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Mini Review

Review on types of nanostructured materials

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ABSTRACT

Nanostructures are engineered structures with features at the nanoscale generally refer to the material systems that are in the range of 1 to 100 nanometers. In a nanostructure, electrons are normally confined in one of the dimensions, whereas in the other dimensions, they are free to move in all directions. These nanomaterials have enormous applications in electronics, medicine, agriculture, biomedical engineering, and environmental remediation techniques, which make these materials among the most promising and evolving materials in the recent era. Nanostructured materials can be categorized into four types such as: (1) inorganic-based nanomaterials; (2) carbon-based nanomaterials; (3) organic-based nanomaterials; and (4) composite-based nanomaterials. Generally, inorganic-based nanomaterials include different metal and metal oxide nanomaterials. Carbon-based nanomaterials include graphene, fullerene, single-walled carbon nanotube, multiwalled carbon nanotube, carbon fiber, an activated carbon, and carbon black. The organic-based nanomaterials are formed from organic materials excluding carbon materials, for instance, dendrimers, cyclodextrin, liposome, and micelle. The composite nanomaterials are any combination of metal-based, metal oxide-based, carbon-based, and/or organic-based nanomaterials, and these nanomaterials have complicated structures like a metal-organic framework.

Keywords: nanostructured materials, nanomaterial classification, nanotechnology, nanoparticles

Introduction

Nanotechnology deals with small structures or small-sized materials. Nanomaterials have emerged as an exciting class of materials that includes a broad spectrum of examples with at least one dimension in the range of 1 to 100 nm. A nanometer (nm) is one billionth of a meter, or 10^{-9}m. One nanometer is approximately the length equivalent to 10 hydrogen or 5 silicon atoms aligned in a line [1]. The small features permit more functionality in a given space, but nanotechnology is not only a simple continuation of miniaturization from micron meter scale down to nanometer scale. Materials in the micrometer scale mostly exhibit physical properties the same as that of bulk form; however, materials in the nanometer scale may exhibit physical properties distinctively different from that of bulk. Materials in this size range exhibit some remarkable specific properties; a transition from atoms or molecules to bulk form takes place in this size range. In recent years, nanoparticles (NPs) and nanostructured materials (NSMs) have generated extensive research interest due to their extraordinary physical, chemical, mechanical, and electrical properties [2]. Nanomaterials and nanostructures can be categorized depending on their shape, size, composition, dimension, and origin. The ability to predict the exceptional properties of nanostructures increases the value of each classification. Nanostructured materials are those with at least one dimension falling in nanometer scale, and include nanoparticles (including quantum dots, when exhibiting quantum effects), nanorods and nanowires, thin films, and bulk materials made of nanoscale building blocks or consisting of nanoscale structures [3].

1. Classification of nanomaterials based on their dimensions

According to a new scheme of nanostructures classification, the nanostructures were classified depending on their dimensions into one of four categories: 0D, where length, height, and breadth parameters are fixed at a single point, for instance at a dot; 1D, where only one the parameter exists, for instance graphene; 2D, where parameters of length and breadth exist, for instance carbon nanotubes; and 3D, where all three parameters exist, for instance Pd and ZnO NPs. Generally, electrons in 0D nanostructures are trapped in a dimensionless space while 1D nanostructures have electrons that can be moved along the (x)-axis no more than 100 nm. Accordingly, 2D and 3D nanostructures have electrons that can be moved along the (x, y)-axis and (x, y, z)-axis, respectively [4].

2. Types and classification of nanomaterials

Nanostructures have different shapes, sizes, structures and origins. They can be spherical, conical, spiral, cylindrical, tubular, flat, hollow, or irregular in shape and be from 1 to 100nm in size. Most nanostructured materials can be generally classified into four material-based categories (organic, inorganic, composite, and carbon-based) [5].

2.1 Carbon-Based Nanostructures

Nanostructures made of carbon are known as carbon-based nanostructures. They can have different morphologies, such as ellipsoid, hollow tube, or sphere. Generally, these nanostructures can be classified into diamonds, fullerenes (C_{60}, C_{80}, and C_{240}), carbon nanotubes (CNTs), graphene, and carbon nanofibers [6].

2.1.1 Fullerenes

A fullerene is an allotrope of carbon whose molecule consists of carbon atoms connected by single and double bonds so as to form a closed or partially closed mesh, with fused rings of five to seven atoms. The molecule may be a hollow sphere, ellipsoid, tube, or many other shapes and sizes. Fullerene (C_{60}) is a carbon-based molecule that is spherical in morphology and made up of carbon atoms held together via sp^2 hybridization. Generally, the other fullerenes (0D), such as C_{76}, C_{80}, C_{240}, etc, are synthesized from larger numbers of carbon atoms. Fullerenes are comprised of between 28 and 1500 carbon atoms that form spherical structures. Single-layer fullerenes have diameters up to 8.2nm while multilayer fullerenes have diameters of between 4 and 36nm [7].

