NANO MATERIALS – ARE THEY FUTURE ENGINES OF DEVICES?

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INTRODUCTION

Identification of the concept of nanotechnology has been usually attributed to Richard Feynman's, lecture in 1959 titled "There's Plenty of Room at the Bottom." In this speech, Feynman described manipulating individual atoms to make materials of different kind many decades before it became possible to do so. The term "nano-technology" itself was probably first used in 1974 by Taniguchi of the University of Tokyo, Japan, to refer to the ability to engineer materials precisely at the nanometer level, driven by the needs of electronics industry. In 1981, the advent of the scanning tunneling microscope enabled scientists to see atom clusters at that scale, while in 1991 IBM demonstrated the ability to arrange individual xenon atoms using an atomic force instrument.

What is nanotechnology? A variety of definitions for nanotechnology have been presented. By the U.S. National Nanotechnology Initiative (NNI) standards, nanotechnology involves all of the following:

- Research and technology development at the atomic, molecular, or macro-molecular levels, approximately 1–100 nanometers in length.
- Creation and use of structures, devices, and systems that have novel properties and functions because of their small and/or intermediate size.
- Ability to control or manipulate on the atomic scale.

The Royal Society and The Royal Academy of Engineering define nanotechnologies as the design, characterization, production, and application of structures, devices, and systems by controlling shape and size at the nanometer scale. Others have more prosaic descriptions that perhaps lack definitional precision but provide insight. As Gary Stix described nanotechnology in *Scientific American*, "The field is a vast grab bag of stuff that has to do with creating tiny things that sometimes just happen to be useful. It borrows liberally from condensed-matter physics, engineering, molecular biology and large swaths of chemistry."

The reason that size matters is that the properties of materials can have some unexpected differences from their behavior in larger bulk forms that makes for new application opportunities. The two reasons for this change in behavior are an increased relative surface area (producing increased chemical reactivity) and the increasing dominance of quantum effects (with effects on the material's optical, magnetic, or electrical properties). Essentially systems with high values area to volume ratio are known to be efficient systems like the brain, leaf and the chips. Quantum effects can give rise to electron exchanges in multiple pathways and hence can be exploited in many of the electronic devices. Because of these two possibilities namely, the efficiency and multiple pathways, Nano materials can be exploited in a variety of devices in almost all the areas of technology, starting from drug delivery to manufacturing processes like catalysis. It may not be possible to cover all the areas of application of nano materials and hence in this presentation, certain restrictions are imposed and the selections have no special significance.

NANOMATERIALS

Not unlike the situation in conventional Materials science and technology, materials are critical if sometimes underappreciated components in achieving the goals of nanotechnology. A central construct of materials science and engineering is that the structure and processing of a material give rise to its properties, which in turn determine its performance in use. This certainly applies to nanomaterials as well and provides a useful framework for understanding in a familiar context.

Nanomaterials have been important in the materials field for quite a long time. An early example was the incorporation of gold nanoparticles in stained glass in 10 A.D. Nanosized carbon materials have been used over 100 years to reinforce types. Rice grains in smashed form are easily digestible is a direct demonstration of the reactivity increase with decrease in size. Another familiar example is the precipitation hardening which metallurgists employ over the past 100 years or so.

What then are the nanomaterials of today and tomorrow? Jones has given an organizational structure for the evolution of nano technology into three categories. The categories are:

- Incremental nanotechnology—improving the properties of materials by controlling their nanoscale structure.
- Evolutionary nanotechnology—taking a step beyond redesigning simple materials at the nanoscale and designing nanoscale devices that do something interesting
- Radical nanotechnology—developing nanoscale machines that would exist at the convergence of nanotechnology, biotechnology, information technology, and cognitive technology.

It should be remarked that this type of classification can be highly personal and hence a variety of ways the whole situation can be imagined in various frameworks.

Incremental nano technological materials include, nanoceramic powders, zinc oxide powders for sunscreens, solid aluminium powders for solid propellant, polymer nano composites for automobile applications, and many other metallurgical advancements in application and knowledge like deformation mode from dislocation-slip to grain boundary sliding as a function of grain size.

