Chapter 1 From Fundamentals to Applications of Carbon Nanostructures: An overview

Citation: Rajagopalan Thiruvengadathan, Poonam Sundriyal, Somnath C. Roy and Shantanu Bhattacharya, "From Fundamentals to Applications of Carbon Nanostructures: An overview," in *Carbon Nanostructures: Fundamentals to Applications* [AIP Publishing (online), Melville, New York, 2021], available at: https://doi.org/10.1063/9780735423114_001

View online: https://doi.org/10.1063/9780735423114_001

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CHAPTER 1

FROM FUNDAMENTALS TO APPLICATIONS OF CARBON NANOSTRUCTURES: AN OVERVIEW

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Thiruvengadathan, R., Sundriyal, P., Roy, S. C., and Bhattacharya, S., "From fundamentals to applications of carbon nanostructures: An overview," in *Carbon Nanostructures: Fundamentals to Applications*, edited by R. Thiruvengadathan, P. Sundriyal, S. C. Roy, and S. Bhattacharya (AIP Publishing, Melville, New York, 2021), pp. 1-1–1-14.

1.1 INTRODUCTION

A humongous increase in global energy demand, rapid depletion of fossil fuels, and environmental effects, such as harmful emissions of greenhouse gases and other pollutants, are critical issues that motivate the advancement of renewable energy sources (Lewis and Nocera, 2006; Chisti, 2007; and Chu and Majumdar, 2012). Traditional energy sources like oil, coal, and gas are quickly being exhausted due to an increase in global consumption. Nuclear energy is an attractive alternative; however, several safety concerns are associated with it besides the massive investment and maintenance costs, including procuring source material. Among the other alternatives for energy generation, hydrothermal energy generation has caught the interest of governments and industries across the globe. However, various geopolitical factors and seasonal irregularity of running water make it an unreliable source of energy. The aforementioned factors unequivocally demand sustainable energy development from renewable sources such as wind, solar, and ocean. This demand will continue to increase with population explosion and industrial expansion, making the capture, storage, conditioning, and utilization of these energy sources extremely vital.

The concept of capturing, storing, and effectively utilizing energy, employing different interfaces and storage devices, is referred to as energy harvesting. Energy harvesting can also be referred to as "energy

https://doi.org/10.1063/9780735423114_001

Carbon Nanostructures: Fundamentals to Applications, Thiruvengadathan, R., Sundriyal, P., Roy, S. C., and Bhattacharya, S.
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scavenging," and discards the use of fossil fuels and other hazardous energy sources, in a sense, and exploits the phenomenal paybacks of renewable energy sources. Decentralization of energy generation units contributes to a significant decrease in transmission and distribution losses, making energy harvesting from renewable sources an impressive alternative. The sheer abundance of renewable energy sources at distributed locations and various economic, environmental, and geopolitical factors are pushing governments and industries to accelerate energy harvesting from renewable energy sources. Intense, yet focused research is continuing to develop alternative clean and sustainable energy technologies.

Carbon and its allotropes, such as graphite, diamond, graphene, fullerenes, carbon nanotubes (CNTs), and amorphous carbon, have excellent advantages. Graphitic carbon and diamond-like carbon have different hybridizations, which are sp^2 and sp^3, respectively. Diamond-like carbon and diamond are highly advantageous since they possess enhanced optical properties, mechanical properties, and impressive thermal stability. These advantages have been attributed to the strong chemical bonds between the carbon atoms. On the other hand, graphite and graphitic carbons exhibit excellent electrical conductivity. Graphite derivatives, such as graphene, fullerenes, and carbon nanotubes, have garnered significant attention due to their important and extremely unique physical properties. At the nanoscale, the structure and the interfacial interactions with surrounding bulk materials determine the physical and chemical properties of nanomaterials. Concomitant with the very high values of thermal conductivity, electrical conductivity, and mechanical strength, the large specific surface area and aspect ratios of carbon nanostructures are all excellent attributes that offer the potential for fabrication of alternative clean and sustainable energy technologies (Stankovich *et al.*, 2006; Avouris *et al.*, 2007; Balandin *et al.*, 2008; Stoller *et al.*, 2008; Baker and Baker, 2010; Dresselhaus *et al.*, 2010; Shao *et al.*, 2010; and Balandin, 2011). Hence, carbon nanostructures and their multifunctional composites have garnered significant attention from the scientific community and corporations alike. The various research and development aspects of carbon nanostructures, with their key applications, focused on in this book are captured in the schematic shown in Fig. 1.1.

