Understanding, Prospects and Constraints of Emerging Nanotechnology

Manickam Sivakumar

Abstract Much effort is currently being devoted in Nanotechnology owing to its diverse range of technological applications. Nanotechnology deals with the design, characterization, production and application of structures, devices and systems by controlling their size and shape at nanometre scale. It focuses on manipulating the most basic components of all matter (atoms and molecules) with great precision and exploiting the novel properties or phenomena observed at that length scale as compared to their bulk-scale counterparts. Thus size effects become predominant at the nano scale. Most of the observed effects at this nano scale could be explained by surface and quantum confinement phenomena. It is an emerging interdisciplinary technology and promises significant advances in various technological applications. Nanotechnology is the new industrial revolution as it has the potential to revolutionise various sectors of the society. Still the potential of this technology has not been fully exploited as many questions still remain to be answered. Notwithstanding these advantages, it is a challenge to the government and industries as yet there are no specific regulations for assessing the toxicity or environmental impact of nanoparticles.

1 Introduction

Nanoscience which typically deals with the manipulation or controlling of materials at an atomic or molecular scale (1–100 nm) to create novel structures, devices and systems as the properties differ significantly in fundamental and valuable ways from those at larger scale (bulk matter). Whereas, nanotechnology concerns with the design, characterisation, production and application of structures, devices, and systems (Fig. 1) by controlling the size and shape at nanometre scale [1]. Alternatively it refers to many different technologies which are extremely small in

M. Sivakumar (✉)
Faculty of Engineering, Department of Chemical and Environmental Engineering, University of Nottingham Malaysia Campus, Kuala Lumpur 43500, Selangor, Malaysia
e-mail: Sivakumar.Manickam@nottinghm.edu.my

J. Ebenezar (ed.), *Recent Trends in Materials Science and Applications*,
Springer Proceedings in Physics 189, DOI 10.1007/978-3-319-44890-9_5

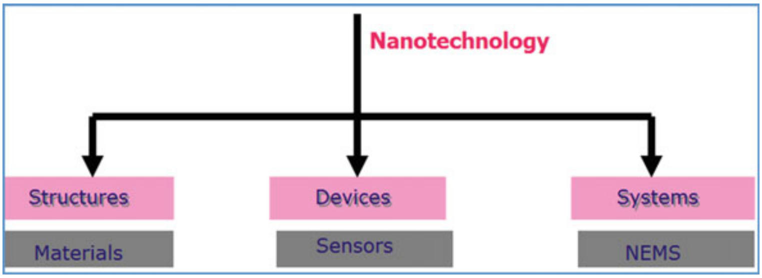

Fig. 1 Nanotechnology applied to structures, devices and systems

scale. In most of the instances, the focus of nanoscience and nanotechnology is on the manipulation of the most basic components of all matter i.e. atoms and molecules with great precision in the nanoscale range of 1–100 nm and then exploiting the novel properties or phenomena at that scale. By this it fills the gap between single atoms/molecules and microstructures.

It is an inherently interdisciplinary science encompassing physics, chemistry, biology, engineering, material science, computer science etc. This century belongs to interface science more precisely between molecular sciences and technology where the role of nanotechnology will be dominating and to prove this already a diverse range of nanomaterials and devices are on the technology road map of various high-tech industries. It is changing the nature of almost every human-made objects and influencing the economy in a greater way. In a more simple term nanotechnology could be described as "making things out of atoms". Although it is a small science but has a huge potential and the wide range of applications is the one force which drive the excitement surrounding the nano.

Although nanoparticles are generally considered an invention of modern science, they actually have a long history as they were used by artisans as far back as the 9th century in Mesopotamia to generate the glittering effect on the surface of pots [2]. The inspiration for molecular nanotechnology is Richard Feynman who gave a lecture on "There is plenty of room at the bottom" during a meeting at American Physical Society in 1959. He indicated that the problems in chemistry and biology can be greatly helped if our ability to see what we are doing and do thing on an atomic level is ultimately developed. Added to this, he precisely mentioned that those developments cannot be avoided [3].

