Nanoscience and nanotechnology for Man-kind: Beyond the Hype?

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Abstract

Nanoscience has outgrown its infancy, and nanotechnology has already found important applications in our daily life - with many more to come. Although the central concepts of the nano world, namely the changes of particular physical properties on the length scale of individual atoms and molecules, have been known and developed for quite some time already, experimental advances since the 1980s and recognition of the potential of nanomaterials led to a genuine breakthrough of the inherently multidisciplinary nano-science field. 'Nano' has been a vogue word for several decades now, and improper use of the term has often aroused false expectations. Nevertheless, one can safely state that nanotechnology has already fulfilled many of its "reasonable" promises. A critical overview is given of recent developments and trends in the field, highlighting the importance and point out future directions, while also touching drawbacks, such as emerging concerns about health and environmental issues.

Keywords : nanoscience, nanotechnology, nanomaterials

1. Introduction

Nano-science and nanotechnology are based on the manipulation of individual atoms and molecules to produce materials from them for applications well below the sub-microscopic level. They involve physical, chemical and biological knowledge at scales ranging between individual atoms and molecules, below the nanometer, up to *ca* 100 nanometer. The subject also concerns the integration of the resulting structures into larger systems.

Many aspects of nanotechnology are based on the fact that the nanoscale world is different from the macroscopic world that we are so well accustomed to deal with in life and in applications. At the micron size level and above, materials have bulk -conventional- properties that obey the laws of classical science, while sub-microscopic objects-mesoscopic between 1 micrometer and 100 nm and nanoscopic below this size range- have properties that are affected by fluctuations around the average and become subject to the strange and unpredictable laws of quantum mechanics. In this way, many exciting new tools and functionalities are opening up in this new technological field. And this leads also to a plethora of new economic challenges and novel pportunities in the scientific realm.

As length scales of materials decrease, surface-area effects become extremely important and quantum effects appear that lead to profound changes in the properties of materials and devices. One effect of the small size of the materials is the increasing percentage of atoms that are situated on the surface of the objects. There is a famous quote from Wolfgang Pauli that was expressed long ago, it says:

"God made the bulk, the surface was invented by the Devil".

With this logic, in nano-sized materials the Devil's realm has been extended enormously. In nanoscience and technology surface physics and chemistry start dominating the materials properties and this must be duly taken into account. The large percentage of atoms on the surface for small entities, and the reactivity that this gives rise to, concerns one of the principal factors that differentiate properties of nanostructures from those of the bulk material. One important result of the high surface area per unit mass is the reactivity of nano-size materials. If, for instance, the surface of nanoparticles is not protected with a surface molecule, interactions between the particles will readily occur. Thus, in nanotechnology common concepts of chemistry loose their validity: gold nanoparticles are very reactive while argon clusters of up to several thousand atoms are stable enough to be used as projectiles in diverse scientific and technological processes.

The property changes resulting from the size effects lead to both advantages and drawbacks. For example, on one side, there is the ability of quantum particles to tunnel through barriers that repel classical particles; this, for instance, underpins the operation of the scanning tunnelling microscope, a revolutionary new way of the observation of nature. On the other side, the same tunnelling effect can be a source of serious problems in ultra small-scale nano-electronic devices.

One other aspect to consider is that as structures enter the nanoscale regime, the van der Waals force increases. For example, it is this force that clamps graphene samples to substrates, and also holds together individual graphene sheets in multi-layer samples.

Authors cannot go here into any detail on the vastly expanding research on nanotechnology and nanoscience. A comprehensive handbook of Bushan[1], for instance, is almost 2,000 pages in its last edition.

2. Nanotechnology, Nano-engineering

The physicochemical properties of nanomaterials significantly depend on their three-dimensional morphologies – sizes, shapes and surface topography – the surrounding media, and their arrangement in space. The correlation of these parameters with the relevant physical and chemical properties is a fundamental requirement for the discovery of novel properties and applications – as well as for advancing the fundamental and practical knowledge required for the design and fabrication of new materials.

