1

Enhanced Carbon-Based Materials and Their Applications

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1.1 Overview

This book entitled "Enhanced Carbon-Based Materials and Their Applications" intends to deliver the synthesis methods and role of carbon-based materials that can be introduced into the device to enhance the performance of several types of electronic devices. The theme of this book is multidisciplinary and provides the broader scientific and industrial community with a timely and carefully referenced overview that provides a summary of carbon-based materials and applications. The book has been written in style to make it accessible for academics to provide an overview of synthesis methods and characterization techniques of carbon nanomaterials. On the other hand, this book also demonstrates the various reported applications for carbon-based and enhanced materials for professionals.

1.2 Glance of Carbon-Based Materials

Carbon is the 4th most abundant element in the universe and the foundation of life, despite the various elements on the Earth. Its existence extended from nonliving substances to living objects. All organic substances that are found in nature consist of carbon. It has unique physical and chemical properties in multiple forms [1]. The carbon material is a big family with many allotropes, and they possess unique structure, texture, and properties. These carbon materials are classified according to their C-to-C bonding, namely, sp, sp^2, and sp^3 hybrid orbitals of carbon atoms. Carbon structures include three primary allotropes known as diamond, graphite, and fullerene. Diamond and graphite are the natural carbon sources that humankind could discover abundantly on Earth [1].

Diamond shows sp^3 hybrid orbitals, consisting of a tetrahedron network of carbon atoms. It can be naturally formed under prolonged high pressure and high

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temperature. In the sp3 hybridized form, the C atom and adjacent C atom are linked up by covalent bonds. Consequently, it leads to a strong bonding and tetrahedral atomic arrangement that allows the diamond to be the hardest substrate among others. Diamond is a colorless transparent substrate, which is heavy and extremely hard. It does not conduct electricity but has high thermal conductivity and melting point. In addition, diamond has high resistance to chemical corrosion. For more than one century, this special allotrope of carbon has only been used as a precious stone in making jewelry, ornaments, and glass cutters. Nonetheless, recent scientific development has extended its application into medical science, material science, semiconductor, and nanotechnology [2–6].

Graphite shows sp^2 orbitals. It is a greyish-black opaque substance with a high-melting point and low coefficient of thermal expansion. In addition, graphite also has high thermal, electrical conductivity, chemical, and corrosion resistance. These properties enable wide applications from pencil lead, high-temperature lubricant, paint, printing, plastic industry, and electrode in battery/cell up to the application as nuclear reactor moderator [7, 8]. A fullerene is the third allotropes of carbon whose molecule consists of carbon atoms connected by covalent bonds to form fused rings of five to seven. Fullerenes are polyhedral carbon cages in which sp^2-carbons are directly bonded to three neighbors in an arrangement of five- and six-membered rings [9]. Fullerene (also called "buckyball") can be constructed by 24, 28, 32, 36, 50, 60, 70, 72, etc., number of carbon atoms. Compared to other types of carbon allotrope, it can be dissolved in common solvents, for example, carbon disulfide and toluene, at room temperature. Recent research on fullerene has enabled its applications in catalysis, water purification, antiviral and antioxidant activities, biohazard protection, magnetic resonance imaging (MRI) medium for diagnostic agents, and the latest nanotechnology advancement in drug and gene delivery [9–14].

Graphite, carbon fiber, etc., have been widely used in the manufacturing and industrial field. Modern applications for carbon materials are focused on the nanostructured form of carbon elements. The world demand for the carbon nanomaterials market is expected to reach US$ 21.97 Billion in 2026. A compound annual growth rate (CAGR) of 4.1% was predicted during this forecast period [15]. The end-use area in industries includes aviation, energy, electrical and electronics, medical and healthcare, packaging and backend, transportation, automotive, and consumer goods. Its nontoxic and biocompatible characteristics have greatly enhanced the possibility of its applications to areas from nonliving to living things. Figure 1.1 summarizes the allotropes/form/type of carbon in a concentric circle. Carbon-based materials can be categorized into different types, which are carbon nanotubes (CNTs), layered sheets (graphene/graphite), carbon black, fullerene, and quantum dots.