2 Classification of Nanomaterials Based on Dimensions

Nanomaterial has at least one of its dimensions in the nanometric regime. Figure 2 shows the classification of nanomaterials based on dimensions in the nanometre range, number of directions where the electron confinement occurs and on the number of free directions for the electrons to move.

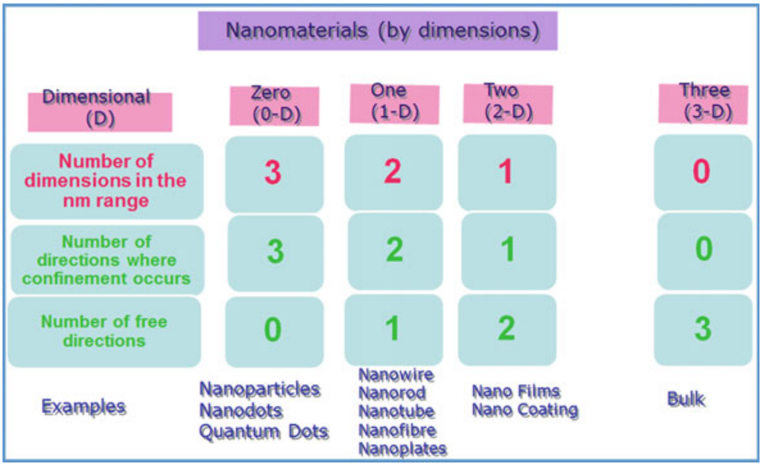

Fig. 2 Classification of nanomaterials by dimensions

3 Observation/Imaging of Nanomaterials

Since the naked eye can see only to about 20 μm it is not possible to observe the nanomaterials with naked eye. Even the light microscopes have the capability to see only up to about 1 μm as the wavelength (600 nm) of light is larger compared to the size of nanomaterial (less than 100 nm). Due to this, light can't bounce-off from the surface of nanomaterial to give an image. Thus, electron microscopes (EMs) are used as the wavelength (0.008 nm at 20 kV) of electrons is smaller and can easily bounce-off from the surface to create images with higher resolution. In 1980s a new way to see the nanoscale materials was developed using scanning probe microscopes such as atomic force microscopy (AFM) and scanning tunnelling microscopy (STM). In AFM, a tiny tip moves up and down in response to the electromagnetic forces between the atoms of the surface and the tip and the motion is recorded to create an image of the atomic surface. Whereas, in STM the flow of electrical current occurs between the tip and the surface and the strength of the current is used to create an image of the atomic surface. Using these techniques not only we are able to see the really smaller atoms but we can move them too.

4 Size-Dependent Properties of Nanomaterials

By looking at the above, is nanoscience just seeing and moving really small things? Definitely no. At the nanoscale when the particle size becomes smaller and smaller, the properties of the materials change at that smaller nano scale in an interesting way. Because, the properties or behaviour of the materials are size-dependent. Due to this, gold in the nanoscale will not be as gold as in the micron scale. Depending on the size, they maybe red, blue, yellow, and other colours owing to the difference in the reflection and absorption of light with its thickness. Due to the small size, electrons are not free to move about as in bulk gold and this restricted movement makes the nanoparticles to react differently with light.

The size is very important as in the everyday scale Newton's law ($F = ma$) works perfectly but at the atomic or molecular level quantum mechanics is needed to describe the phenomena and properties. Nanomaterials are in a borderline (atomic or molecular and micro/macro) where either or both the approaches may be appropriate. The physical (hardness, melting point, diffusion rate), chemical (reactivity, catalysis), optical (colour, transparency) and electrical (conductivity) properties of the materials are size-dependent. Table 1 gives the characteristics of size-dependent gold building blocks.

Alternatively we can expect strange things at the nanoscale. Table 2 shows how the materials when reduced to nanoscale can show different properties compared to what they exhibit on macroscale enabling unique applications.