In general, there are three ways to engineer complex entities of reduced dimensions. The first consists in the manipulation of atoms into the desired structures. Such bottom-up fabrication forms device structures directly from mechanisms of material growth such as atomic layer deposition methods. The objectives are to achieve:

1. The ultimate precision: almost every atom in exactly the right place in space.
2. To make complex and molecularly intricate structures as easily and inexpensively as the materials we are accustomed to work with now.
3. Reduce manufacturing costs to little more than the cost of the raw materials and energy.

The evolution that was realized in the bottom-up approach over the last 20 years is the well-known IBM image constructed in 1989 from 35 individual xenon atoms on a nickel surface using a scanning tunnelling microscope (STM) for positioning the atoms. The STM was invented to image surfaces at the atomic scale, but has been used as a tool with which atoms and molecules can be manipulated to create structures. The tunnelling current can be used to selectively break chemical bonds or to induce chemical associations. Such an atom by atom handling approach enables almost any structure to be built, but is too slow for bulk fabrication of copies in mass production.

The top-bottom strategies for manufacturing nano-sized materials consists in downscaling conventional methods, such as in the procedures used in the semiconductor industry's International Technology Roadmap for Semiconductors. At present, top-down nanofabrication produces nanometer scale devices from bulk materials by lithography techniques, which include photolithography and electron beam lithography. Top-down nanofabrication and nano-engineering procedures were used from the late 1950s on for nanostructured electronics and they are still relevant for nanoelectronics at present. Standard optical and electron beam lithography techniques struggle to produce mask feature sizes below 30 nm, but scanning probes provide a resolution of 15 nm at a speed comparable to electron beam lithography. Nano-patterning enables other applications, that are increasingly adopted in nanotechnology and improvements directly gives rise to new applications, for instance in sensors, accelerating the rate at which new applications can be developed in the future.

The established pick-and-place assembly techniques or the top-bottom approach may be unsuitable in many situations and this brings us a third approach to engineer complex nano-size objects, self-assembly. This follows from the science of supra-molecular chemistry, which involves the ability of atoms and molecules to react spontaneously to form complex structures as a result of their physical and chemical interactions. Self-assembly is based on engineering the interactions between particles by chemically functionalizing their surfaces, so that they self-assemble to form the desired structure. The principles of supramolecular chemistry were pioneered by e.g. the Nobel laureate Jean-Marie Lehn and others in the 1970s and 1980s. Supramolecular chemistry shows how molecules (a prominent example is DNA) are imbued with instructions for their spontaneous self-assembly.

Table 1 shows the size range of nanotechnology in the framework of a number of other size dependent phenomena. The table shows dimensions of a few typical nanostructures. We can compare these dimensional aspects of nanotechnology, with its size range between 1 nm and 100 nm, with the dimension of a number of other objects: a C-atom is 0.16 nm; a single walled nanotube is 2 nm; the DNA separation of plane of adjacent base pairs is 0.34 nm and the diameter of the DNA helix 2 nm, a red blood cell is something as 8 µm, a human hair 50-100 µm. The table also shows the range of materials used from metals to insulators, simple inorganic salts and complex organic molecules, even DNA with its immense potential for self-assembly starts playing a prominent role. There is also an enormous and quickly increasing range of applications and functional uses.

Table 1 : typical dimensions of nanostructures[2].

Nanostructure	Size (nm)	Material
Clusters, nanocrystals, quantum dots	Radius 1-10	Insulators, semiconductors, metals magnetic materials
Other nanoparticles	Radius 1-10	Ceramic oxides
Nanobiomaterials	Radius 5-10	Membrane protein
Nanowires	Diameter 1-100	Metals, semiconductors, oxides, sulphides, nitrides
Nanotubes	Diameter 1-100	Carbon, chalcogenides
Nanobiorods	Diameter 5 nm	DNA
Surfaces and thin films	Thickness 1-1000	Insulators, semiconductors, metals, DNA
2-D arrays of nanoparticles	Area several nm^2 – μm^2	Metals, semiconductors, magnetic materials
3-D superlattices of nanoparticles	Radius several nm	Metals, semiconductors, magnetic materials

2.1. Two Examples

Important aspects of nanomaterials depend on their composition/structure or on their size. An example of nano-size materials based on structural aspects are those based on carbon and its different allotropes.