Recent advancements in the meticulous synthesis of carbon nanostructures, their functionalization, implementation of self-assembly methods, and the formation of multifunctional carbon nanostructure-based composites have all facilitated the significant improvement in energy storage performance (Stankovich *et al.*, 2006; Avouris *et al.*, 2007; Balandin *et al.*, 2008; Stoller *et al.*, 2008; Baker and Baker, 2010; Dresselhaus *et al.*, 2010; Shao *et al.*, 2010; and Balandin, 2011). In addition to presenting the fundamental aspects of synthesis and the characterization of carbon nanostructures and polymer-based conducting nanocomposites, this book lucidly details the technological advancements made on a variety of energy storage techniques, including electrochemical storage, hydrogen storage, solar energy, and other applications, namely, photocatalysis, chemical and biological sensing, and electromagnetic applications.

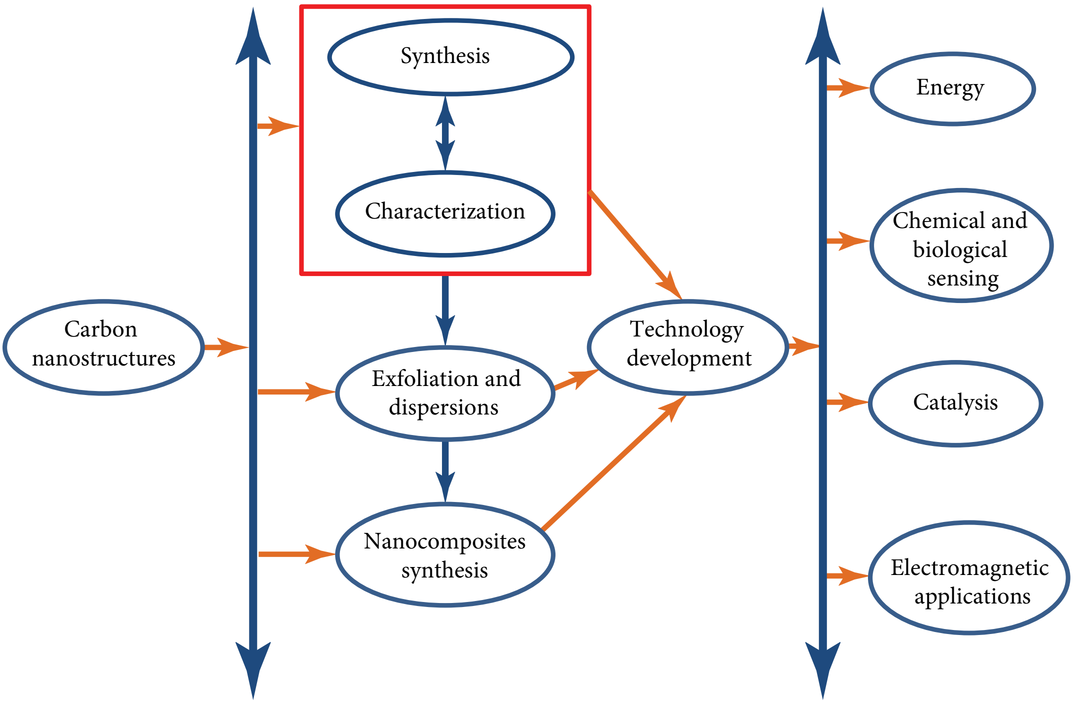

FIG. 1.1
A schematic of the research and development activities of carbon nanostructures and their key applications.

