Chapter 5
Next-Gen Energy Storage Devices:
Carbon-Based Materials for Flexible Supercapacitors

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ABSTRACT

The rapid growth of portable electronics and an increased need for sustainable energy sources have grown interest in developing next-generation energy storage technologies. This chapter deals with the development and optimization of supercapacitors synthesized with carbon materials such as graphene, carbon nanotubes, activated carbon, and carbon aerogels. In this regard, the recent progress in the synthesis of carbon-based materials is reviewed relevance to capacitance, conductivity, and mechanical stability. Moreover, this chapter gives overall coverage of issues relating to the production and fabrication of carbon-based flexible supercapacitors. Additionally, the applicability of these carbon-based flexible electrodes in wearable electronics, flexible displays, and next-generation smart devices is explained in detail. The chapter also discussed the general overview of the present status of carbon-based flexible supercapacitors in next-generation energy storage devices, in addition to the future perspectives.

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1. INTRODUCTION

The rapid growth in the development and manufacturing of portable electronics, wearable, and flexible displays has given rise to the requirement for advanced energy storage solutions having the properties of both high efficiency and long life. For example, an energy storage device must have high power density, quick charge/discharge, and mechanical flexibility, features that traditional batteries cannot provide (Jiang et al., 2024). Consequently, there is an increased interest in supercapacitors, especially those that can be flexible and lightweight which do not degrade their performance with mechanical deformation. Supercapacitors lie in between conventional capacitors and batteries, offering an excellent combination of both high charge density and long life cycle. In contrast to batteries, in which energy flows due to chemical reactions, supercapacitors store energy physically from adsorbed ions on the electrode surface, hence allowing very fast charge/discharge cycles (J. Ma et al., 2024). However, the high energy density in supercapacitors remains quite a challenge to attain without the loss of other vital performance metrics. To overcome this, advanced electrode materials can be utilized for the design of superior energy storage devices. In that respect, based on high conductivity, large area of contact, and adjustable surface properties, carbon-based electrodes came out as a suitable candidate for flexible supercapacitors (Ghafoor et al., 2024). For ultra-high-performance supercapacitor devices, many forms of carbon have been well explored, from graphene to carbon nanotubes and nanofibers, activated carbon, carbon aerogels, and carbon obtained from biomass. Such materials emerge with exclusive advantages in the high surface area, good mechanical strength, and the potential to be fabricated into flexible and lightweight structures (Cheng et al., 2024). They store energy through charge accumulation on the electrode and electrolyte interface. The various carbon-based materials that have been majorly researched and studied for use in flexible supercapacitors include activated carbon, CNTs, graphene and CNFs. These materials are greatly valued due to high porosity and large surface area that enable a large accumulation of charges. Such as graphene is often applied in supercapacitor designs because of its single-layer structure of carbon atoms that give it exceptional conductivity (Aruchamy et al., 2023). Another valuable approach can be given by CNTs due to their high mechanical strength that besides flexibility contribute to their good conductivity in the electrodes of the supercapacitor. As a result, these nanotubes can be integrated into fabrics or coated on flexible substrates, which renders the synthesis very promising for the realization of wearable technologies (Xiao et al., 2024). Also, the combination of CNTs with polymers or metal oxides creates new materials capable of storing energy more efficiently. Carbon nanofibers are another option for flexible supercapacitors, synthesized by using various techniques such as electrospinning. These fibers may randomly orient or align, forming mats or films, flexible with a high surface area. Such carbon nanofibers, doped with heteroatoms or combined with other conductive materials, can offer an improved capacitive behavior and become competitive toward high-performance flexible supercapacitors (Y. Wang et al., 2023). The design of flexible supercapacitors has also focused on incorporation of carbon materials into architectures that can maintain their mechanical integrity even after bending, twisting, or stretching. This usually requires the development of new fabrication techniques, like printing or coating, onto flexible substrates to prepare electrodes so that their performance can be sustained under mechanical deformation. Besides that, the flexible and efficient operation of the device significantly depends on the proper electrolyte and separator materials (Su et al., 2024).

Therefore, this chapter covers the developments of carbon-based materials for the next generation of flexible supercapacitors. It introduces the working principles of a supercapacitor in the introductory part, followed by an overview of various carbon allotropes that are currently being investigated for this

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