Available online at www.joac.info

ISSN: 2278-1862

Journal of Applicable Chemistry

2016, 5 (4): 714-718

(International Peer Reviewed Journal)

Review

Nanomaterials: Materials with immense potential

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Accepted on 8th July 2016

ABSTRACT

Science of nanomaterials has emerged to become a frontier area of research due to their novel properties and potential applications. Nanoscience is based on the recognition that particles less than the size of 100 nanometers exhibit new properties and behaviour. The nature and properties of matter on the nanoscale are dramatically different from their bulk form. Bulk materials have fixed properties regardless of their size. But nanomaterials have size and shape dependent properties which make them totally different from bulk materials. Some nanostructures include quantum dots, nanoparticles, nanorods, nanowires, nanobelts / nanoribbons, nanosheets, core/shell nanostructures and carbon nanotubes etc. Different aspects of nanoscience have been discussed in this article in nut shell. Why changes in the properties occur when the size of the materials reduced down to the nanometer range has also been discussed. Lastly, some applications of nanomaterials have also been delineated.

Keywords: Nanoscale, Nanomaterials, Nanostructures, Quantum dot, Sensor.

INTRODUCTION

Since the dawn of human civilization materials have been of great interest to human beings. Conventionally, civilizations were named after the materials discovered at that period like Stone Age, Bronze Age and Iron Age. In the last two decades there have been tremendous developments in the field of materials science. It has provided us with a new array of materials with a wide range of applications and a great variety of possibilities for processing and characterizing the materials. The new class of material that is of recent interest is called nanomaterials or nanostructured materials. The prefix ‘nano’ in the word nanomaterials means one billionth sub multiple of any unit. Nanometer is a unit of length equals to one billionth of a meter (10^{-9}m). For illustration, one nanometer is about a few ten thousand times thinner than human hair, diameter of a Hydrogen atom is 0.1 nm and width of a DNA molecule is about 2.5 nm. Materials whose at least one dimension out of the three dimensions is of the order of nanometer (typically within 1-100 nm range) are called nanomaterials. Nanostructures occur in different geometric configurations. Nanoscience is the creation, study of the properties and utilization of materials on the nanometer-scale. Nanostructured materials have been the subject of intense research lately because of unusual physical properties exhibited by these materials having such ultra fine dimension and for their potential applications [1-3]. The behaviour of such nanoscale clusters neither correspond to those of free atoms or molecules making up the particle nor to that of the bulk solid with identical chemical composition. They may be crystalline or amorphous in structure. These materials show us great promise for providing us with many breakthroughs that may change the direction of technological advances in a wide range of applications in near future. Nanostructures occur in different geometric configurations such as quantum dots, nanoparticles, nanorods, nanowires, nanobelts/nanoribbons, nanosheets, core/shell nanostructures and carbon nanotubes etc. Nanowires and nanorods differ in aspect ratio (length/diameter). Latter have smaller aspect ratio (Generally in the range 3-5). Synthesis of different nanostructures has posed challenging tasks to materials scientists. Predominantly physical and chemical methods have been used by different researchers to grow nanomaterials in different forms [2]. Famous Physicist Richard Feynman was the first scientist to speculate the possibility and potential of nano-sized materials in 1959 at the annual meeting of American physical society in his lecture, entitled "There is plenty of room at the bottom". He envisaged the manipulation of individual atoms to make new small structures having different properties. Manipulation of individual atoms has become possible after the discovery of Scanning Tunneling Microscope (STM). The unique properties of materials due to ultra fine particle size were recognized after Feynman's lecture and opened up a new field of research and study known as nanoscience and nanotechnology. However, the term 'Nanotechnology' was coined by Norio Taniguchi in 1974. Nanoscience is a truly interdisciplinary research area which is bringing physicists, chemists, biologists and engineers together. Though the study of nanomaterials has emerged as a new branch but nanoscale functional devices and structures of nanometer dimension existed in nature as long as life itself because biological building blocks are of nanometer dimension. Human beings also have been taking advantage of nanomaterials since time immemorial. Lycurgus cup, kept at British museum, of fourth century AD changes its colour from green to deep red when a light source is placed inside it. This is actually made of Soda lime glass containing silver and gold nanoparticles and change of colour occurs due to the scattering of light by the nano-sized metal particles present in the medium. Beautiful colours of glass windows found in the medieval churches are also due to the presence of metal nanoparticles dispersed in the glass. Photography, a technology of eighteenth century, also utilized production of silver nanoparticles on the photographic film. However, a boom in the research activity in nanoscience took place around late 20^{th} century. Michael Faraday was pioneer in introducing new areas in nanotechnology and specifically colloidal gold suspensions. Colloidal gold is a micro-sized or nano-sized suspension of gold particles in a solution. He reduced gold chloride to gold nanospheres and was the very first scientist to recognize that the ruby color of colloidal gold is as a result of fine gold nanoparticles in the solution. Gold in the bulk form have golden-yellow color but colour of gold suspensions can have colour varying from intense red to blue depending upon the size of the particle. Faraday was the first scientist who suggested that these colors of gold colloidal suspensions are formed due to presence of suspended gold particles in the solution back in 1857 [4]. Gustav Mie explained the variation of color of colloidal gold with the size of nanospheres based on the theory of scattering and absorption of light by nanoparticles [5].