Nanomaterials are designed in a variety of shapes such as particles, tubes, wires, films, flakes, shells, etc. but all have one or more nanometre-sized dimension. For example, in case of CNTs, the diameter is in the nanoscale but the length can be several 100 nm or even longer. Whereas the nanoplates and nanofilms show the thickness in the nanoscale but the other two dimensions can be much larger. In nanotechnology, the size is manipulated without affecting the composition as the size is independent degree of freedom. The tightly controlled size and size

Table 1 Characteristics of size-dependent gold building blocks

	Size	Metal/non-metal	Colour
Atoms	10^{-10} m	–	Colourless
Clusters	<1 nm	Metal	Orange
Nanoparticles	3–30 nm	Metal (transparent)	Red
Particles	30–500 nm	Metal (turbid)	Crimson to blue
Bulk (film)	μm	Metal	Yellow

Table 2 Properties of metals: nano versus bulk

	Bulk	Nano
Cu	Opaque	Transparent
Al	Stable	Combustible
Au	Solid (room temperature); chemically inert	Liquid (room temperature); potent chemical catalyst
Pt	Inert	Catalyst
Si	Insulator; grey	Conductor; red
Au	Yellow	Red
Hg	Metal	Non-metal
Cd	Melting point of 1700 °C	Melting point of 800 °C

distribution are very important to obtain unique size-dependent properties. It is preferred that nanomaterials must be composed of monodispersed or nearly monodispersed nanoparticles.

5 Key Factors that Impact the Properties of Nanoscale Materials

The key factors to understand the nanoscale-related properties are dominance of electromagnetic forces, importance of quantum mechanical models, higher surface area to volume ratio and random (Brownian) motion. It is very important to understand these four factors when researching new materials and properties. Increased surface area (surface phenomena) and quantum confinement effect (quantum phenomena) are the principal factors responsible for much of the fascination existing with nanotechnology.

5.1 Surface Effect or Phenomena

For the same volume, nanomaterials have larger surface area and thus more surface is available for interaction. With a reduction in the size of particles, greater proportion of atoms will be found at the surface compared to inside or higher the percentage of atoms with smaller particle size. Whereas, when the particle is larger a smaller fraction of atoms (or molecules) are on the surface. In this case, atoms on the surface have fewer neighbours than those on the interior. It is to be noted that only atoms on the surface interact with another material and take part in a chemical reaction. Table 3 gives the relation between the particle size and surface molecules (%).

5.1.1 Impacts of Smaller Particle Size

Surface Area

The first and the most important consequence of a small particle size is huge surface area. With larger surface area, surface effects dominate. Larger surface energy

Table 3 Relation between the particle size and surface molecules (%)

Particle size (nm)	Surface molecules (%)
1	100
10	27.1
100	2.97
1000	0.3
10,000	0.03

makes nanomaterials thermodynamically unstable or metastable. Due to which the interaction of nanoparticles is induced leading to agglomeration or coagulation.

Conductivity

As particle size decreases, the band gap widens or the distance between conduction and valence band increases which lead to a decrease in thermal conductivity.

5.2 *Quantum Phenomena*

In the bulk materials, the electronic energy levels are continuous. Whereas, in nanocrystals they are not continuous but discrete which is due to the confinement of electronic wave function to the physical dimension of the particles. Quantum confinement (QC) is achieved by reducing the volume of the solid to the extent that the energy levels inside become discrete. This leads to creating small droplets of isolated electrons, the number of which will be few and countable. By this the charge and energy of sufficiently small volume of materials are quantised just like atom. This results into making fake atoms. In a particle, the freely moving electrons (excited or conduction) which may be in hundreds or thousands are confined inside a volume. Whereas, the vast majority of the electrons are tightly bound within inner orbitals which are not confined. Novel electronic devices are developed using this QC effect [4].

Two fabrication approaches could be followed to constrain the dimensions of a given volume. First, the bottom-up approach which builds low-volume structures atom by atom. In the second top-down approach, materials are removed from one or more of the three dimensions (L/W/H) of a larger solid. The above two approaches produce a structure small enough for quantum behaviour to manifest. Although three dimensions are available to confine electron, the QC indicates confining at least one of the dimensions to less than 100 nm. With the continuous confining of more of the dimensions leads to progressive discretisation which is a new way to understand the real atoms and the behaviour of electrons. In QC, different quantum structures are obtained depending on the constrainment. For example, constraining the electrons inside a region of minimal width leads to quantum well; further constraining the depth of electrons domain leads to quantum wire; with the minimisation of all the three dimensions results into quantum dot [4].