The most important material that has found application in the evolutionary nano technology is the carbon materials. It is known that the carbon Nano Tubes (CNT) is 30 times stronger than steel at 1/6 of the density of steel and also possess nearly 50% higher thermal conductivity than that of diamond. However, carbon nanotubes are no means the sole materials of focus for evolutionary nanotechnology. A variety of electronic materials, nanowires, quantum dots semiconductor nanocrystals, nanoscale thin films and organic nano materials also belong to this category. These materials can have high impact not only in electronic industry but also in efficient energy conversion devices and storage.

Radical nanotechnology is viewed as having an impact much farther into the future. Examples include next generation military uniforms that are designed to defend against chemical and biological weapons, provide ballistic protection, monitor health, administer medical aid, and provide communication capabilities. Much farther in the future are concepts which converge with biology, information technology and cognition.

NANOFABRICATION

Since nanomaterials have little mass and are dominated by surface area and size effects, the processes and equipment for nanotechnology-based manufacturing are expected to differ significantly from those currently used for bulk materials.. One of the key differences is the concept of manufacturing on an atom-by-atom basis, namely bottom-up processing which has been usually practiced by chemists. Conventional manufacturing methods, termed as top-down techniques, start with a block of material, etching or milling it down to the desired shape and size. The main challenge for top-down manufacture is the creation of increasingly small structures with sufficient accuracy, whereas for bottom-up manufacture, the challenge is to make structures large enough, and of sufficient quality, for use as materials. These two methods have evolved separately and have now reached the point where the best achievable feature size for each technique is approximately the same. Most of the current nanomaterials with potential for structural use are powder based, produced from processes such as inert-gas condensation, electro-deposition, atomization, and mechanical alloying. They need to be consolidated into shapes with minimal porosity without creating significant structural coarsening and loss of the desirable nano-structural properties. This requires a balance of minimal high-temperature exposure and adequate pressure, and innovative methods of consolidation need to be developed to produce successful materials.

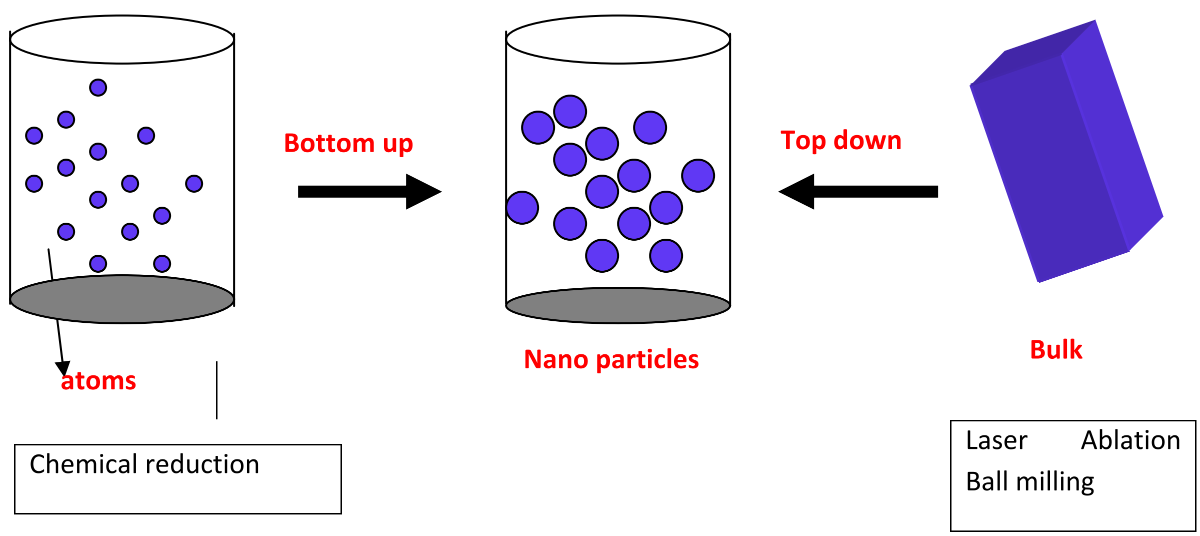

Fig. 1.2. Pictorial representation of the two approaches

SIZE DEPENDENT PROPERTIES OF NANOMATERIALS

It is therefore clear that nanomaterials and nanotechnology, depend on size dependent properties. In general they can be recognized as follows:

(i) Chemical properties – reactivity, catalysis
(ii) Thermal property – melting temperature
(iii) Mechanical property – adhesion, capillary forces
(iv) Optical properties – absorption and scattering of light
(v) Electrical properties – tunneling of current
(vi) Magnetic properties – super paramagnetic effect.

This list can be extended to include many other sensing and biochemical properties and functions. Normally the size of a nanometer is compared to that of the human hair which is 80,000 nm wide. To illustrate the comparison, in Fig. 2. the human hair fragment together with a net work of single-walled carbon nanotubes is given.

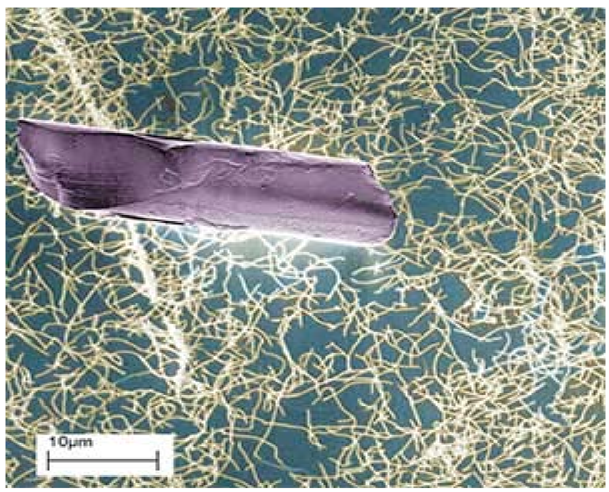

Fig. 2. Human hair fragment and a network of single-walled carbon nanotubes (reproduced from: http://www.nanowerk.com/nanotechnology/introduction/introduction_to_nanotechnology_1.html)

Even though a variety of methods can be adopted for the preparation of nanomaterials, in this presentation two of the commonly employed methods are briefly described. One of the most successful methods adopted for the synthesis of nano materials is the sol gel processing route under appropriate experimental conditions.

The sol gel process involves the combination of chemical reactions which turns a homogeneous solution of reactants into an infinite molecular weight polymer. This polymer is a three dimensional interconnected pores. The polymer is isotropic, homogeneous and uniform and it replicates its mold exactly and miniaturizes all features