When an element exists in several structural forms, it is said to exhibit allotropy; the individual forms are called allotropes. The most current naturally occurring examples are carbon black or coal, graphite, one of the softest materials, and diamond, the hardest material. Carbon is the element that provides the basis for life but is also important for many technological applications, including drugs and numerous chemicals. It is the basis of the chemical industry. Modern allotropes of carbon are featuring actors in the nano-revolution. Buckminsterfullerene was discovered in 1985. It consists of a spherical, ellipsoid, or cylindrical arrangement of dozens of carbon atoms. Fullerenes were named after Richard Buckminster Fuller, the architect who designed the geodesic dome which resembles spherical fullerenes in their appearance. Spherical fullerenes looks like a soccer ball, and are also called “buckyballs” whereas cylindrical fullerenes are identified as "buckytubes" or "nanotubes." Fullerenes are often called carbon-60 because it is the most widely studied and used, although there exist also higher mass fullerenes with different geometric structures, such as, with 70, 76, 78 and 80 carbon atoms. Carbon-60 was the start of the development of a number of carbon allotropes that went on with the study of nanotubes and graphene – known since long but first isolated as individual graphene planes in 2004. Fullerenes are similar in structure to graphite and composed of stacked graphene sheets of linked hexagonal rings; but they may also contain pentagonal (or sometimes heptagonal) rings. In 1993, a class of carbon nanotube was discovered, with just a single layer. These single-walled nanotubes are generally narrower than the multi-walled tubes. With diameters typically in the range of 1-2 nm,they tend to be curved rather than straight. There are differences between single tubes and those in which several cylinders are nested inside each other in multi-walled nanotubes. Graphene consists of one-atom-thick planar sheet of sp^2- bonded carbon atoms that are packed in a honeycomb crystal lattice. Graphite itself consists of many graphene sheets stacked together.

With their outstanding properties and potential applications these synthetic carbon allotropes play an important role in nanoscience and nanotechnology. Many applications illustrate their unique scientific and technological importance. At present, particularly graphene is a fast growing product of nanoscience and technology. Its two-dimensional hexagonal lattice of carbon atoms has been found to have remarkable physical and chemical properties, and is also being considered for many diverse applications.

The remarkable properties manifested by nanotubes and graphene arise from their structure as an atomically thin mesh of carbon atoms arranged in a honeycomb hexagonal pattern. The very strong carbon–carbon bonds produce an exceptionally high strength-to-weight ratio. As was quoted in the Nobel Prize announcement graphene has a breaking strength which is more than 100 times stronger than the strongest steel. An almost invisible hammock made out of graphene could hold a cat without breaking. The hammock would weigh less than one mg, corresponding to the weight of one of the cat’s whiskers.

The symmetry of the carbon atom arrangement in the hexagonal lattice also provides low electrical resistance opening up electronics applications. Small variations in carbon structure are able to create diverse new properties. Nanotubes can be made semiconducting or metallic by changing their diameter, length or their twisting angle between the lines of hexagons and the direction of the tube.

A group of nanomaterials based primarily on size are nano-particles and nano-powders. Clusters, nanosize particles and nanopowders have a wide range of simple compositions, carbon, gold, silver, or are more complex as oxides, or semiconducting such as, for instance, in quantum nanodots.

There is a wide and widening range of applications: they are used in catalytic processes, as coatings, as delivery agents for drugs, imaging agents. They are also used as the building blocks for functional structures and complex assemblies. But before we go on with them we turn our attention now to the other prominent item of this symposium, nanoscience.

2.3. Nanoscience

If science and technology have been connected, but distinctly different endeavours in the past, in the nano realm, they become intimately intertwined and so much connected to become indistinghuisable. Increasingly, they are now leading together to newly commercialised and innovative products and future-oriented applications.