1.2 FUNDAMENTAL ASPECTS OF CARBON NANOSTRUCTURES: AN OVERVIEW

With carbon nanostructures proving their widespread application in the development of sustainable technologies, during the past three decades research efforts have been devoted to the development of a variety of synthesis methods (Ajayan *et al.*, 1993; Iijima and Ichihashi, 1993; Yudasaka *et al.*, 1997; Shi *et al.*, 1999, 2000; Baker and Baker, 2010; Guldi and Martín, 2010; Terrones *et al.*, 2010; and Ruffieux *et al.*, 2016). Among the various synthesis methods, chemical vapor deposition and arc discharge have been reported to be economically viable on an industrial scale. Development of sustainable and cost-effective methods employing green chemistry and natural resources like biomass is attractive. Various characterization experiments have proven that the properties and interactions of carbon nanostructures are morphology dependent, thereby pushing researchers to ratify the structure–property relationship. A plethora of experiments at multiple length scales ranging from macro- to micro- to nanoscale have been performed using a variety of analytical tools to determine the structural, thermal, electrical, and optical properties of carbon nanostructures (Chap. 2). The various functionalization methods discussed in this book (Chap. 3) have enabled the realization of tailored and tunable polymer-based nanocomposites. Specifically, the inclusion of carbon nanostructures such as CNTs and graphene in polymers has been found to produce composites with desirable properties, fostering application development.

In recent years, flexible energy storage devices have caught the attention of various researchers and industries across the globe. The primary requirement for such devices is the availability of a wide range of flexible materials. Carbon nanostructures have found an interesting application in flexible devices that are made from carbon-based nanostructure composite materials. In order to enhance the properties of the chosen polymer matrix, successful dispersion of carbon nanofillers is an essential requirement, which can be enhanced through various chemical functionalization and physisorption of surfactant methods (Bahr and Tour, 2002; Bandyopadhyaya *et al.*, 2002; Grossiord *et al.*, 2005; Attal *et al.*, 2006; and Ma *et al.*, 2010). Chemical functionalization of carbon nanostructures is imperative, since it enhances the electroactive phases of insulating polymer matrices, such as polyvinylidene fluoride (PVDF) (Dang *et al.*, 2007; Kim *et al.*, 2009; and Yu *et al.*, 2009). Therefore, research in the field of chemical functionalization and characterization of such composites has been given the utmost importance for improving the performance of various devices. For example, harnessing of solar energy is dependent on the use of conducting polymers and their composites, despite their lower efficiency in comparison to silicon-based solar cells. However, the cost-effectiveness and ease of fabrication of polymer-based flexible composites makes them attractive materials for the fabrication of thermoelectric materials that convert heat energy to electrical energy, as has been amply demonstrated in the scientific literature.

Although the dispersion of fillers such as CNTs and graphene in a polymer matrix to fabricate polymer nanocomposites has been addressed, the effect of filler size and crystallinity on the thermal performance and flammability of the polymer nanocomposite should also be taken into account based on the application requirement (Moniruzzaman and Winey, 2006; and Fu *et al.*, 2010). Fillers with flame-retardant properties can severely inhibit the flammability of polymers. It has been shown that flame-retardant fillers significantly reduce the flammability of polymer nanocomposites by as much as 60%, in comparison to polymer nanocomposites, which do not employ flame-retardant fillers. These aspects are addressed in Chap. 4.

1.3 CARBON NANOSTRUCTURES IN PHOTOCATALYTIC APPLICATIONS

Photocatalysts play an important role in energy harvesting due to their potential to use two of the world's most abundant natural resources—water and sunlight—for sustainable and clean energy generation.

Carbon nanostructures, such as CNTs, carbon quantum dots, graphene, and graphitic carbon nitride, have been utilized to develop photocatalysts that are cost-effective, safe, and renewable (Zhang *et al.*, 2010a; Leary and Westwood, 2011; Yang *et al.*, 2013; and Low *et al.*, 2014). Carbon nanostructures act as a better alternative to pristine carbon since they successfully inhibit charge recombination, act as sensitizers by extending the solar light absorption region, facilitate the localization of reactants by providing a hydrophobic environment, and significantly increase the area for interaction, thereby effectively improving the overall photocatalytic efficiency. Carbon-based nanomaterials and their composites have been effectively utilized in water splitting for generating hydrogen and have proven to be effective in environmental reverification. Chapter 5 provides a detailed account of the application of carbon nanomaterials as efficient photocatalysts.

