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Textile energy storage: Structural design concepts, material selection and future perspectives

Shengli Zhai [a,b], H. Enis Karahan [b], Li Wei [a], Qihui Qian [b], Andrew T. Harris [a], Andrew I. Minett [a], Seeram Ramakrishna [c], Andrew Keong Ng [d], Yuan Chen [a,*]

[a] School of Chemical and Biomolecular Engineering, The University of Sydney, NSW 2006, Australia
[b] School of Chemical and Biomedical Engineering, Nanyang Technological University, 62 Nanyang Drive, Singapore 637459, Singapore
[c] Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576, Singapore
[d] Singapore Institute of Technology, 10 Dover Drive, Singapore 138683, Singapore

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ABSTRACT

As a crucial element of human civilization, textiles reflect the range of materials indispensable for a variety of fundamental technologies that had been mastered throughout the history. In recent years, textiles are in a growing research frontier where fabrics and yarns can directly serve as electrical energy storage devices by themselves to develop wearable energy solutions. Integrated textile energy storage devices may power new functions, such as sensing, therapy, navigation, and communication, while preserving good wearability similar to original textiles. In this review, we introduce the design concepts and structures of textile energy storage devices currently explored including fabrication approaches. We particularly highlight key findings of creating two-dimensional textile and one-dimensional yarn supercapacitors and batteries. Critically, we discuss the challenges for future research development and present our perspectives. We expect to stimulate more research in creating textile energy storage devices for wide practical applications.

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1. Introduction

Textile materials (or cloths) are flexible networks of natural or synthetic fibers produced in a variety of techniques such as

* Corresponding author. Tel.: +61 286274620.
E-mail address: yuan.chen@sydney.edu.au (Y. Chen).

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weaving, knitting, or felting to name a few. They are crucial elements of human societies meeting a wide range of human needs, for clothing, household items, transport devices, construction materials, agriculture tools, medical applications, and artistic expression. In addition to those traditional uses, textiles are recently found in developing smart materials that can sense and respond to environmental stimuli from mechanical, thermal, chemical, electrical or magnetic sources [1], enabling new functions such as sensing, therapy, navigation, communication, and original fashions [2,3]. All these additional functions must be powered by stable and lasting energy sources. In science fiction, as appears in the Foundation series by Isaac Asimov, miniaturized nuclear devices can be used to power smart textiles. However, current realizable solutions are to attach a conventional battery or a supercapacitor on textiles. However, readily available batteries and supercapacitors are often bulky in size, mechanically rigid, and have low energy density which leads to electrical connection problems, bulkiness, poor wearability, and limited washability [4,5].

A new strategy of fabricating smart textiles is to develop textile energy storage systems, in which parts of textiles can directly serve as electrical energy storage devices by themselves. Integrated textile energy storage devices may preserve the original textile structure leading to better wearability in end-products. The large surface area of textiles can also increase energy storage capability. In a perspective article published in early 2014 [6], Gogotsi et al. summarized energy storage devices created on or made as textiles, and a large number of new studies have appeared afterwards in the last two years. A simple search on Web of Science™ in the topic of “textile energy storage” returns more than 300 articles, among which about half of those were published in 2014 and 2015. We feel that it is essential to timely summarize key new developments in this emerging research frontier. Our aims are to provide the state-of-the-art of current research developments, to point out key challenges faced by researchers, and to stimulate future research in creating textile energy storage devices for wide practical applications.

In this review, we first introduce the design concepts and structures of textile energy storage devices being studied, and explain their fabrication approaches. Next, we summarize key points of creating two-dimensional (2D) textile supercapacitors and batteries, followed by results of one-dimensional (1D) yarn supercapacitors and batteries. Lastly, we offer our perspectives on the major challenges and possible solutions to future research and development.

2. Structure and design basics of textile energy storage devices

The basis of current approaches employed in textile energy storage is to create batteries or supercapacitors integrated within a flexible textile matrix. As illustrated in Fig. 1a, supercapacitors store electrical energy by the physical adsorption of electrolyte ions on the surfaces of their electrodes called electrochemical double layer capacitance (EDLC) and/or by reversible redox reactions, intercalation or electrosorption at or near the surface of some electrodes which is called pseudocapacitance [7]. Electrode materials used for supercapacitors are required to have large specific surface area for ion adsorption, a suitable combination of micropores and mesopores for fast ion mobility, good electrical conductivity for electron transfer and surface wettability, and preferably favorable surface functionalities for pseudocapacitance [7–10]. Lithium-ion (in short Li-ion) batteries (Fig. 1b), on the other hand, store electrical energy by moving lithium ions between an intercalated lithium compound in cathode and a carbon-based anode. Other types of batteries may convert stored chemical energy in electrodes into electrical energy using different chemical reactions. In general, electrode materials used in batteries must have high energy storage capacity and enable efficient chemical reactions. For both supercapacitors and batteries, the electrolyte allows the movement of ions during charge and discharge events [11,12]. An ion permeable membrane called separator prevents short circuit of electrodes and conductive current collectors transfer electrons from electrode materials to

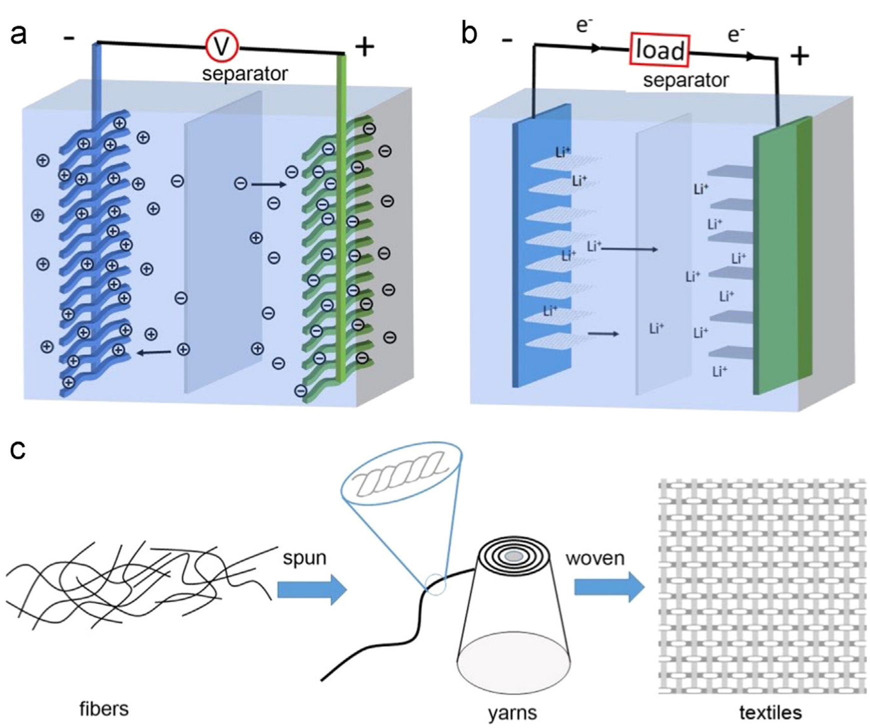

Fig. 1. Schematic illustrations of energy storage mechanisms of (a) a supercapacitor and (b) a lithium-ion battery and (c) standard textile fabrication process of converting short fibers into long yarns and eventually to large textiles.