2.1.2 Carbon Nanotubes

Since the discovery of nanostructures, carbon nanotube (CNT) structures (1D) have attracted great interest in most areas of basic science and engineering. Carbon nanotubes, a graphene nanofoil with a honeycomb lattice of carbon atoms, can be wound into hollow cylinders to form nanotubes. They can have diameters as low as 0.7nm for a single-walled carbon nanotube (SWCNT) and 100nm for a multiwalled carbon nanotube (MWCNT) and their lengths can range from a few micrometers to several millimeters. CNTs have great potential in materials science owing to their unique physicochemical properties. Their ends can either be hollow or closed through a half fullerene molecule. Nowadays, semiconductor materials and doping semiconductors have attracted the attention of many researchers due to their abundant applications [8].

2.1.3 Graphene

Graphene (2D) is an allotrope of carbon composed of a hexagonal lattice of honeycomb structure made up of carbon atoms consisting of sp^2-hybridized bonded carbon in a 2D planar surface. The thickness of a graphene sheet is about 1nm. Graphene stands out for being tough, flexible, light, and with a high resistance. It's calculated that this material is 200 times more resistant than steel and five times lighter than aluminum. With these properties, graphene has applications in the energy, construction, health, and electronics sectors [9].

2.1.4 Nanodiamonds

Nanodiamonds are nanometer-size diamonds with unique structures and characteristics that make them useful for many industrial applications. A nanodiamond is a diamond particle with a size in the nanometer range or one-millionth of a millimeter. Nanodiamonds are made of a diamond core and outer layers of amorphous carbon. The shape, core, and surface are the most critical aspects of the structure of nanodiamonds. Nanodiamonds or diamond NPs are saturated hydrocarbons that have diamond-like fused ring structures that have biological and electronic applications as well as applications linked to quantum engineering [10].

2.2 Organic-Based Nanostructures

Dendrimers, liposomes, micelles, polymer NPs, etc., are usually known as organic nanostructures or polymers. These include nanostructures made mostly from organic material, excluding carbon-based or inorganic-based nanostructures. These nanostructures are nontoxic, biodegradable, and some of their structures, e.g., liposomes and micelles, have hollow cores (also known as nanocapsules). They are sensitive to electromagnetic and thermal radiation, i.e., light and heat. Organic nanostructures are most widely utilized in the field of biomedicine for applications like drug delivery systems [9,11].

2.2.1 Dendrimers

Dendrimers, as a unique class of polymers, are highly ordered, branched macromolecules and tree-like structures with nanoscale dimensions. The surface of a dendrimer contains numerous chains that can be modified to perform specific chemical functions. Dendrimers are prepared from monomers by either convergent or divergent step-growth polymerization [12].

2.2.2 Polymeric Micelles and Nanocapsules

Polymeric micelles possess amphiphilic block copolymers assembled to form nanoscopic core-shell structures. Both the intrinsic and modifiable properties of polymeric micelles make them well suited for systemic delivery of water insoluble drugs. As noted above, micelles have hollow cores known as nanocapsules. A nanocapsule is a nanoscale shell made from a nontoxic polymer. Nanocapsules have many uses, including promising medical applications for drug delivery purposes, nutraceuticals, food enhancement, and in self-healing materials [10,13].

2.3 Inorganic-Based Nanostructures

Inorganic nanostructures and nanoparticles are structures and particles that are not made from carbon-based or organic-based NPs. These nanostructures include metal and metal oxide NPs. Metal-based and metal oxide-based NPs are commonly categorized as inorganic nanostructures. These nanostructures can be synthesized into metal NPs, such as Pd or Au, metal oxide NPs like TiO_2, and also semiconductors, such as ceramics and silicon [14].

2.3.1 Metal-Based Nanostructures

Nanostructures (nanoparticles) that are synthesized from metals to nanometric scales, either using constructive or destructive methods, are called are metal-based nanostructures. Metal-based nanoparticles fascinated scientists for over a century and are nowadays heavily utilized in biomedical and material sciences. Almost all metals can be synthesized into nanostructures or NPs. Generally, aluminum (Al), gold (Au), silver (Ag), copper (Cu), cobalt (Co), cadmium (Cd), lead (Pb), iron (Fe), and zinc (Zn) metals are used for nanoparticle synthesis. Inorganic metal NPs possess unique properties, such as large surface areas, surface charge densities, pore sizes, and stability, and can be cylindrical or spherical in shape, crystalline or amorphous in structure, and small in size as low as 10–100nm [15].

2.3.2 Metal Oxide-Based Nanostructures

Metal oxide-based nanostructures are synthesized mainly because of their increased efficiency and reactivity. Metal oxide-based nanostructures are prepared in order to modify the properties and characteristics of their respective metal-based NPs, e.g., in the presence of oxygen, iron (Fe) NPs immediately oxidize to iron oxide (Fe_2O_3) at room temperature [16]. The commonly utilized metal oxides for nanostructure synthesis are iron oxide (Fe_2O_3), magnetite (Fe_3O_4), aluminum oxide (Al_2O_3), zinc oxide (ZnO), titanium oxide (TiO_2), silicon dioxide (SiO_2), and cerium oxide (CeO_2). These novel nanoparticles are anticipated to have a substantial impact in many fields, such as electronics, aerospace, medicine, and (photo)catalysis, due to their exceptional properties [17].