1.4 CARBON NANOSTRUCTURES IN ENERGY STORAGE APPLICATIONS

The number of publications concerning energy-related aspects and applications of carbon nanostructures (such as CNTs, graphene and its analogues, carbon nanodots, and carbon nanofibers) is shown in Fig. 1.2. The significance of carbon nanostructures in application development is evident from the increasing trend in the number of publications over the past three decades. Some applications have matured to a higher technology readiness level, while some applications are still being intensively studied in research laboratories across the world. Judging by the sheer number of published papers, research on energy-related application aspects of carbon nanostructures dominates other research domains of carbon nanostructures. Several chapters of this book are devoted to presenting in-depth reviews on energy-related aspects.

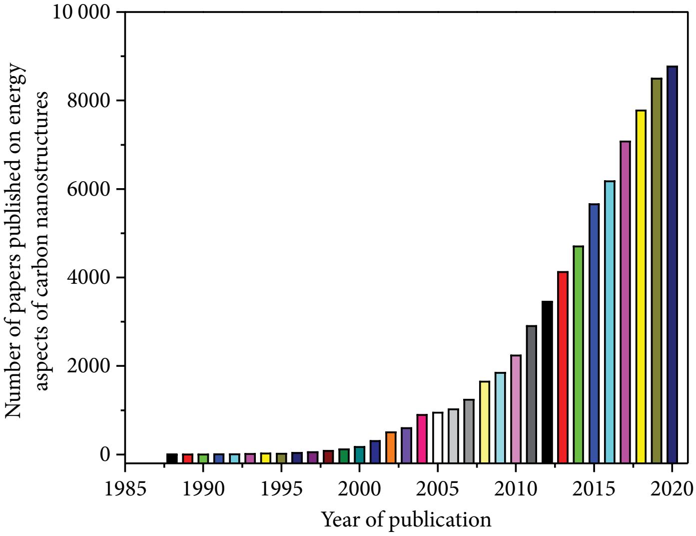

FIG. 1.2
The number of publications on energy-related aspects and applications of carbon nanostructures over the past three decades.

1.4.1 Carbon nanomaterials for supercapacitors

Among the energy storage devices, supercapacitors have garnered substantial attention in recent years due to a strategic shift toward green energy and a significant increase in utilization of off-grid units like electronics and electric vehicles, which heavily depend on mobile energy sources like batteries. Supercapacitors provide excellent electrochemical advantages and help bridge the gap between electrolytic capacitors and batteries. They exhibit superior energy density over electrolytic capacitors and faster charging/discharging than batteries. Based on the charge storage mechanism, supercapacitors can be classified as electrostatic double-layer capacitors (EDLCs), pseudocapacitors, and hybrid capacitors. For the fabrication of EDLCs, carbon materials, specifically carbon nanotubes, graphene, porous carbon, and activated carbon, have been identified as suitable due to their high energy storage and cost-effectiveness (Zhang *et al.*, 2010b; Yu *et al.*, 2011, 2014; Zhi *et al.*, 2013; and Sheberla *et al.*, 2017). The energy density of supercapacitors based on porous carbons is significantly increased due to the enhanced surface area per unit mass of these carbons, their large pore volumes, excellent mechanical stability, and inherent chemical inertness. Porous carbon finds extensive application in the field of electrochemistry due to its large potential window between water splitting reactions, reduced or constant background current, and quick and facile electron-transfer kinetics.