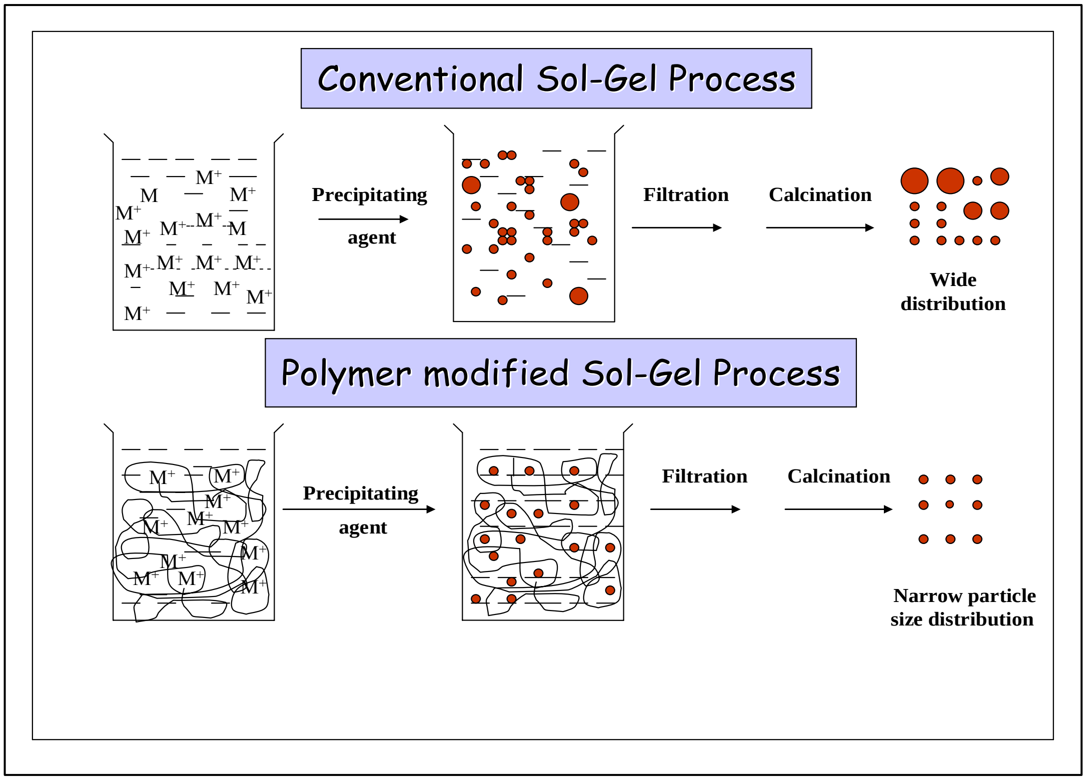

Fig. 3. Pictorial representation of conventional and polymer modified sol-gel process

without distortion. Thus the polymer net works provide nanostructure and nanophase porosity. A pictorial representation of this technique is shown in Fig. .3.

A variety of reaction conditions are employed for suitably architecture the nano materials. In the case of metal nanomaterials preparation various capping agents are employed and a pictorial representation of the same is shown in Fig. 4.

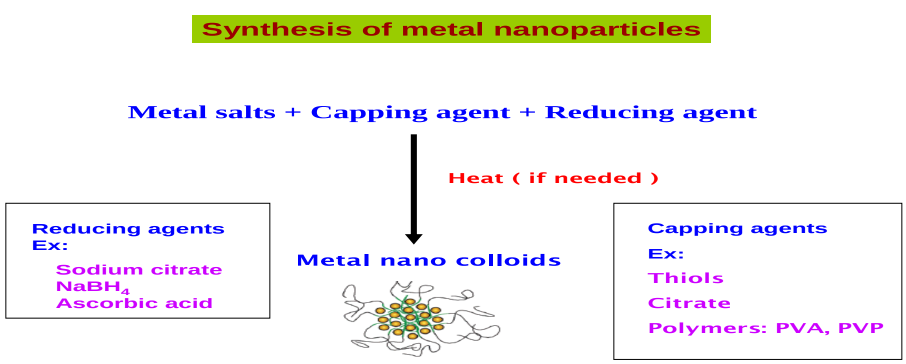

Fig. 4 Pictorial representation of the formation of metal nanoparticles employing capping agents

The factors that control the nucleation and growth routes of the nano particles formed are given in Table 1. The nucleation and growth of the particles are the crucial factors for controlling the size of the nano particles formed. This is usually achieved by choice of the suitable capping agents and also the functionality of the capping agents, their hydrophobic and hydrophilic parts interacting suitably with the particles formed and thus preventing the growth mechanism.

Table 1:Governing factors for the growth of nanostructures
• Kinetics of nucleation and growth
• Concentration of stabilizing agent
• Structure of the stabilizing agent
• Nature of the capping agent
• pH of the medium employed and temperature

There are various other methods that can be employed for the preparation of nano materials. One of the methods is termed as reverse micellar technique. A pictorial representation of this method is shown in Fig..5.

