracy and other wings of policy-making in India, and this may be one of the reasons why in India progress in nanoscience and nanotechnology development is slow compared to other developed countries. In support of this, Mr Kapil Sibal, Cabinet Minister of Science and Technology, has remarked, "Until a coordinated and pro-active approach is adopted towards the integration of front line sciences, the best of inventions conceived by our scientists will fail to get project coordination work that will evade us investments and higher yield in areas of agriculture, horticulture, food products and even in manufacturing".[6]

With due consideration of the importance and wide applications of nanotechnology as a research and learning focus, the Amity Institute of Nanotechnology (AINT) has been established, and started M.Tech. courses in 2003, under the auspices of the Ritnand Balved Education Foundation (RBEF). This Institute has close collaborations with other National Institutes like NPL, IIT, BARC, TIFR etc. Besides teaching, the Institute has initiated research programmes in different directions, such as carbon nanomaterials, nanophosphors, drug delivery, water purification, nano-oxides, etc.

It is expected that there will be no sector of industry that will not use nanotechnology in the future. According to Dr Pankaj Podder, a scientist with the Nanoscience Group, National Chemical Group, Pune, the fields of nanoscience and nanotechnology have brought physicists, chemists, biologists, engineers and medical scientists together for the first time in order to brainstorm and engage in multidisciplinary research. Though the field of nanoscience and nanotechnology are in their infancy in India, the country is making dedicated efforts to catch up fast in these areas. In fact, this year, the Indian Government launched a scheme, called the "National Nanoscience and Technology Mission", with a proposed outlay of Rs. 1000 crores spread over five years, although it should be noted that the funding is considerably less than that available on developed countries like the UK, where Government funding alone for R&D in nanoscience and nanotechnology is estimated at £45 million per year from the year 2003 to 2009.

[6] N. Kulkarni, Source: Biosphectrumindia, www.nanoindia.com/news: Nanotechnology in India (2006).

It appears that there is a great demand for students who do their M.Tech. in nanotechnology both in India and abroad. Job opportunities exist in academic and other research institutes and in the R&D divisions of companies, and offer high salaries. Dr Mark Welland, Director of the Nanoscience Centre at Cambridge University and Fellow of the Royal Academy of Engineering, has indicated that India is likely to get a big benefit from nanotechnologies because of its well-trained manpower in the IT sector, and developing expertise in nanotechnology will aid in manufacturing computer hardware cheaper, making India an even more attractive global destination for IT.[7]

Highlights of some initiatives and research activities in nanoscience and nanotechnology in various institutes in India

The Department of Science and Technology, New Delhi (Government of India), announced a 'National Initiative in Nanomaterials' and organized an International Conference on Nano Science and Technology in Kolkata in December 2003. Several research organizations, Universities and other educational institutes participated in the conference and presented a wide range of nano research activities. The premier institute, the "Jawaharlal Nehru Centre for Advanced Scientific Research", Bangalore, has pioneered the research activities in nanoscience in India, and under the able leadership of Prof. C.N.R. Rao, the Centre has carried out research activities in nanoscience that have been able to establish a sophisticated infrastructure, including equipment such as atomic force microscopes.[8] The major nanoscience activities are: development of carbon nanotubes (both multi-walled and single-walled), nanocrystals of various metals such as gold, silver, palladium etc., and metal oxides of iron, for applications in surface coating and data recording purposes. Single electron nanostructures (quantum dots), Y-junction nanotubes (for possible use as diodes), nanotubes of different inorganic materials, dip pen nanolithography, and nanowires from diverse materials, etc., are all in the developmental stages.

The Indian Institute of Science, Bangalore, is another premier research centre where considerable research activities in nanoscience and nanotechnology development are continuing. Modern infrastructure with the required equipment for conducting nanoscience has been established. The centre has several prominent nanoscience research developments, such as nanoparticle-based semiconductors for applications in electronics and optics, and doped nanoparticles of copper, cobalt, manganese etc. for other applications. The centre has done considerable nano-research relating to the development of advanced materials. For example, since the energy level spacing or band gap in quantum dot materials increases as the size of the material diminishes, 'tailor-made' materials are therefore possible with varying band gaps as a function of particle size, for possible applications in electronic devices for use in fields such as telecommunications (low band gap is required for fluorescence in the infrared region), and in biological applications (they often require the green region of the spectrum of electromagnetic radiation). The centre has developed a cadmium sulfide-based light sensor. Other research activities such as the development of highly luminescent nanoparticles with different emission wavelengths are progressing.

