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A Brief overview of Nanomaterials

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Abstract

Nanomaterials are gaining significant importance in nanotechnological applications because of their exceptional chemical, physical and mechanical properties and superior performance in comparison to their bulk form. This chapter focuses on the brief introduction about nanomaterials, their classification as zero-dimensional (0-D), one-dimensional (1-D), two-dimensional (2-D), and three-dimensional (3-D).

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Some features related to the optical, electrical, magnetic, and mechanical properties are briefly discussed with a large number of references, which could be beneficial for beginners in the research area.

Keywords: Nanomaterials, optical properties, electrical properties, magnetic properties, mechanical properties

Introduction

A nanometre is one-millionth of a millimeter. Nanomaterials are defined as a set of substances where at least one dimension is less than approximately 100 nanometers. On 18 October 2011, the European Commission adopted the following definition of a nanomaterial: "A natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1 nm - 100 nm. In specific cases and where warranted by concerns for the environment, health, safety or competitiveness the number size distribution threshold of 50% may be replaced by a threshold between 1% to 50%" [1]. Nanomaterials are the major subject of interest in the scientific community due to their nature and unusual mechanical, electrical, optical, and magnetic properties to their bulk counterparts. Nanomaterials have shown the potential for revolutionizing the creation of materials and their products. Size reduction can provide a new whole range of physical, chemical, and biological properties and potential

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applications on a larger scale. Due to these features, nanomaterials have provided a strong bridge between the materials science and nanotechnological applications. Moreover, the availability of the nanomaterials is sourced from laboratory-based synthesis methods with certain required properties for nanotechnological applications. Nanomaterials could be formed incidentally as a by-product of industrial processes in the form of nanoparticles [2]. Materials properties are strongly dependent on their shape, size, surface area, and structure. Nanomaterials can exist in 0-3 Dimension in the form of the quantum dot [3], dendrimers [4], particles [6], nanotubes [7], nanofibers, nanowires, nanorods [8], nanospheres [9], thin films [10], and nanocomposites [11] assembled in a particular form, bonded, aggregated fashion [12]. Nanomaterials classification is based on the number of dimensions, namely zero-dimensional (0-D), one-dimensional (1-D), two-dimensional (2-D) and three-dimensional (3-D) nanostructures [13].

A. Zero-Dimensional (0-D)

In 0-D nanomaterials, all the dimensions are scaled within the nanoscale means, no dimensions are larger than 100 nm. The most common form of 0-D nanomaterial is a nanoparticle. Nanoparticles can be amorphous, crystalline, single-crystalline, polycrystalline, and composed of single or multi-chemical elements. Nanoparticles exist in various shapes and forms and occur independently or fused in a matrix. In 0-D nanomaterials, an electron is confined in 3-D space, thus no electron delocalization (freedom to move) occurs. In the last decades, significant advancement has registered in the field of 0-D nanomaterials. Several chemical and physical methods such as mechanical (ball milling, attrition milling, mechanochemical processing), gas-phase synthesis (plasma, laser ablation, chemical vapor deposition) , in situ (lithography, vacuum deposition, spray coating) , thermal routes (aerosol reactor, self-propagating high-temperature synthesis) , and wet chemistry (Sol-Gel Method, Colloid chemistry, Impregnation, Supercritical fluids) and other (Biomimetic, Microwave, Ultrasound) techniques have been developed for the synthesis of nanoparticles. The sol-gel method for the synthesis of zero-dimensional nanomaterials in a single step is a well-established method . Engineered zero-dimensional nanomaterials such as inorganic quantum dots (QDs) , upconversion nanoparticles (UCNPs), graphene quantum dots (GQDs), carbon quantum dots (CQDs), fullerenes, magnetic nanoparticles (MNPs), noble metal nanoparticles are well documented due to their applications in a wide range of fields with the increasing demand in material science, electronic devices, biosensors, medical imaging, etc. QDs, a specific type of semiconductor nanocrystals absorb light then re-emit the light in a different color. The optical properties of nanocrystals are defined by their size and surface chemistry in contrast to their bulk counterparts. In structure, QDs consist of a metalloid crystalline core and a shell that shields the core. QDs cores

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can be of semiconductors, noble metals, and magnetic transition metals while shells are formed by a variety of materials. Hence, the number of atoms or size of the quantum dot can adjust the sensitivity to different wavelengths of light.