Why nanostructures are unique?

Nanomaterials have size and shape dependent properties which make them totally different from bulk materials. Bulk materials have fixed properties regardless of their size but this is not true in case of nanomaterials. Many of the properties of material have been found to change when particle size becomes smaller than a critical size. The size dependence of behaviour allows us to tailor their properties by tuning their size. Matters are made from atoms. The properties of materials at the nanoscale depend on how the atoms are arranged. If the atoms of an object are rearranged then a new object would come up. Nanoscience not only allow scaling down some characteristic size of the investigated material objects and effective control their properties but also introduce fascinating features and effects in some properties of the object. The size-dependent properties are directly related to surface atoms. Number of atoms on the surface of nanomaterials is comparable with the number of atoms inside the nanostructure. Number of surface atoms in a bulk material is negligible in comparison with atoms inside the bulk. Ratio of Surface area to volume in nanoparticles is very high usually in the range of 10^6-10^9. Such a huge surface area to volume ratio gives nanomaterials unique characteristics. It has been found that the size of gold nanoparticle has a significant effect on its physical, chemical, and optical properties. Gold in bulk form is an inert metal with golden-yellow luster capable of conducting heat and electricity. However, nanoparticles of gold no longer glitter with metallic luster. Light reflected from gold nanoparticle varies in colour depending upon the size of the particle. Gold solution have a bright yellow color, but a solution of 20 nm gold nanoparticles has red ruby color while 200 nm nanoparticles has bluish color[3]. High surface area improves physical and chemical interaction of these particles with surroundings. Gold particles of nanometer size are highly reactive and can be used as catalyst. The melting point of gold is also reduced to half of its bulk value when grain size is reduced below 10 nm. Similar changes in magnetic and conducting properties have also been observed in different nanomaterials for different sizes. This happens because particles which are smaller than the characteristic lengths associated with the particular phenomena exhibit new behaviour. Different characteristic lengths are associated with different phenomena. The size of the cluster where the transition to bulk behaviour occurs appears to depend on the property being measured. The electronic structure, conductivity, reactivity, melting point, mechanical properties, optical properties, and magnetic properties have all been observed to change when size of the particle becomes smaller than a critical size. Quantum confinement is an important phenomenon in nanoscience. When the size of semiconductor nanostructure approaches material's exciton Bohr radius, electron energy levels become discrete instead of continuous energy bands. This phenomenon is called quantum confinement and the nanostructure is called quantum dot [6]. Quantum confinement results changes in the atomic structure as a result of the direct influence of the ultra-small length scale on the energy. Bandgap and other associated electronic and optical properties of semiconductor nanocrystals can be tuned by varying their size as a consequence of quantum confinement effect. There have been several attempts to exploit this effect for useful applications. In some cases completely new behaviour have been observed in nanoclusters, not seen in their bulk form such as magnetism in nanoscale materials constituted from nonmagnetic atoms. It has also been observed that nanostructuring results in increasing the mechanical strength. Giant magnetic coericivity (around 2500 Oe) has been reported for nano-sized iron particle. This happens when particle size approaches the dimension of single ferromagnetic domain [7].