Most carbon-based materials are naturally stiff, lightweight, and highly conductive [16, 17]. In addition, they can be easily engineered to achieve targeted material properties. For example, CNTs have been assembled into fibers with ultrahigh specific strength and stiffness, which are much higher than commercially available engineering fibers [17]. These lightweight, stiff CNT fibers show their potential in

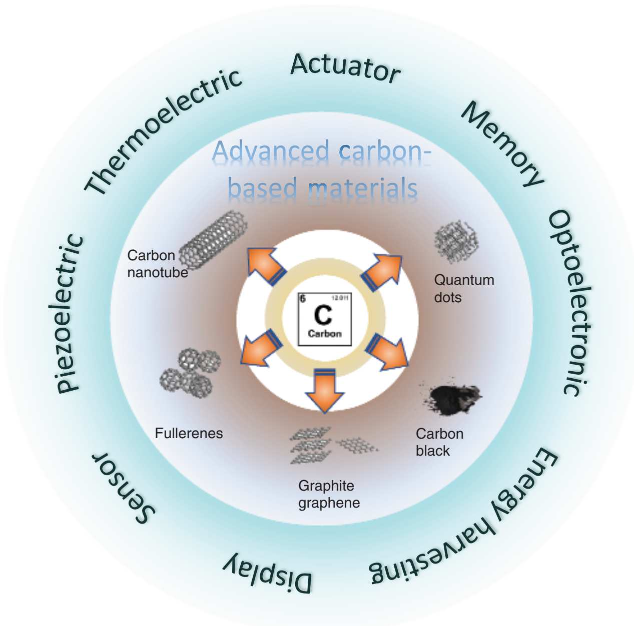

Figure 1.1 Multiforms of carbon-based materials and their applications in contemporary electronic and optical-related technologies.

many structural applications, such as the construction of energy-efficient airplanes and space structures. Although single-crystal graphene shows excellent properties, single crystals need to be assembled into the macroscopic structure in many practical applications. A single piece of graphene is delicate, but linking them through chemical or physical approaches can form a stronger 3D network [18, 19]. It has been reported that porous structured 3D graphene assembly can be even lighter than air and ten times as strong as mild steel [19]. In addition to the inherent properties of carbon nanomaterials, the high surface area and large pore volume of the 3D porous structure can create more space for the transportation or storage of the electron/ion, gas, and liquid, which enables remarkable sensitivity for sensors, large capacity for supercapacitors, and high-power density batteries [20].

On the other hand, carbon-based materials always face irreversible aggregation and insolubilization issues when preparing aqueous suspensions due to their van der Waals attractions between single crystals and hydrophobicity. Stable and distributed aqueous or organic suspensions are the key factors to enable repeatability and homogeneity, which directly limit their industrial applications. Several functionalization approaches have been utilized to treat carbon-based materials to reduce aggregation and insolubilization [21]. The commonly used method modifier to achieve stabilized aqueous or organic dispersions is an amphiphilic or covalent surfactant. For instance, graphene nanosheet was stably dispersed in water, *N*,*N*-dimethylformamide (DMF), and dimethyl sulfoxide (DMSO) by covalently functionalized polydisperse graphene with amine-terminated ionic liquid [22]. Amphiphilic surfactant poly(sodium 4-styrenesulfonate) (PSS) has been coated on graphitic nanoplatelets to provide stable aqueous dispersion with the aid of ultrasonic treatment. Reduced graphene was stabilized via association with the hydrophobic backbone of PSS, while the hydrophilic sulfonate side groups sustained the graphene-PSS in water [23].

1.3 Applications

In this book, we infer "enhanced carbon-based materials" as modified properties of pristine carbon materials derivatives that can be used to enhance the performance of devices. In the examples mentioned above, the formed functional variants in enhanced carbon-based nanomaterials play a crucial role in distinguishing specific applications. Plenty of methods can be used to enhance the carbon materials, and the resulting enhanced carbon-based materials can be categorized as (i) doping, (ii) alloying, and (iii) surface attaching of alien atoms/molecules in order to alter their physical and chemical properties. Those three methods mentioned above achieve the same goal in the nanoscale material form, resulting in surface energy/chemistry change. This is due to its high surface-to-volume ratio of nano-regime properties. The change in the surface energy enhances a better coupling for signal transduction used for different applications with the attachment of dedicated alien substances, especially luminescent molecules/substances for biomarkers, chemical/protein-based drugs/genomic elements for medical applications, moieties for catalysis or plasmonics, and polar/nonpolar materials for modulation on wettability [24–30]. Again, those attachments in different forms enhance the carbon materials and enable the multiple functions used for various applications.