B. One-Dimensional (1-D)

In 1-D nanomaterials, one dimension is outside the nanoscale while the other two dimensions are in the nanoscale. This leads to needle-like-shaped nanomaterials with a large length-to-diameter ratio. 1-D nanoscale materials include nanotubes, nanorods, and nanowires, nanobelts, nanoribbons, and hierarchical nanostructures. 1-D can be amorphous, crystalline, single-crystalline, polycrystalline, chemically pure or impure, standalone materials, or embedded within another medium. These nanoscale materials offer a significant advantage over bulk. In 1-D nanomaterials, electron confinement take place in 2-D, whereas delocalization occurs along the long axis of the nanowire/nanorod/nanotube. 1-D nanomaterials for instance carbon nanotubes (CNTs) have attained significant attention after the pioneering work by Iijima [13]. CNTs are 1-D nanostructures with a substantial length-to-diameter ratio, in which the carbon atoms are arranged as a hexagonal lattice, resulting from exceptional covalent sp^2 carbon bonding. CNTs are of two types, single-walled carbon nanotubes (SWCNTs), the fundamental cylindrical structure, and multi-walled carbon nanotubes (MWCNTs), made of coaxial cylinders with interlayers. CNTs have shown excellent mechanical,

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electrical, thermal, and electrochemical properties and resulted in various potential applications for instance field emission display, energy storage, sensors, drug delivery, etc.

C. Two-Dimensional (2-D)

In 2-D nanomaterials, two of the dimensions are not restrained to the nanoscale. 2-D nanomaterials include nanofilms, nanolayers, and nanocoatings. 2-D nanomaterials can be amorphous, crystalline, made up of various chemical compositions, used as a single layer, or as multilayer structures. In the case of 2-D nanomaterials, the conduction electrons will be restricted across the thickness but delocalized in the sheet plane. These can be deposited on a substrate as well as integrated with a surrounding matrix material. In recent years, 2-D nanomaterials have become an important area in materials research, due to their many low dimensional characteristics and functionalities in comparison to the bulk properties. Moreover, due to the desired properties of the surface, 2-D nanomaterials have developed novel applications in sensors, photocatalysts, nanocontainers, nanoreactors, topological insulators, etc. There are several types of single atomic 2-D nanomaterials, such as germanene (germanium), phosphorene (phosphorous), graphene (carbon), stanene (tin), silicene (silicon), In the last two decades, graphene is one of the most studies on 2-D nanomaterials after its discovery in 2004 by A. Geim and K. Novoselov [14], felicitated by the Nobel prize in physics in 2010. Graphene consists of a layer with a π-conjugated

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structure of 6-atom rings, having thickness between 0.35 and 1.0 nm. Graphene family mainly comprises of single-layer graphene, bilayer graphene, multilayer graphene, graphene oxide (GO), reduced graphene oxide (rGO) as well as chemically modified graphene and are widely employed for potential applications in electronics, optics, sensors, biomedical sector, solar cells, automotive, aerospace, etc.

D. Three-Dimensional (3-D)

Bulk nanomaterials are materials that are not confined to the nanoscale in any dimension. These materials have three arbitrarily dimensions above 100 nm. Materials possess a nanocrystalline structure or involve the presence of features at the nanoscale. Bulk nanomaterials can be composed of numerous arrangements of nanosize crystals in different orientations. Concerning the nanoscale features, 3-D nanomaterials can consist of nanoparticle dispersions, nanowires, nanocoils, nanocones, nanopillars, and nanotubes bundles. Besides, 3-D nanomaterials due to their structural and functional properties are important materials for a wide range of applications in the area of catalysis, sensors, batteries, biomedical, defense, etc. Nanocomposites referred to material having fillers in the nanometer size range at least in one dimension. Nanocomposites properties are highly dependent on the properties of the compounded filler, the host matrix, and the interfacial properties. This is typically done to increase the material's stiffness or environmental stability. Besides, various other additives are also added to improve or modify the performance of the nanocomposite. There are three major classifications of nanocomposites, ceramic matrix nanocomposites, metal matrix nanocomposites, polymer matrix nanocomposites.

Properties

Nanotechnology deals with nanostructures or nanomaterials. Materials at micrometric size exhibit similar fundamental properties as of bulk form; however, at the nanoscale materials physical properties can be quite different from those of bulk of the same substance. Nanomaterials at this scale exhibit remarkable specific properties. A brief overview of optical, electrical, magnetic, and mechanical properties is discussed below.