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[7] S. Chattopadhyay, News writer, The Telegraph, (Careergraph) (30 Nov. 2006), Kolkata.
[8] M.S. Rajan, NANO, *The next revolution*, New Delhi, National Book Trust India, (2004).

The National Chemical Laboratory (NCL), Pune, has accomplished exciting work in different fields of nanoscience, particularly bio-based systems. The possibilities of making self-assembled nanoparticles of metals and compounds by using an appropriate micro-organism (bacteria, fungi, algae etc.) have been explored, and could be the basis of developing bio-friendly processes. The major thrust of NCL in nanoscience and nanotechnology research is on nanomaterials at the interface between chemistry and biology. Groups of researchers consisting mainly of physicists, chemists, biochemists and molecular biologists have screened a large number of different kinds of fungi for the successful synthesis of nanoparticles of metal and metal sulfides. They have also used fungi such as *Verticillium* sp. and *Fusarium oxysporum* for generating silver and gold nanoparticles. They have also prepared quantum dots of cadmium sulfide utilizing fungi. A fungus-enzyme system could be used advantageously in synthesizing nanoparticles of different shapes and sizes as well as chemical compositions. Such a bio-based process of nanoparticle production may be economically viable for commercial exploitation. Under the leadership of Dr Prasad Bhagavatula, the Nanoscience Group of the Physics and Materials Chemistry Division is pursuing the synthesis of shape- and size-controlled of nanomaterials, as well as of core-shell materials, etc.

The Indian Institute of Chemical Technology (IICT), Hyderabad, has also developed peptide-based carbon nanotubes. In a similar line, the Nanotech Research Laboratory at the Centre for Advanced R&D, Allahabad, explored lichen biomass as a 'nanofactory' for producing nanoparticles relevant to the development of nano-drugs. Such eco-friendly bio-processes have good potential for commercial production. The scientists in the Microbial Science Division of the Agharkar Research Institute, Pune, have done considerable research on biological strategies for the production of metal-based nanocrystallites. They are able to synthesize cadmium sulfide nanoparticles (size about 1.5 nm) from metallic cadmium using some yeast strains.

The scientists at the Surface Physics Division of the Saha Institute of Nuclear Physics, Kolkata, are studying the basic thermal properties of thin polymer films. In the S.N. Bose National Centre for Basic Sciences, Kolkata, Prof. Anup Raychoudhury and his group are experimenting with condensed matter nanoscience, including low temperature characteristics. At the Rubber Technology Centre, IIT Kharagpur, scientists are developing *in situ* polymerization technique for synthesizing polymer nanocomposites, for applications in various fields. Such hybrid nanomaterials exhibit superior mechanical strength over conventional composites.[9] Polymer-clay composites have been developed for applications in a variety of fields exploiting their mechanical, electrical etc. properties.[10]

Small metal particles dispersed on oxide supports have been used as high surface area catalysts for many years in industrial chemical processes, e.g. the production of silver nanoparticles used for the epoxidation of ethylene in ethylene glycol production, oxide-supported rhodium, palladium and platinum particles used in the treatment of automobile exhausts in catalytic converters, and electrocatalytic platinum-ruthenium nanoparticles in fuel cells. Nanoparticles have been shown to possess many enhanced characteristics compared with

[9] D. Ratna, B.C. Chakrabarty, H. Dutta, and A.K. Banthia, International Conference on Nanomaterials: Synthesis, Characterization and Applications, 4–6 November 2004, Kolkata, Proceedings, P-145.

[10] K.P. Dasan, G. Unnikrishnan and E. Purushthoman, International Conference on Recent Trends in Nanoscience & Technology, 7–9 December 2006, Kolkata, Proceedings, P-226.

micro- and larger particles, which will be more beneficial and valuable to mankind than the conventional materials in the micrometre size range. Only recently, the impact and benefit of nanomaterials on and for economic growth and technological advancement, as well as their capability to create new products, to spawn new industries, and to reshape or revolutionize traditional industries are beginning to be broadly recognized.