Composite electrodes comprised of materials based on different charge storage mechanisms exhibit superior electrochemical properties. The fabrication of composite electrodes is necessary since electrodes based purely on carbonaceous materials exhibit good flexibility but have poor specific capacitance values. The desired properties of high surface area, porosity, electronic conductivity, numerous active sites, and enhanced physical and chemical stability are obtained by fabricating composite electrodes. Pseudocapacitors have been identified to exhibit much higher specific capacitance due to their reversible faradaic reactions. However, they cannot be utilized in the fabrication of flexible electrodes due to their inhibited flexibility. Pseudocapacitive substances, such as conducting polymers and their composites, have garnered significant attention due to their multiredox reactions and electronic properties, good processability, cost-effectiveness, and easy synthesis. However, despite the listed advantages offered by these materials, they have poor cyclic and mechanical stability. To address these disadvantages, pseudocapacitive materials are incorporated with carbonaceous materials to fabricate composite electrodes that exhibit superior mechanical strength, enhanced electrochemical attributes, and improved cyclic stability. Therefore, the flexibility of carbon nanostructures coupled with the enhanced electrochemical properties (especially specific capacitance) of pseudocapacitive substances, like conducting polymers and metal oxides, permit electrodes to undergo cycles of volumetric changes without suffering any deterioration, which significantly increases the cyclic stability of these composite electrodes. Therefore, intense research in the domain of pseudocapacitive substances that significantly improve the specific capacitance and cycling stability is encouraged. Advancements made on both EDLC-based and pseudocapacitance-based supercapacitors are discussed in Chap. 6.

Hybrid supercapacitors employ the charge storage mechanisms of both EDLCs and pseudocapacitors. They exhibit a superior capacitance retention at least one or two orders more than electrolytic capacitors and have a greater number of charging/discharging cycles. Carbon nanostructures, such as graphene and CNTs; inorganic materials, such as metal oxides; and conducting polymers, such as polyaniline (PANI) and polypyrrole (PPy), have been identified to be suitable for the fabrication of hybrid electrodes. To overcome the low energy density of supercapacitors and low power density of batteries, asymmetric hybrid supercapacitors comprised of supercapacitors and battery-type electrodes have been assembled, which offer higher energy as well as higher power densities (Zhang *et al.*, 2010a; Yu *et al.*, 2011, 2014; Liu *et al.*, 2013a; Zhi *et al.*, 2013; El-Kady *et al.*, 2015; Sheberla *et al.*, 2017; and Hu *et al.*, 2019). Recently, MXene-based materials and bismuth ferrite-based materials with inclusion of carbon nanomaterials have generated substantial interest in the development of hybrid supercapacitors owing to their ability to show superior performance in terms of enhanced energy and power densities. Chapter 7 is entirely focused on this new class of materials as electrode materials for hybrid supercapacitors. Therefore, adopting different fabrication techniques and achieving electrochemical attributes of hybrid supercapacitors is an avenue open for further research and development, as discussed in this book.

1.4.2 Fabrication methodologies of flexible energy storage devices

Various fabrication methods, including inkjet printing and lithography-based miniaturization processes, have been utilized for the successful fabrication of flexible energy storage devices employing polymer-based carbon nanocomposites (Meng *et al.*, 2010; Nyholm *et al.*, 2011; Jiang *et al.*, 2013; Chen and Dai, 2014; and Zhao *et al.*, 2014). Inkjet printing is an additive manufacturing method, showing enormous potential for the fabrication of thin film-based energy storage devices, especially from the viewpoint of large-scale production. Energy storage units, which are an integral part of the power-generation assembly especially related to intermittent energy sources, have seldom been manufactured using various printing technologies, which opens an avenue for further research. The lack of flexible energy storage units, scalability issues encountered when manufactured in large numbers, and improper device structure are some of the problems encountered in developing printable solutions. To overcome these issues, high-yield desktop printing employing cellulose paper and textile fabrics have been utilized for manipulating nanomaterials to fabricate printed, solid-state, and flexible lithium-ion supercapacitors. Various inks have been successfully optimized for easy development within the printable range. The substrates used for fabricating these energy storage devices have been made sufficiently conductive by employing a layer-by-layer approach, where reduced graphene oxide (rGO) ink has been used over different surfaces. Other components of a printable supercapacitor, such as the positive and negative electrodes and electrolytes, can be fabricated using the power offered by computer-aided design to facilitate the scaling up of the manufacturing process to industrial standards. This method has proved to be highly effective in fabricating flexible supercapacitors with excellent cyclic stability, high energy density, reproducibility, and repeatability. The scalability of the manufacturing method gives improved control over various parameters, such as dimension, thickness, size, and shape of various patterns. Therefore, printing methods have been found to be highly effective for fabricating flexible energy storage devices like supercapacitors (see Chap. 8).