A. Optical properties

Optical properties are one of the most interesting and useful characteristics of nanomaterials. Their characteristics such as spectral width and position, and sensitivity to light polarization. Nanomaterials' optical properties are influenced by many parameters such as size, shape, chemical composition, doping, etc. One of the simplest examples is the blue shift of absorption and photoluminescence spectra of semiconductor nanoparticles with the decrease in particle size. The optical band gap increases with the decrease in particle size of semiconductor materials. In today's scenario, biomedical applications and drug delivery based on the optical properties of quantum dots has been an important area. This concept is based on the fluorescent light emission from the

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quantum dot present inside the specimen, which is produced when the electrons are excited from the lower band to the upper band with ultraviolet radiation. The electron in higher energy levels subsequently loses energy by a non-radiative transition to end in the lowest level of the upper set. A photon is then emitted when the electron drops to the topmost energy level of the lower set. Further, negative-index metamaterials (negative index materials) are synthetic structures where the refractive index has a negative value. So far, this has not been discovered in natural materials. Metamaterials have been made with negative effective permittivity and permeability. A crystal with Magnetic Split Ring Resonator (SRR) as the motif can be used for the construction of a negative refractive index material. When the SRR scale is of the order of ~200 nm, it could lead to obtaining a negative refractive index in the mid-infrared range (100 THz). Optical properties of nanomaterials lead to important applications such as optical detectors, lasers, sensors, photonic crystals, imaging, photovoltaics, etc.

B. Electrical properties

In a nanoscale conductor, quantum effect and classical effects are an important phenomenon in comparison to the bulk materials where conduction electrons are delocalized and travel freely until they are scattered by phonons, grain boundaries, impurities, etc. While in quantum effect, continuous bands are replaced with discrete energy states and in classical effect, the mean free path for inelastic scattering becomes comparable to the size of the system. In nanomaterials, changes in the reduction of the size of the materials play a major role. In semiconductors, quantum confinement of both the electron and hole leads to an escalation in the effective bandgap of the material with reducing crystallinity. These effects can lead to altered conductivity in nanomaterials. The electrical properties of the nanomaterials depend on their size, surface area, chemical composition, and doping. The electric properties of the polymer nanocomposites were increased by the addition of inorganic compounds to the polymer systems.Doping materials due to their perovskite nanostructures and piezoelectric properties could improve electrical properties, such as electrical conductivity and the dielectric constant.

C. Magnetic properties

Nanomagnetism is an intense and highly interesting subject of modern solid-state magnetism and nanotechnology. Scientists have discovered that the bulk Au and Pt are non-magnetic, while they are magnetic at the nanoscale. Surface atoms are not only unlike bulk atoms, but they can also be altered by interaction with other chemical elements. This phenomenon unlocks the prospect to alter the physical properties of the nanoparticles. It is well known that the coercivity of magnetic materials is strongly dependent on their size. It increases with the particle size reduction to the nanometer range going through a maximum at the single domain size, and then decreases again for very small

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particles due to the thermal effects and comes to zero at the superparamagnetic particle size. However, for metals that contain metal oxides on the surface, the lattice parameters of metals may modify with varying particle size due to mismatches between the lattice parameters of the metal and the metal oxides, which additionally causes interfacial stress on the surface. Therefore, the magnetization value will alter with the variation in particle size. Besides, the magnetic properties are subjective by other factors, such as the composition of the nanostructure and the synthesis methods. Magnetic nanoparticles are used for applications in medicine, biotechnology, and environmental fields. Particularly, they are used for magneto-controlled targeting such as drug delivery, magnetic resonance imaging, diagnostic applications, biosensing, purification of RNA and DNA, cell separation and purification, etc. Magnetic nanomaterials with complex topology (such as nanorods, nanowires, and nanotubes) are being used in several nanotechnological devices, including tunable microfluidic channels with magnetic control, data storage units in nano-circuits, and magnetized nano-tips for magnetic force microscopes.

D. Mechanical properties

Nanomaterials have dissimilar mechanical properties compared to micro or bulk materials. Due to the large surface area of the nanomaterials and they are easy to alter, follow-on an increase in mechanical properties such as hardness, strain and stress, adhesion, and the elastic modulus [103]. However,

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two materials, neither of which is formed by pressing and sintering, have fascinated much attention and they will certainly be employed for industrial applications. These materials are polymers, which comprise nanoparticles or nanotubes to improve their mechanical functionalities, and plastic-deformed metals, which demonstrate astonishing properties. The mechanical properties of such materials depend heavily on the type of filler and how the filling is done. Particulate-filled polymer-based nanocomposites show a broad range of failure strengths and strains. This is subject to the shape of the filler, particles or platelets, and the degree of agglomeration. Besides, polymers filled with silicate platelets show excellent mechanical properties. The larger the particles of the filler or agglomerates, the poorer are the properties obtained. On the other hand, with carbon nanotubes, it is possible to produce composite fibers with extremely high strength and strain. The polymer ceramic nanocomposites are the most exciting nanocomposites, where the ceramic phase is platelet-shaped. Composites consisting of a polymer matrix and defoliated phyllosilicates exhibit excellent mechanical and thermal properties.