2.4 Composite-Based Nanostructures

Nanocomposites can be described as multiphase nanostructures with one phase being at the nanoscale dimension. They can either combine nanostructures with other NPs or NPs with bulk-type or larger materials (e.g., hybrid nonporous materials) or more complicated structures. Nanocomposites can be any combination of metal-based, carbon-based, or organic-based nanostructures with any form of ceramic, metal, or polymer bulk materials [14, 18].

2.5 Other Nanostructures

2.5.1 Nanocrystalline Materials

Nanocrystalline (NC) materials are single-phase or multiphase polycrystalline solids with a crystallite size of only a few nanometers ($1nm=10^{-9}m=10A°$) usually less than 100 nm. Grain sizes of 100–500nm are classically considered “ultrafine” grains. The grain size of NC materials is determined by X-ray diffraction. Also, crystallite size can be obtained directly using transmission electron microscopy. There are several methods used to prepare NC materials. These methods can be categorized according to the phase the material transitions before creating a nanocrystalline final product [19].

2.5.2 Nanoporous Materials

Nanoporous materials consist of a regular organic or inorganic framework supporting a regular, porous structure. The size of the pores is generally 100nm or smaller. Most nanoporous materials can be classified as bulk materials or membranes. Over the past few years, nanoporous materials have attracted a lot of attention due to their excellent porous properties [19]. Nanoporous materials are divided into three groups, based on pore size:

- l Microporous (< 2nm)
- l Mesoporous (2–50nm)
- l Macroporous (>50nm)

Properties and applications of each nanoporous structure depend on pore size and surface area. Some examples of nanoporous solids are metal-organic frameworks, zeolites, ceramics, activated carbon, silicates, various polymers, aerogels, pillared materials, and inorganic porous hybrid materials [17, 20].

2.5.3 Nanofiber Materials

Nanofibers are nanosized fibers. Today there are several methods for the preparation of nanofibers including self-assembly, electrospinning, template synthesis, and phase separation. In addition, nanofibers can be prepared using various polymers such as keratin, collagen, silk fibroin, cellulose, gelatin, poly (lactic acid) (PLA), poly (lactic-co-glycolic acid) (PLGA), poly (ethylene-co-vinyl acetate) (PEVA), and polysaccharides such as alginate and chitosan. Nanofibers are considered important by many researchers because of the advantages they offer, such as being lightweight and having small diameters, having high surface-to-volume ratios, and controllable pore structures [21].

2.5.4 Nanowire, Nanoflower, and Nanospring Nanostructures

Nanowires are similar to normal electrical wires apart from the fact that they are very small. They are defined as having a ratio of length to width larger than 1000nm. Alternatively, they can be defined whereby their diameter and thickness is nanoscale but their length is unconstrained. Nanowires are known as 1D materials due to the large difference between their diameter and length. This leads to nanowires having special properties such as quantum mechanical effects. There are a variety of nanowires, such as metallic, insulating, superconducting, and semiconducting [20,21]. Nanostructures and NPs are commonly synthesized with different morphologies, such as nanoflowers, nanowires, and nanosprings, depending on their required properties and applications [22].

2.5.5 Quantum Dots

Quantum dots (QDs) are a particular kind of semiconducting crystalline nanostructure containing a metallic semiconductor core that is most commonly coated in a shell to improve its optical behavior. A quantum dot has a discrete quantized energy spectrum. Typical quantum dot sizes range between 2 and 20nm. The color they glow depends on the size of the nanoparticle. The capability to tune the size of QDs is advantageous for many applications. Due to their unique properties, such as bright fluorescence, broad UV excitation, narrow emission, and high photostability, QDs have an enormous impact on pharmaceutical research and drug development [23].

Conclusion

Interest in Nanostructured materials has attracted so much attention in recent years because of their superior and tunable physical, chemical, and biological features compared with bulk materials. Nanostructured materials can be classified in function of their size, shape, composition, and origin. Most nanostructured materials can be generally classified into four material-based categories (organic, inorganic, composite, and carbon-based). Generally, inorganic-based nanomaterials include metal-based and metal oxide nanoparticles. Graphene, fullerene, single-walled carbon nanotube, multiwalled carbon nanotube, carbon fiber, an activated carbon, and carbon black are the different categories of carbon-based nanomaterials. The organic-based nanomaterials are made mostly from organic matter, aside from inorganic-based or carbon-based nanomaterials for instance, dendrimers, cyclodextrin, liposome, and micelle. The composite nanomaterials may be any combinations of carbon-based, metal-based, or organic-based nanomaterials with any form of metal, ceramic, or polymer bulk materials and these nanomaterials have complicated structures like a metal-organic framework.

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