In the trend toward miniaturization, electronics require small, flexible, lightweight, and multifunction devices. These demands have driven the rapid development of nanotechnology. Enhanced carbon-based materials have become the most desirable materials for future electronics. They have driven the development of revolutionary technologies, such as advanced materials, renewable energy, biomedical, and smart electronic devices, due to their superior mechanical and electrical performances. These applications associated with enhanced carbon-based materials have shown low-power consumption, high sensitivity, selectivity, and efficiency. Figure 1.2 shows that the research on carbon-based materials has increased by leaps and bounds in the recent three decades since 1980 [31]. Over the past three decades, the number of published articles with the keywords "carbon" and "carbonuous" has increased tremendously, more than 12 times from 10 690 in 1980 to 137 176 in 2021. Carbon-based materials have shown great versatility since they can be easily functionalized physically and chemically modified with other elements. The excellent and tunable mechanical, electrical, thermal, optical, and chemical properties of carbon-based nanomaterials are desired to be included in electronic gadgets to improve overall performance further [32].

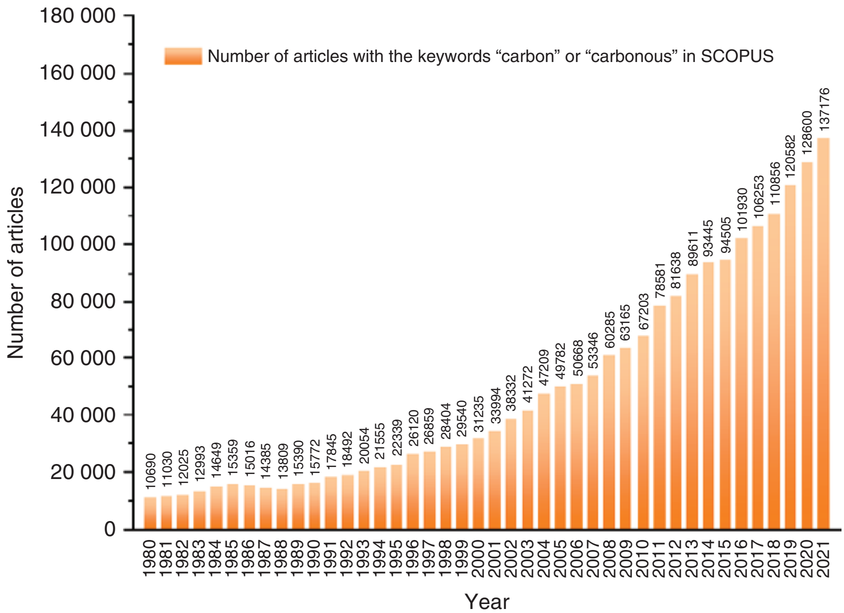

Figure 1.2 Number of published articles with the keywords “carbon” and “carbonuous” from 1980 to 2021.

1.4 Outline of This Book

The book consists of 10 chapters to provide a brief overview of state-of-the-art carbon-based and enhanced nanostructures and their applications. Chapter 2 outlines the fundamental insight into carbon-based materials synthesis and material characterization techniques. Chapter 3 presents the advanced functionalization techniques of carbon-based materials and their applications, such as carbon-based sensors that consist of planar graphene and graphene hybridized material. Their specific material properties, preparation methods, and sensing behaviors are discussed. The following chapters (Chapters 4–9) focus on the overview of carbon-enhanced materials. The integration of these materials is of great importance for the performance enhancement of various future electronics applications, including nonvolatile memories, optoelectronic devices, thermoelectrics, energy harvesters, actuator, and display. In addition, an overview of this book will be summarized in the conclusions, and future directions for the applications of carbon-based and enhanced materials are discussed.

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