1.5 CARBON-BASED NANOMATERIALS FOR CHEMICAL AND BIOLOGICAL SENSING APPLICATIONS

Recently, sensors have found extensive applications in diverse arenas, such as medicine and health. Sensors can be used to detect environmental pollutants, metabolites, blood molecules, parasites, etc. One of the areas of research in the field of sensing is to utilize carbon nanostructures and their composites. Application of neat graphene to fabricate sensor-based devices on a massive scale is a fundamentally challenging task, as there are a number of issues, such as adhesion, reproducibility, cost, and complexity of transfer processes to suitable substrates. In contrast, functionalized graphene has functional moieties like epoxy, hydroxyl, carbonyl, and carboxylic groups that can promote adhesion to metal nanoparticles. The metal–rGO nanocomposite finds many applications in chemosensors, biosensors, and drug delivery, in addition to other applications including charge storage (Hu *et al.*, 2010; Jiang, 2011; and Shrivastava *et al.*, 2016). The metal–rGO nanocomposite exhibits impressive properties like increased surface area, high electrical conductivity, thermal stability, and increased chemical resistance, making them ideal for sensing applications. Research and development in several fundamental and application-related issues is the current need. Such activities must address and lead to reducing the duration of synthesis, develop an environmentally benign process through the use of green chemicals, enable energy-efficient processes through use of moderate process parameters such as temperature and pressure, and, finally, make the production of such sensors economically viable. Chapter 9 addresses the synthesis processes, characterization techniques, and sensing applications for environmental pollutants and biologically relevant molecules/species using metal–rGO-based nanocomposites.

The field of sensing finds a plethora of applications in this rapidly modernizing world. However, the ever-increasing industrialization across the globe poses a significant threat to environmental health due to the alarming concentrations of toxic gases found in the atmosphere. Techniques and technologies to monitor the concentration of these harmful gases and vapors in our surroundings have become necessary for public health and safety. Various man-made disasters that have occurred due to the failure to detect toxic gases early further necessitate the development of accurate and fast gas sensors. With their high surface-to-volume ratio, nanomaterials have been determined to be ideal materials for utilization in gas-detecting technologies. Carbon nanomaterials such as graphene and CNTs have caught the eye of various researchers and industries in the past decades for their potential application in the development of state-of-the-art gas sensors (Kaniyoor *et al.*, 2009; Yavari and Koratkar, 2012; Llobet, 2013; Mao *et al.*, 2014; Gupta Chatterjee *et al.*, 2015; and Singh *et al.*, 2017). Use of carbon nanostructures like graphene and CNTs in the detection of gases, such as hydrogen, ammonia, nitrogen oxide, hydrogen sulfide, carbon dioxide, and oxygen, are being heavily researched. Various fabrication techniques and proposed sensing mechanisms employing carbon nanostructures is a field open for further research and development. Chapter 10 presents a detailed description of the application of carbon-based nanomaterials for gas sensing with an in-depth review on contemporary research reported in the literature.