The reactivity of nano materials is usually attributed to the ratio of the number of surface to bulk species. This number can be as high as 60 % in the case of nanomaterials. This can be illustrated with the following data. A typical material

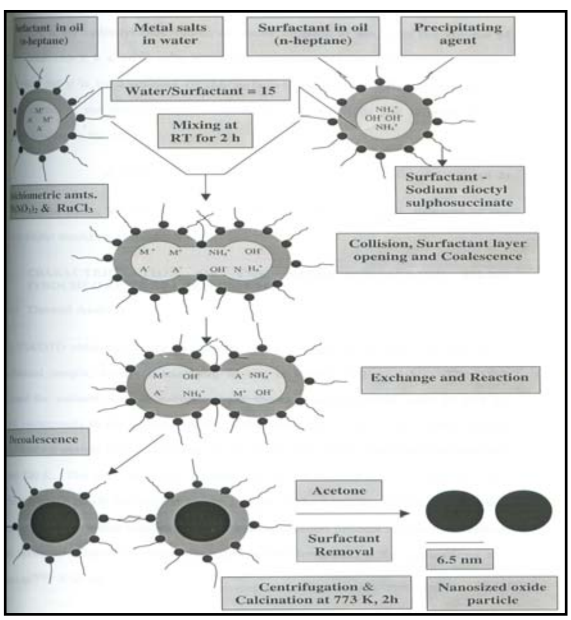

Fig. 5. A pictorial representation of reverse micellar technique for the preparation of nanomaterials

possesses approximately 10^{23} atoms/cm^3 (volume density) and approximately 10^{15} atoms /cm^2 (surface density). For a cube with a side length of 1 nm the total number of atoms is ~10^{23} atoms/cm^3 X (10-7 cm)^3 ~ 100 whereas the number of surface atoms is ~10^{15} atoms/cm^2 X 6 X (10^{-7}cm)^2 ~ 60 and this gives a ratio of surface to total atoms of 60%. Surface atoms possess more energy than bulk atoms and hence the surface atoms are chemically more reactive.

Nanomaterials thus exhibit remarkable reactivity. This can be exploited in a number ways. It is envisaged that nanomaterials find applications in every sector of human life requirements. This presentation will attempt to outline some of the applications of nano materials in a few of the essential sectors of human life.

Appendix

Though nanomaterials have taken the centre stage of materials research today an exact definition of nano materials is still a point of contention. This is evident from the following definitions provided by different researchers from their points of view. (Only the essential lines from each of these definitions are reproduced here and for the original full text of the definitions the readers can look up: http://www.nanowerk.com/nanotechnology/introduction/introduction_to_nanotechnology_1.html).

"For me, nanotechnology is all about building things. Judging by current rates of progress in fields as diverse as protein engineering and nanoelectronics, the emergence of atomic-precision manufacturing on an industrial scale is still some decades away… ***"Thomas Theis*** is director of physical sciences at the IBM Watson Research Center.

"One way of defining nanotechnology is to talk about length scales. A different way is to see it as an upcoming economic, business and social phenomenon. Nano-advocates argue it will revolutionize the way we live, work and communicate. If it will dramatically affect everyone, shouldn't everyone have a say in what developments take place — with what impacts, under whose control, and with who benefiting (and losing)?......." ***Doug Parr,*** *is the chief scientist for Greenpeace in the UK*

"There isn't just one nanotechnology; there are many nanotechnologies and these are primarily enabling technologies and not end products in themselves. It would not surprise me if the term nanotechnology disappeared from general use in the next decade, with the terms nanomaterials and nanobiotechnology assuming greater currency….." ***Peter Binks*** *is chief executive officer of Nanotechnology Victoria, a consortium of four research organizations focused on the commercialization of nanotechnologies in Australia.*

“I see nanotechnology as a toolbox that provides nanometre-sized building blocks for the tailoring of new materials, devices and systems. The nanometre length scale (that is < 100 nm) offers unique size-dependent properties in physico–chemical phenomena….. ***“Jackie Ying*** *is the executive director of the Institute of Bioengineering and Nanotechnology in Singapore, and adjunct professor of chemical engineering at the Massachusetts Institute of Technology.*