Thus, quantum wells and wires have at least one dimension for the electrons to move freely (partial confinement), but quantum dot exhibits total confinement. The above quantum structures are ideal candidates for high-density data storage. Metal particles of 1–10 nm and semiconductors up to 100 nm can behave like QDs. Due to this, the applications necessitating QC employ semiconductors as the dimensions can be more easily achieved. Overall, QC of electrons provides one of the most powerful means to control the electrical, optical, magnetic, and thermoelastic properties of solid state functional materials [4].

6 Nanomanufacturing

There are a range of techniques applied in the nanomanufacturing which are classified under bottom-up and top-down approaches that include ball milling, sol-gel, wet chemical precipitation, epitaxy etc.

The desired objectives to be looked in the nanomanufacturing are:

1. The synthetic methods should be reproducible
2. The methods should produce monodispersed nanoparticles
3. The produced nanoparticles should be free from surface defects
4. The methods should be easy, cheap, scalable and environmentally friendly

Many different approaches have been applied to the fabrication of nano-entity, such as co-precipitation, microemulsion, supercritical sol-gel processing, hydrothermal synthesis, or high energy ball milling. Directed to the problems of these conventional methods, new synthetic methods have received increased attention in recent years. Its impact is more pronounced in the area of pharmaceuticals as increasing number of newly developed drugs are sparingly soluble in water and are often also insoluble in organic solvents, and thus the formulation of these drugs is a major obstacle to their clinical application. Because of their extremely low solubility, these drugs usually also possess poor bioavailability. Common ways of solving this problem include the use of solubilizers, cyclodextrins, and mixtures of solvents. But these methods have various shortcomings. An alternative to overcome these obstacles is the nanoformulation of these drugs. Nanotechnology is projected to influence with great promise for the future of cosmetics, diagnostics, drug therapies and biotechnologies. It has the potential to meet the needs of growing population, challenges of climate change and other ecological disturbances.

7 Applications

The following Table 4 shows the nanoparticles in our daily life.

Besides very common applications, in the petroleum engineering it is highly useful in the oil exploration. Conventional sensors to detect the oil are not reliable and inaccurate under harsh conditions. Whereas, owing to the small size nanosensors have the capability to probe the properties of oil that are deep in the reservoirs. They are extremely sensitive in measuring temperature, pressure, and underground stress. Besides, they are able to work under harsh conditions (extreme

Table 4 Nanoparticles in our daily life

Carbon black (nanoscale carbon)	Used for writing and painting added to rubber to make tires with more wear resistance
Nanophosphors	CRTs display colours
Nanoscale alumina and silica	To polish or smoothen silicon wafers
Iron oxide nano magnetic particles	Hard disks in the computers
Nano zinc oxide and titania	To block the UV light (useful in sunscreens and cosmetics)
Nano platinum	Catalytic converters (nano size is important for the critical operation)
Nanoscale thin films	Silicon chips (computers, digital cameras, photonic devices)
Nanoscale silica	Dental tooth fillers

high temperature and pressure). They also work safely even in the presence of electromagnetic fields. More importantly they are accurate and reliable [5]. The exhaust gases from the car contain CO and NO which are poisonous and harmful. To overcome the release of these gases, nano catalysts such as Pt is exploited in the catalytic converter, the usage of which converts the harmful CO and NO into harmless CO_2 and N_2 [6].