Essential for future developments – and this is main task of nanoscience – is to keep track of the composition and the structure. These most important aspects of nanoscience as a determining factor in advances are summarized in the two historic quotes. Richard Feynman already emphasized in his well known historic talk of 1959 how important it is to be able to "see" things on the atomic level, meaning with this that it is imperative for scientific development that it is necessary to be able to measure the position of atoms with absolute confidence. The second quote comes from Francis Crick in 1989 in his historic account on the discovery of the double helix model of 1953.

"If you want to know the function, determine the structure"

It underlines the importance of the determination of structure to explain the function of a material. Today, atomic scale observation and determination of structure are possible with high accuracy. For instance, atoms can be localised in space with a precision of the order of a few tens of a picometer.

The reasons for the need of the determination of structure are numerous. One example is a topic of growing importance, biomimetics – also called bionics or biognosis – derived from the Greek word "biomimesis" and with the meaning of mimicking biology or natural concepts. The concept involves taking ideas from nature to exploit them in an application. Nature has gone through natural evolution over several billion years and by trial and error evolved into objects with high performance.

One, often quoted example of biomimetics, consists in surface treatments to induce non-wetting, super-hydrophobicity and self-cleaning. Various natural surfaces including the leaves of several plants – for instance the lotus plant - are super-hydrophobic and do not wet. This is due to the presence of a wax coating on a high surface roughness surface structure as revealed by scanning electron microscopy. The effect has been called the "Lotus-Effect" and may become of great biological and technological importance, when used in technological applications this effect has various applications, e.g., self-cleaning windows and solar cells, paints, utensils, roof tiles, textiles. It can also reduce drag in fluid flow, e. g. in microscopic or nanochannels.

“How it comes that geckos can climb walls?”

is a question addressed by Andre Geim in his Nobel Lecture 2010. The answer is because of sticky feet due to submicron size hairy toes. These can now be mimicked with polydimethylsiloxene (PDMS) structures of micron sized dimensions.

3. Applications

The range of application areas of nanotechnology include applications in microelectronics for circuits, sensors, displays, data storage…materials of all kinds for paints, coatings (including suntans), energy applications for solar cells, fuel cells etc, in environmental applications, scientific instrumentation of various kinds. The market of nanotechnology products is expanding rapidly. From 147 billion USD in 2007 it is expected to increase to over one trillion in 2015, a healthy growth rate of almost 30% per annum!

3.1. Applications in Biology

Of special importance are also applications in the biosciences, pharmaceutics and medicine. Biological processes take place at the molecular level with interactions on extremely small size level and this is also the realm of nanoscience and nanotechnology. Basically analytical biology and biochemistry evolve around the determination of basic molecular properties related to size, weight and position. In addition, there is a complex interplay between molecules in living systems resulting in a continuous alteration of these properties at the molecular level. There is consequently a need for methods that provide insight into these processes to increase understanding of fundamental processes. Opportunities in cell biology and most importantly in medicine in general abound with possibilities for sensors, molecular imaging, early detection of diseases etc.

A significant challenge in translating nanoscale methods into medically or biologically relevant tools results from the disparity in scientific culture separating medical disciplines from the physical sciences. Traditionally, for example, experts in cellular signaling and signal transduction are applying biochemical methods and molecular approaches to address biological problems relevant to health sciences. Based on their background, they may not take immediate advantage of the rapid evolution in chemical, physical, and material sciences facilitating the usage of more sophisticated nanoscale technologies and methods for addressing complex problems within their discipline. In turn, scientists advancing nanotechnology may not be aware of the most pertinent questions and analytical challenges to be addressed in cell physiology or - more generally – in biomedicine.

4. Nanotoxicology, Ecotoxicology

The interactions between nanomaterials and cells, animals, humans and the environment are complex and much research is necessary to understand in detail how the physical, chemical and other properties of nanomaterials influence these interactions, and thus determine the ultimate impact of nanomaterials on health and the environment. Research during the last twenty years has confirmed that nanoscale materials manifest unexpected toxicity. Their impact on human health and the environment is, at present, quite incompletely understood. There is also an ongoing debate about the regulation of nanomaterials.