Most metals in the solid state form close-packed lattices, thus silver, gold, etc. form a face-centred cubic (FCC) lattice. Each atom in the lattice (except at a surface) has 12 nearest neighbours and thus the 13 atoms constitute the smallest theoretical nanoparticle for an FCC lattice.[2] Thus, by adding more layers, one can get nanoparticles with 55, 147, 309, etc. atoms, which are called 'structural magic numbers'. Purely metallic FCC nanoparticles such as Au_{55} tend to be very reactive and hence need be stabilized.[2] Most types of nanoparticles tend to aggregate to form larger (and hence less efficient from the viewpoint of whatever property is being nano-enhanced) materials unless "capped" by a suitable material. This capping, however, reduces the surface available for reactions. Therefore, suitable structured materials need be developed to hold the nanoparticles together without the capping material.

The scientists at the CSIR Regional Research Laboratory, Jorhat, have recently reported *in situ* generation of Ni^0-montmorillonite K10 (Composite I) and Zn^0-montmorillonite K10 (Composite II) by polyol reduction of nickel acetate- and cobalt acetate-impregnated montmorillonite K10.[11] The TEM study reveals that the size of metal nanoparticles in Composite I is about 30 nm and hence they are comparatively smaller than those of Composite II, in which the maximum particle size of the metal limits it to 40 nm. TEM images of Ni^0- and Zn^0-montmorillonite K10 composites are shown in Figure 2.

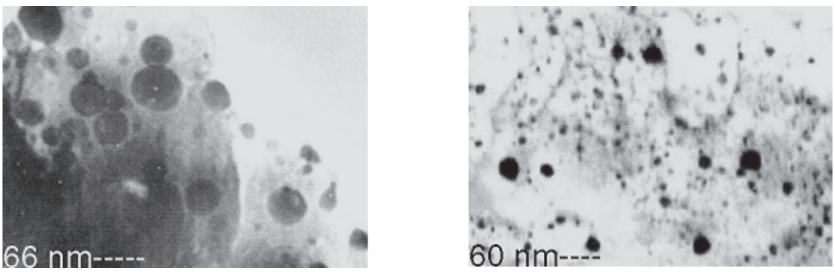

Figure 2. Transmission electron micrographs (TEM) of (left) Ni^0- and (right) Zn^0-montmorillonite K10.

An X-ray diffraction (XRD) study has shown the face-centred cubic structure in both the composites. They have also been characterized by thermal and infrared (IR) absorption and reflectance studies. Such nanometal-clay composites may find applications as bifunctional catalysts (with both metal and acid functions). In another piece of work, the *in situ* synthesis of metal clusters of sizes 4.1 and 3.2 Å of Ni^0 and Zn^0 respectively in the interlamellar spaces of montmorillonite clay have been reported.[12, 13]

[11] O.S. Ahmed and D.K. Dutta, *Langmuir,* 19 (2003) 5540.
[12] S. Ayyappan, G.N. Subbanna, R. Srinivas Gopalan, C.N.R. Rao, *Solid State Ionics*, 84 (1996) 271.
[13] O.S. Ahmed and D.K. Dutta, *Thermochim. Acta*, 395 (2003) 209.

Different expected fields of applications of nanomaterials and their markets

Since nanoparticles possess unique chemical, physical and mechanical properties, they can be used for a wide variety of novel applications. Some important ones are (the list is not exhaustive):

1. Next generation computer chips,
2. High energy density batteries,
3. High power magnets,
4. High sensitivity sensors,
5. High performance weapons,
6. Longer-lasting satellites,
7. Longer-lasting medical implants,
8. Large electrochromic devices,
9. Phosphors for high-definition television,
10. Pollution abatement,
11. Higher performance insulating materials.

The uses of nanoparticles are set to escalate and the market has the potential to increase dramatically over the next ten years as more uses for these materials are developed and commercialized. There are however many challenges facing the nanomaterials companies that need to be overcome before this potential can be fully realized.

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