8 Challenges

The challenges existing with nanotechnology are (a) to develop instruments to assess exposure to engineered nanomaterials in the air and water (b) to develop and validate methods to evaluate the toxicity of engineered nanomaterials (c) to develop models to predict the potential impact of engineered nanomaterials on the environment and human health (d) to develop reverse systems to evaluate the impact on the environment and the health impact of engineered nanomaterials over their entire life-span which speaks to the life-cycle issue (e) to develop the tools to properly assess the risk to human health and to the environment. The Food and Drug Administration (FDA) attempts to ensure materials that are safe and effective. Whereas, Environmental Protection Agency (EPA) ensures that there is no demonstrable harm to an environment or to people in that environment. Even the regulatory agencies need to have adequate resources to monitor nano molecules properly [7].

Health, safety and environmental (HSE) effects of nanomaterials are very important and have not been looked seriously and it is the area of focus in the recent days. The health hazards of nanomaterials are not well defined. There is no long-term data on human exposure as well as on environmental damage. New technologies that show great promise have a history of being rushed to market without adequate HSE testing. Nanoparticles have been proven to bioaccumulate, ending up in humans. NASA studies show that mice that are exposed to airborne nanotubes develop tumour like pulmonary growth after 90 days of exposure [8].

9 Risk Assessment and Management

Many assumptions about risk assessment and risk management that work in the macro world but some issues may be unique to nanomaterials owing to their small size. It is predicted that the surface area of a nanoparticle is really a key parameter in determining how much of the material produces a toxic effect. The charge of a particle affects how much can be absorbed across the cell membrane.

The risk assessment in nanotechnology has four components: (a) identification of hazard, where the adverse effects of nanomaterials are qualitatively evaluated (b) assessing the exposure, where the types (routes and media) magnitude or levels of exposure are evaluated (c) evaluation of dose response, where the relationship between dose and incidence of an adverse effect is looked into (d) characterisation of risk, where the probable incidence of adverse health effects under various conditions of exposure is quantitatively estimated [9].

Following are some of the ethical issues related to nanotechnology: (a) research ethics and the use of implanting nano-devices in humans (for example, implanting artificial devices) (b) increasing of uneven military power (c) increasing of economical gap between developed and developing countries (d) increasing possibilities of misused personal information i.e. revealing a medical information to insurance companies.

10 Conclusion

Nanotechnology is an example of the medici effect at work and people from diverse fields working together more intensively to solve the important problems in our society. It is changing practically every part of our lives and it is a field for people who want to solve technological challenges facing societies across the world. It is a combination of education, science, engineering, business, policy and many more. Nanotechnology promises significant advances in electronics, materials, biotechnology, alternative energy sources and other applications. Nanocrystals, nanotubes, nanowires and nanofibers are considered to be the next generation materials. There are few key challenges facing society globally; water, energy, health, sustainable development, environment, knowledge and economy and nanotechnology is believed to solve some of these.

References

1. Dowling, A.P.: Mater. Today, 7 **12**, 30–35 (2004)
2. Dutta, R.K., Sharma, P.K., Kobayashi, H., Pandey, A.C.: Adv. Polym. Sci. **247**, 233–276 (2012)
3. Feynmann, R.P. Available at http://nano.xerox.com/nanotech/feynman.html.
4. Rogers, B., Adams, J., Pennathur, S.: Nanotechnology: Understanding small systems, 3rd edn. CRC Press, USA (2007)
5. Barron, A.R., Tour, J.M., Busnaina, A.A., Jung, Y.J., Somu, S., Kanj, M.Y., Potter, D., Resasco, D., Ullo, J.: Oilfield Rev. **22**(3), 38–49 (2010)
6. Knecht, M.R.: TR Walsh. From surface analysis to applications, Springer, Bio-inspired nanotechnology (2014)
7. Maynard, A.D., Aitken, R.J., Butz, T., Colvin, V., Donaldson, K., Oberdörster, G., Philbert, M. A., Ryan, J., Seaton, A., Stone, V., Tinkle, S.S., Tran, L., Walker, N.J., Warheit, D.B.: Nature **444**(7117), 267–269 (2006)
8. Lam, C.W., James, J.T., McCluskey, R., Hunter, R.L.: Toxicol. Sci. **77**(1), 126–134 (2004)
9. Suzuki, T.: Nanotechnology Commercialisation, CRC Press, USA (2016)