Conclusion

Nanotechnology has attained tremendous advancement in the past several decades. Nanotechnology can be defined as the understanding, control, and manipulation of materials, having dimensions roughly within the 1-100 nm range. They are materials with basic structural

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units, grains, particles, tubes, wires, thin films or other constituent components smaller than 100 nm in at least one dimension. There are several types of nanomaterials with different dimensionalities (0-D, 1-D, 2-D, 3-D), morphologies, states, and chemical compositions, which play crucial roles on their functional properties. The functional properties gives escalation to potential application of nanomaterials in technological applications for instance in energy storage, drug delivery, sensing & imaging, textile, environmental, defence, aerospace and many others. 0-D, 1-D, 2-D, 3-D based nanomaterials have the potential to discourse many global challenges being faced by society and continuously improve the quality of life.

References

1. *"Nanomaterials - Chemicals - Environment - European Commission." [Online]. Available: https://ec.europa.eu/environment/chemicals/nanotech/. [Accessed: 04-Jan-2021].*
2. *M. Das Purkayastha, A. K. Manhar, M. Mandal, and C. L. Mahanta, "Industrial Waste-Derived Nanoparticles and Microspheres Can Be Potent Antimicrobial and Functional Ingredients," J. Appl. Chem., vol. 2014, pp. 1–12, Sep. 2014.*
3. *J. Jeevanandam, S. K. Balu, S. Andra, M. K. Danquah, M. Vidyavathi, and M. Muthalagu, "Quantum Dots Synthesis and Application," in Contemporary Nanomaterials in Material Engineering Applications, Springer, Cham, 2021, pp. 229–265.*
4. *I. Gitsov and C. Lin, "Dendrimers - Nanoparticles with Precisely Engineered Surfaces," Curr. Org. Chem., vol. 9, no. 11, pp. 1025–1051, Jul. 2005.*
5. *R. M. Crooks, M. Zhao, L. Sun, V. Chechik, and L. K.*

Yeung, "Dendrimer-encapsulated metal nanoparticles: Synthesis, characterization, and applications to catalysis," Acc. Chem. Res., vol. 34, no. 3, pp. 181–190, 2001.

6. *A. Kumar et al., "Carbon nanotubes synthesis using siliceous breccia as a catalyst source," Diam. Relat. Mater., vol. 97, no. March, p. 107433, 2019.*
7. *S. J. Park, S. Kim, S. Lee, Z. G. Khim, K. Char, and T. Hyeon, "Synthesis and magnetic studies of uniform iron nanorods and nanospheres," Journal of the American Chemical Society, vol. 122, no. 35. American Chemical Society, pp. 8581–8582, 06-Sep-2000.*
8. *[8] A. Nieto-Márquez, R. Romero, A. Romero, and J. L. Valverde, "Carbon nanospheres: Synthesis, physicochemical properties and applications," J. Mater. Chem., vol. 21, no. 6, pp. 1664–1672, Feb. 2011.*
9. *B. K. Gupta, A. Kumar, P. Kumar, J. Dwivedi, G. N. Pandey, and G. Kedawat, "Probing on green long persistent Eu2+/Dy3+ doped Sr3SiAl4O11 emerging phosphor for security applications," J. Appl. Phys., vol. 117, no. 24, p. 243104, Jun. 2015.*
10. *D. W. Schaefer and R. S. Justice, "How nano are nanocomposites?," Macromolecules, vol. 40, no. 24, pp. 8501–8517, Nov. 2007.*
11. *J. Yin, Y. Huang, S. Hameed, R. Zhou, L. Xie, and Y. Ying, "Large scale assembly of nanomaterials: Mechanisms and applications," Nanoscale, vol. 12, no. 34.Royal Society of Chemistry, pp. 17571–17589, 14-Sep-2020.*
12. *C. Buzea and I. Pacheco, "Nanomaterials and their classification," in Advanced Structured Materials, vol. 62, Springer Verlag, 2017, pp. 3–45.*
13. *Sumlo Iijima, "Helical microtubules of graphitic carbon," Nature, vol. 354, pp. 56–58, 1991.*
14. *K. S. Novoselov et al., "Electric field in atomically thin carbon films," Science (80-.)., vol. 306, no. 5696, pp. 666–669, Oct. 2004.*

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