1.6 CARBON FOR BIOMASS-TO-SYNGAS CONVERSION

Energy harvesting primarily focuses on shifting from traditional energy sources like oil, coal, and gas toward renewable energy sources. However, the petrol and diesel market still holds a large share of the global fuel market since most vehicles and transportation devices depend on these resources. Biomass has been identified to be a renewable source to produce petrol and diesel synthetically. It is inherently carbon neutral, but faces the disadvantage of higher costs associated with the transportation to a centralized production facility, as biomass is available in distributed locations. Moreover, the downscaling of conventional technologies for the conversion of biomass-derived syngas to liquid fuels is not yet economically feasible. The conversion of biomass to fuels is primarily a two-step process: conversion to synthesis gas (or syngas) via gasification, followed by the conversion of syngas to fuel via Fischer–Tropsch synthesis (FTS) (Wilhelm *et al.*, 2001; Zhang *et al.*, 2005; Petrus and Noordermeer, 2006; Leckel, 2009; Yung *et al.*, 2009; Xu *et al.*, 2013; and Xiong *et al.*, 2015). The FTS process can utilize carbon nanostructures like activated carbons and multiwalled CNTs as catalyst supports. The electivity to fuel type in the FTS reaction is primarily influenced by the reactor type, catalyst used, and operating conditions. Since FTS is primarily a polymerization reaction, it is accompanied by the release of a significant amount of heat. The selectivity to liquid fuels can be improved by reducing the exothermic reaction at a faster rate. Heat-integrated microchannel reactors have proven to be effective in removing the exothermic reaction due to their very high heat transfer coefficient, which is typically greater than 5000 W/m^2K, thereby removing the hotspot in catalyst support and increasing the selectivity to liquid fuels. Carbon nanostructures, due to their synergistic effect, can be used to support microchannel reactors for the facile conversion of syngas to liquid fuels. Further research in the application of carbon nanostructures for converting biomass to fuels is encouraged, as discussed in Chap. 11.

1.7 CARBON FOR PERFORMANCE ENHANCEMENT OF PEROVSKITE SOLAR CELLS

Perovskite materials have drawn considerable attention for solar-based renewable energy techniques due to their simple fabrication process and high photoconversion efficiency (Liu *et al.*, 2013b; Stranks *et al.*, 2013; Green *et al.*, 2014; Zhou *et al.*, 2014; Jeon *et al.*, 2015; and Yang *et al.*, 2015). In the past few years, significant research efforts have been devoted to large-scale manufacturing of perovskite solar cells. However, high cost and stability issues still limit the modularization and commercialization of these devices. Carbon allotropes, such as graphene, carbon nanotubes, graphite, and fullerene, with exceptional optical, mechanical, and electrical properties offer hope for performance improvement. Also, the hydrophobic nature of carbon protects perovskite film from moisture and improves the stability of the device. Chapter 12 presents a critical review and various developments in this critical area of research.

1.8 CARBON NANOSTRUCTURES FOR HYDROGEN STORAGE

Implementation of hydrogen energy as fuel requires development of efficient storage means. The methods utilized for hydrogen storage are liquid hydrogen, hydride formation, metal intercalation, high-pressure gas, and adsorption in porous materials. It is also known that hydrogen storage at ambient pressure and temperature in a compressed tank raises safety issues. To store the hydrogen in liquid form requires high input energy for the liquefaction of hydrogen gas. Among these methods, hydrogen adsorption on porous materials is widely used in various applications. Hydrogen adsorption of metals to form metal hydrides is a very common but challenging approach that has been intensively studied in the past. It has been shown that carbon-based nanomaterials with various morphologies, highly porous structure, and facile interactions with gas molecules exhibit high adsorption capability for various gases. An efficient storage technique requires closely packing hydrogen gaseous molecules to achieve the highest possible volumetric density. The light weight of carbon-based materials and reversible gas adsorption/desorption characteristics are value-added propositions for efficient hydrogen storage. Carbon-based materials also show high volumetric density and reversibility in capturing and releasing the gas molecules. Additionally, carbon-based materials are comparatively lighter and cheaper than most other types of materials available for hydrogen storage. It is also well known that the morphological and textural properties of carbon nanostructures, such as pore size, pore volume, pore distribution, and surface area of carbon-based materials, also play a critical role in hydrogen storage capacity (Dillon *et al.*, 1997; Liu *et al.*, 1999; Cheng *et al.*, 2001; Züttel *et al.*, 2002; Patchkovskii *et al.*, 2005; and Wang and Kaskel, 2012). However, achieving maximum adsorption at moderate experimental conditions is desired. Chapter 13 will discuss the essential attributes, including the choice of carbon-based nanomaterials, for efficient hydrogen storage. Future perspectives of carbon-based materials for hydrogen storage are also highlighted.