One obvious difficulty in nano-toxicology is that materials that are not at all harmful in their bulk form may well be toxic on the nanoscale. Nanoparticles are more likely to react with cells and various biological components such as proteins, and to travel through organisms, which increases their chances of interacting with the organism to induce inflammatory and immunological responses. For example, nanoparticles may acquire a ‘corona’ of proteins when exposed to biological fluids, and this layer is thought to influence the way the cell interacts with a nanoparticle.

In Europe, the regulations for registration, evaluation, authorization and restriction of chemicals, in short the REACH regulations are in force since 2007. New European cosmetics regulations require ingredients that contain nanomaterials to be listed on product labels by 2013. In the United States, the US Food and Drug Administration issued draft guidance to help producers to determine whether their products utilize nanomaterials while the Environmental protection Agency has issued draft guidelines for nanomaterials.

On the subject of nanoparticles the European Commission issued a draft definition in 2011 that stipulates:

…a material that consists of particles with one or more external dimensions in the size range 1 nm–100 nm for more than 1% of their number”; and/or has internal or surface structures in one or more dimensions in the size range 1nm–100 nm ”; and/or has a specific surface area by volume greater than 60 m per cubic cm3, excluding materials consisting of particles with a size lower than 1 nm…

It can be concluded that distinctions are necessary between real risks and perceptual risks, and between both of these and regulations. Regulations with no scientific justification could effectively do more harm than good. The quantification of risks in coherent way is the key to future. It is needless to say that in line with the increasing market size there is both in the USA and Europe, a steeply increasing environmental, health and safety budget.

5. Conclusions

Nanotechnology is now well-established and is applied to many unrelated products and technologies. Its use in science and technology includes improvements of existing technology but also opens up exciting new opportunities. By achieving ultimate precision manufacturing – every atom in the right place – nanotechnology complex and intricate structures and can do this easily and inexpensively, reduces manufacturing costs and providing savings of raw materials and energy.

In addition we see a very intimate link between nanoscience and nanotechnology on one side and emerging strategies for development, I showed you also the close link with nature provided by biomimetics, mimicking biology or natural concepts, as an example. The title of this article contains a question mark: nanoscience and nanotechnology for mankind, are we beyond the hype? The answer is a clearly and unequivocally… No. This symposium’s title is “Nano-science & Technology for Mankind”. Both will indeed be determining contributors for Mankind’s future. We do not exaggerate when calling it a new industrial revolution.

References

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Nanotechnology - Moving beyond the hype. As a result, it seems reasonable to assume that the route to ultra-advanced computational, engineering and construction projects can in many cases only realistically be achieved through mastery of matter at the atomic scale. However, nanotechnology has a long way to go to live up to these substantial expectations. Advanced nanotech applications such as utility fogs or graphene processor chips that operate in the multi hundred gigahertz range are nowhere near commercially viable or even technologically possible. During the past two decades, the hype around nanotechnology has been almost deafening. At the launch of the National Nanotechnology Initiative in 1999, US President Bill Clinton remarked â€˜Imagine the possibilities: materials with ten times the strength of steel and only a small fraction of the weight â€” shrinking all the information housed at the Library of Congress into a device the size of a sugar cube â€” detecting cancerous tumors when they are only a few cells.Â Nano- and Microfabrication for Industrial Applications by Regina Luttge is a clear guide to current and emerging nano- and microfabrication technologies in a range of academic and industry disciplines, which illustrates key concepts with case studies from biomedical and other application areas. 13 The role of nanoscience and nanotechnologies in the development of information technology is anticipat-ed in the International Technology Roadmap for Semiconductors, a worldwide consensus document that predicts the main trends in the semiconductor industry up to 2018. This roadmap defines a manufacturing standard for silicon chips in terms of the length of a particular feature in a memory cell.Â 14 Alternatives to silicon-based electronics are already being explored through nanoscience and nanotechnologies, for example plastic electronics for flexible display screens.