Fiber Supercapacitors for Wearable Energy Storage

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Future wearable electronics and smart textiles face a major challenge in the development of energy storage devices that are high-performing while still being flexible, lightweight, and safe. Fiber supercapacitors are one of the most promising energy storage technologies for such applications due to their excellent electrochemical characteristics and mechanical flexibility.

fiber supercapacitors | flexible | energy storage | wearable electronics | smart textiles

1. Introduction

In recent years, there has been a substantial increase in demand for flexible and wearable electronics for health monitoring, implantable devices, and consumer applications [1][2]. While smart watches, wristbands, glasses, and e-textiles composed of semi-rigid components have been on the market for years, it is still challenging to commercialize fully flexible electronics [3][4]. It is even more challenging to create smart textiles that integrate flexible electrical components without restricting the users' physical activities [5]. Among all electrical components, energy storage devices are always critical as they are the major component to supply power. To be integrated into future flexible electronics, especially smart textiles, energy storage devices are required not only to be flexible and durable, but also to provide sufficient energy and power while being safe [6][7].

The power sources for existing commercial wearable electronics are all based on lithium-ion batteries, which offer relatively high energy density but are insufficient in terms of flexibility and safety [8]. Typical electrode materials for lithium-ion batteries are intrinsically rigid and brittle. The chemistry of such batteries is potentially explosive and involves toxic chemicals. Furthermore, the electrodes of lithium-ion batteries deform while being charged and discharged, making them more susceptible to deformation-caused damages [9]. An excellent alternative for commercial lithium-ion batteries is flexible supercapacitors, which have been extensively investigated for flexible and wearable energy storage applications, because they offer flexibility, durability, and safety that cannot be matched by battery systems [10][11][12]. Supercapacitors are intrinsically safer than batteries because they rely on static charge storage mechanisms or fast surface reactions instead of vigorous reactions in bulk electrodes in batteries. Some electrode materials for supercapacitors such as carbon nanotubes and graphene are intrinsically flexible. Combined with flexible polymer-based electrolytes, it is sufficient to create fully flexible, durable, and safe supercapacitors.

Many of the reported flexible supercapacitors are in the form of thin films, in which two electrode layers are sandwiching an electrolyte/separator layer. Such configuration cannot be smoothly integrated into textiles, and it also sacrifices the wearer's comfort by blocking the airflow through the textiles [13][14][15]. To address these problems, fiber supercapacitors are created, which are used as yarns or threads that are ready to be woven or knitted into textiles [16][17][18][19][20]. As a result, fiber supercapacitors are one of the most promising solutions to the power sources for future smart textiles [16][21][22][23][24][25].

2. Why Fiber Supercapacitor?

Supercapacitors are energy storage devices with electrochemical properties that fill the gap between conventional capacitors and batteries [26]. Depending on the energy storage mechanism and active materials, supercapacitors can be classified into electric double-layer capacitors (EDLCs) and pseudocapacitors [27]. In EDLCs, the electrical charge is stored at the electrode/electrolyte interface by a physical process without Faradaic reactions. Typical electrodes for EDLCs are carbon-based materials with high specific surface areas, such as activated carbon, carbon nanotube, and graphene. The charge storage mechanism in pseudocapacitors, on the other hand, occurs through the fast and reversible surface redox process of active materials, such as transition metal oxides/hydroxides and conducting polymers. To make supercapacitors flexible, electrode materials are assembled in either fiber-based or thin film-based structures. The flexibility of these supercapacitor devices is enhanced or limited by the intrinsic mechanical properties of electrode materials, electrolytes, substrates, separators, and the geometry and size of the overall structures [28][29].

Supercapacitors with thin film-based structures are usually assembled by sandwiching a layer of electrolyte-filled separator between two layers of electrodes. The two electrode layers can be made of the same material (symmetric type) or different materials (asymmetric type) [30]. Some active electrode materials are intrinsically flexible and free-standing, such as thin films assembled by carbon fibers, carbon nanotubes, and graphene [21][29][31][32][33]. However, these materials have high elastic modulus and limited flexibility unless the films are extremely thin. This leads to a significant trade-off between their flexibility and areal energy storage performance, in which thinner electrodes present higher flexibility but lower areal capacitance [34]. Other rigid and brittle electrode materials can also be assembled into flexible electrodes with the assistance of flexible substrates, such as plastic thin films and wearable textiles [21][29][31][32]. However, both the flexibility and energy density of such electrodes are limited by the substrates, which are electrically and electrochemically inert. Moreover, all of the thin film-based flexible supercapacitors will sacrifice the comfort of the wearers when integrated into wearable textiles, as they inevitably block airflow between the body and the environment [13].

The limitations of thin film-based supercapacitors for textile energy storage applications can be mitigated by utilizing fiber-based device configurations. Fiber-based flexible supercapacitors use coaxial, twisted, or parallel one-dimensional electrodes that integrate mechanical support, current collector, and active electrode materials in a single fiber/yarn/thread [14][16][35][36][37], with diameters ranging from micrometers to millimeters [38]. The fiber geometry with more degrees of freedom enables the highest possible flexibility of supercapacitor devices. Such designs also allow the devices to be integrated or directly woven into wearable fabrics without sacrificing the comfort of the wearers [39][40]. The excellent flexibility and small size can also make fiber supercapacitors more durable upon frequent mechanical deformations, such as bending, stretching, and twisting [41][42]. It is worth mentioning that fiber-shaped lithium-ion batteries have also been studied for the same purpose. Although such devices can achieve remarkable energy density (e.g., of 215 mWh/cm^3 [43]), lithium-ion batteries have primary concerns regarding its safety and durability. Consequently, flexible fiber supercapacitors can be a better power solution for electronic and wearable devices, offering advantages in terms of safety and design [44][45].

Despite the promises of fiber supercapacitors and tremendous progress in this field in the past years, some important practical questions have not been well answered so far, which makes it difficult to assess the practicality and potential of fiber supercapacitors. For example, how much energy density is required of a fiber supercapacitor to power a realistic wearable device? Are reported energy and power densities of fiber supercapacitors already sufficient or still insufficient for practical applications? How flexible are the reported fiber supercapacitors compared to wearable textiles? Do we have to sacrifice wearers' comfort to integrate such devices into smart textiles? Researchers aim at providing brief answers to these questions and suggesting future research directions for more practical fiber supercapacitors [46]. In other words, the objective herein is to show the feasibility and potential of flexible fiber supercapacitors in real-world applications by providing a comprehensive evaluation of the practicality and potential associated with flexible fiber supercapacitors. To do this, researchers first review the types and advantages of fiber supercapacitors. Then researchers compare the energy and power densities of reported fiber supercapacitors with the power requirements of various smart and wearable electronics to evaluate how practical their energy storage performance is. Afterward, the mechanical flexibility of reported fiber supercapacitors with that of wearable yarns and textiles are estimated and compared, to understand how flexible those devices really are. Finally, the prospects for using fiber supercapacitors as power sources for future smart textiles and the challenges that must be overcome in order to fully leverage their potential in this domain are discussed.

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