1.9 CARBON NANOSTRUCTURES FOR ELECTROMAGNETIC APPLICATIONS

Among carbon nanostructures, graphene is a two-dimensional zero-bandgap semiconductor with unusual mechanical and electronic characteristics. Electron transport in graphene can be described by the Dirac equation, and electrons and holes in graphene are called Dirac fermions. Conduction and valence bands touch at points in the band structure (E-k diagram), namely, Dirac points, which are the points of two touching Dirac cones. Therefore, magnetism in graphene is an intriguing research topic both scientifically and technologically. It has been shown in the literature that graphene can be employed in spintronics applications through altering its electronic structure with an applied magnetic field or inducing magnetism by defects (Yazyev, 2010; and Han *et al.*, 2014). Magnetic inclusion in graphene can result from defects, vacancies, or adding another atom, which can alter the magnetic and electronic properties of graphene. Chapter 14 will focus on magnetism and its effect on the electronic properties of graphene, including the quantum Hall effect, the insulator-to-metal transition, and spin-polarized electron transport.

On another note, research and development in the past decade have focused on the miniaturization of electronic and communication devices exhibiting superior performance in both military and civilian applications. However, it is equally mandatory that the performances of these devices should not be affected due to electromagnetic interference (EMI). EMI is a type of pollution affecting the performance of electronic devices as well as human health. Traditionally, metal-based EMI shields have been employed in which the required level of shielding is achieved by reflection mechanism. However, due to the cost of processing and the increased weight associated with metal-based shields, shielding by reflection may not be appropriate in all situations. In contrast, conducting polymer nanocomposite (CPC)-based shields with incorporation of conducting fillers like graphene, CNTs, graphite nanosheets/nanoplatelets, and carbon nanofiber (CNF) are preferred, owing to their ability to exhibit enhanced shielding performance via improved absorption of EM radiation (Thomassin *et al.*, 2013; Gupta *et al.*, 2014; Song *et al.*, 2017; and Zhao *et al.*, 2017). Moreover, such nanocomposites exhibit desirable characteristics, such as flexibility, corrosion resistance, and light weight. To make CPCs, polyvinylidene fluoride (PVDF) and polyaniline (PANI) have been extensively used. The possibility of inducing electroactive phases of PVDF with inclusion of carbon nanostructures is the driving force behind this research. Chapter 15 reviews the electromagnetic shielding performance of such CPCs through a detailed summary of reported results and analysis. Chapter 15 also highlights the research opportunities in this field via inclusion of both conducting and magnetic fillers in CPCs, which could lead to technological innovations.

1.10 CONCLUSION

It is evident that the enormous utility of carbon nanostructures is amply exemplified in scientific literature through the development of well-matured technologies, such as supercapacitors, hydrogen storage, sensing, shielding to electromagnetic interference, and photocatalytic application. This book aims to provide a detailed account on the synthesis, postprocessing, physical and chemical properties, and application development toward energy harvesting of carbon-based nanomaterials, electrochemical energy storage and sensing, supercapacitors, and photocatalytic applications. A state-of-the-art overview and in-depth analysis on the application aspects of the two most important carbon nanomaterials—carbon nanotubes, and graphene and its analogues—are the focus of this book. Through inclusion of up-to-date experimental knowledge behind synthesis, processing, and application development, this book is expected to educate graduate students, postdoctoral researchers, and professionals on a multitude of aspects, thereby serving as a handbook as well. Each chapter is written by a leading expert in the field of materials physics, materials chemistry, and engineering, which ensures that both a critical review and emerging perspectives of various technologies are provided to the readers. The qualitative and the quantitative results are summarized in the form of colorful illustrations, graphical plots, and tables.

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