Synthesis of Nanomaterial

There are two different approaches to build nanostructure. One is Top-down approach and the other is Bottom–up approach. In Top-down approach we start from something big and chisel out what we want. In Bottom–up approach we start from something small like atoms or molecules to construct new forms of matter. It has been observed that different synthesis conditions result in different morphologies of the nanostructures. The growth kinetics and thermodynamics involved in the synthesis of nanostructures obey different mechanisms under different growth conditions. Numerous synthesis techniques have been employed by different research groups for the synthesis of nanomaterials in different forms [2].

Potential applications of Nanomaterials

Nanostructured materials are not only in the cutting edge of the hottest materials research nowadays, but they are finding applications influencing our life styles in many ways [8]. There are a large number of new opportunities that can be realized by down-sizing materials into the nanometer scale. Electronics has shown successfully that miniaturization results greater performance ever since the invention of transistors. Nanomaterials are being applied in a wide variety of fields that include coatings, Textiles, Cosmetics, Water treatment, Pollution control, Sensors, Health care, Tissue engineering, Medical diagnosis, and Communication Engineering. Magnetic storage is a promising field that employs metallic nanostructures [9]. Magneto resistance is a phenomenon for which the resistance of a material is changed by the application of magnetic field. Giant Magnetoresistance (GMR) effect, where there is a significant decrease in the resistance when exposed to a magnetic field, has improved the possibility of increase in the storage density of hard disk of computer. This happens when particle size approaches the dimension of single ferromagnetic domain. High quality laser beam has been achieved at low cost after the discovery of quantum dot lasers. Wavelength of the beam is a function of the diameter of the dot. Due to large surface to volume ratio of the nanomaterials they are potential catalysts. Catalyst plays very important role in chemical reaction. CuI nanoparticles have been used successfully as efficient catalyst that can be recycled without any significant loss of catalytic activity [10]. Since the discovery of carbon nanotubes (CNTs) [11], much attention has been paid to exploit their potential as field emitters due to their low work function, high aspect ratio, high mechanical stability, and high conductivity. Nanostructured materials can also be used as chemical and gas sensor. Because of its small size, the electrical or optical properties of the nanostructured sensing element are changed if they interact with a few chemical molecules only. Therefore the detection of a very low concentration of chemical vapors is possible. ZnS, an important optoelectronic semiconductor, also has the potential application as Chemical sensor. The measurement of concentration of oxygen is desirable in many situations like environmental monitoring, chemical process controlling etc. A slight amount of oxygen in inert gas can cause severe surface degradation of semiconductor material by oxidation. ZnS nanobelts have been successfully used as oxygen sensing element [12]. Another important class of sensor is Biosensor that is used for health monitoring. Biosensor is a device used for the detection of an analyte that combines a biological component with a physicochemical detector component. It has been reported that the complex of CdSe/ZnS core–shell quantum dots conjugated with enzymes successfully used as probe to sense blood glucose [13]. Nanotechnology has enabled target specific delivery of pharmaceutical with minimum but effective dose to the affected cells and tissues only without damaging the healthy tissues [14]. This involves the identification of precise targets like specific cells or tissues, and choice of appropriate nanocarriers to achieve the required purpose. This has been possible since the dimensions of nanoscale materials are similar to those of biological molecule. Gold and silver nanoparticles also have antibacterial and antifungal properties. Nanomaterials have also found their way in day to day products due to their unique properties. Titanium dioxide nanoparticles [15] and Zinc oxide nanoparticles find application in the sunscreen lotion and textile [16] due to their better absorption coefficient towards UV rays compared to their bulk counterpart.

Future prospects and challenges of Nanoscience

Nanotechnology is expected to impact every walk of life very soon. A good understanding of the new physics and chemistry at the nanometer scale will lead to the design of new functional materials and devices. Nanoscience poses a challenge to manipulate atoms to design materials with pre-defined features. But exact positioning of atoms is still a challenge even after tremendous development in microscopy. Chemical synthesis alone can create molecules with exactly defined atomic composition and geometric structure. Though synthesis of nanoscale materials in the laboratory scale has been achieved successfully, but large scale inexpensive methods of synthesis is still a major challenge to exploit the enormous potential of nanomaterials for the full flowering of Nanotechnology.

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