“Nanoscience and nanotechnology can be regarded as areas defined by a chosen boundary, but I find it more fruitful to see them as directions united by shared objectives. Central among these is the atomistic understanding and control of an increasing range of physical systems and phenomena…..” ***K. Eric Drexler*** *wrote Nanosystems and Engines of Creation and is chief technical advisor to Nanorex.*

“Nanoscience is a very handy word for rather small things with a rather big impact. Why should we care about such small things? We may find properties that are useful for everyday life….” ***Elisabeth Schepers*** *is in the department of museums education at the Deutsches Museum in Munich, where she has recently been working for the EU Nanodialogue project.*

“……that invention is truly the watershed between nanotechnology and everything really small, like molecules, which came before but were, in the main, only accessible collectively…..” ***Kary Mullis*** *shared the Nobel Prize for Chemistry in 1993 for his work on the polymerase chain reaction technique. He is currently working on chemical methods to control and direct immune responses.*

“The converging interests of nanotechnology foresee the precise control of individual atoms or molecules, leading to an unprecedented ability to design material and device capabilities…..” ***Chunli Bai*** *is executive vice president of the Chinese Academy of Sciences, director of the China National Center for Nanoscience and Technology, and chief scientist of the China National Steering Committee for Nanoscience and Nanotechnology.*

“Indeed, one could reasonably argue that it is meaningless to refer to the innate properties of nanoscale systems without due reference to the influence of environmental factors such as surface termination, substrate interactions and electrical and mechanical contacts. Although this sensitivity is a challenge for nanoscale materials processing, it brings with it the potential for unprecedented levels of control of material and device properties…….” ***John J. Boland*** *is professor of chemistry and director of the Centre for Research on Adaptive Nanostructures and Nanodevices at Trinity College, Dublin, Ireland.*

“Nanotechnology is concerned with work at the atomic, molecular and supramolecular levels in order to understand and create materials, devices and systems with fundamentally new properties and functions because of their small structure….” ***Robert Langer*** *is the Institute Professor at the Massachusetts Institute of Technology, the* *recipient of the 2002 Draper Prize and a member of the National Academies of Sciences and Engineering and the Institute of Medicine.*

"Actually, nanotechnology has been around for over a hundred years. Irving Langmuir was one of the first to truly develop the technology in the General Electric labs in the 1920s and 1930s. Nanoscience is a label given now to the new work emerging from the technology we have developed to manipulate, visualize and make atomic and molecular structures. It would have been called surface science in the 1960s and 1970s. In the immediate future, we will see incremental changes in materials for energy generation and storage, improved and safer cosmetics and other domestic products, and new methodologies for healthcare, water treatment and pollution control……" ***Peter Dobson*** *of Oxford University has recently started two companies that use nanotechnology: Oxonica and Oxford Biosensors.*

"I want to be sure that the benefits of nanoscience reach all mankind. Although the research is being carried out in only a few countries and laboratories, I do hope that the poorest of the poor will benefit from the results of research in nanoscience and nanotechnology. " ***C. N. R. Rao*** *is a national research professor and the honorary president of the Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore, India.*

"My bottom line, however, is that the field should worry less about self-serving definitions (including my own!), and more about how to be of true benefit to humankind…..……" ***Mauro Ferrari*** *is professor of molecular medicine at the University of Texas Health Science Center, of experimental therapeutics at the M. D. Anderson Cancer Center, and of bioengineering at Rice University.*

For generating a working definition of nanotechnology, it can be defined as "development and utilization of structures and devices with organizational features at the intermediate scale between individual molecules and about 100 nanometers where novel properties occur as compared to the bulk materials." Though the term nanotechnology was first employed by Tokyo Science University Prof. Norio Taniguchi of Tokyo Science University in 1974 to describe the precision manufacture of materials with nanometer tolerances, the idea has been around for many centuries and it is often credited to Prof Richard Feynman for his 1959 lecture at Cal Tech titled there is plenty of room at the bottom. It is interesting to quote a few lines of this famous lecture.