Recent Advances in Textile Based Energy Storage Devices

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Abstract: Besides the importance of energy harvesting tools, energy storage devices have become an essential need of modern society. From supercapacitors to lithium and sodium ion batteries, these devices are widely used to power our house-hold and commercial electronic appliances. However, the weight and size of current energy storage devices limit their compatibility with futuristic miniaturized electronic gadgets like google glass and smart textiles. To this end, a new family of fiber-shaped energy devices has been recently discovered as an effective solution. Compared to their two- and three dimensional counterparts, these one-dimensional energy devices show some unique and promising advantages including smaller size, lighter weight, three-dimensional flexibility and weavability. These fiber-based energy devices have a potential to be integrated in a daily use textile fabrics if some concerns like flexibility, comfort and toxicity are taken into account. This short review summarized the recent developments in fabricating these miniaturized energy devices and discusses the state of the art techniques used by various research in realizing textile based lithium ion batteries. Moreover, it outlines the important parameters, which are useful while reporting the mechanical stability and electrochemical performance of these miniaturized energy storage devices.

Keywords: Textiles, Fabrics, Fibers, Lithium ion batteries, Energy storage devices.

1. INTRODUCTION

The advent of wearable electronics like Apple Watch, Google Glass and Samsung Bracelets has given a promising course to electronic industry and an era of ubiquitous energy is rapidly coming toward us. Already, some concepts and prototypes of flexible electronics have been demonstrated like Jawbone UP \textsuperscript{1}, Philips Fluid Flexible smartphone \textsuperscript{2}, Nokia Morph Concept \textsuperscript{3} and iPhone ProCare \textsuperscript{4}. Products like these, in future, would be directly worn on human body while working stably under deformations like bending and stretching. Moreover, latest advancement in textile industry have made it possible to integrate an electronic device within a fabric making it a compelling alternative in diverse fields of commercial \textsuperscript{5}, medicine \textsuperscript{6}, military and aerospace \textsuperscript{7} technology. However, this rapid development in flexible and wearable products strongly demands indispensable power systems that are flexible, adaptable and prone to miniaturization.

Electrochemical capacitors and batteries are two typical energy storage devices, comprised of two electrodes, a separator and electrolyte, which are widely used in almost every appliance of daily life. The capability of storing energy strongly relies on the properties of electrodes, including micro-architecture, conductivity, specific surface area, and electrochemical performances. Despite various achievements in conventional planar energy storage devices, much effort is required to design and fabricate a battery, which can be integrated or embedded inside a flexible and wearable matrix of textile. In this context, fiber based energy storage device is an ideal contestant due to its deformation and light weight. First effort to realize the concept of fiber based energy storage device came from Baughman’s group \textsuperscript{8} in 2002, where they used single wall carbon nanotube (SWCNT) as a fiber electrode, exhibiting specific capacitance and energy density of 5 F/g and 0.6 Wh/Kg, respectively while maintaining this performance for over 1200 cycles. This work motivated researchers and companies, both from battery and material science, to use novel strategies for producing fiber based energy storage devices. So far, researchers have managed to develop scalable production of graphene \textsuperscript{9} and carbon nanotubes \textsuperscript{10} based fibers that have been employed for light weight and flexible supercapacitors \textsuperscript{11–18}. However, reports on fiber based lithium or any other kind of batteries are scarce. Table 1 summarized the attempts to build textile based energy prototypes using various state of the art techniques and highlights the achieved capacities. The reason lies in nature of active materials used in batteries, which limits the flexibility and softness of the fiber making it thick and rigid for real world application.

Herein, we present a mini review of the recent progress made and challenges faced in the development of next-generation flexible energy storage systems, with a special focus on fiber based batteries. Initially, we will discuss the properties of textile fabric that must be accounted for making wearable energy storage device for the end user. A brief introduction of lithium...
ion batteries (LIB) and their working principals have been discussed followed by the description of fabrication process, electrode structure, mechanism, and properties of wearable fiber shaped LIBs reflecting the key achievements of each step. The review would be useful for the researchers from the fields of material, electrochemical and textile sciences who wish to work on the interface of flexible energy storage devices.

2. CLASSIFICATION OF TEXTILES AND THEIR PROPERTIES

Textile or textile fabric is a thin flexible sheet produced by entangling or interfacing ‘yarns’ using various procedures including weaving, knitting, chroching and braiding [19]. In turn, yarns are continuous strands made of ‘fiber’ while each fiber is made up of millions polymeric chains with discrete chemical structure. Based on their sources, fibers are classified either as natural or man-made. Those coming from natural sources like plant and animals include protein fibers (wool and silk), cellulose fibers (cotton and linen) and mineral fibers (asbestos). On the other hand, man-made fibers are either prepared by chemical synthesis followed by fiber formation (synthetic fibers) or the natural fibers, chemically treated/ regenerated to form a fiber with required properties. The synthetic fibers include polyamides (nylon), polyesters, acrylics, polyolefin, vinyl, and elastomeric fibers, while the regenerated fibers include rayon and cellulose acetate fiber. Additionally, these fibers are twisted to make yarn and further knitted, woven or braided to produce the final textile product. Moreover, it is also possible to twist two or more yarns together to form a more fine yarn. The process is known as plying and the yarn is known as plied yarn or sometimes referred as a thread. Morphologically, textile fibers may be staple or filament. Staple fibers are relatively short, measured in millimeters or inches while filament fibers are relatively long, measured in meters or yards. Most natural fibers are staple; the only natural filament fiber is obtained from silk. On the other hand, man-made fibers can be staple or filament. They can also be cut or broken into staple to give fabrics that look and feel more like wool, cotton, or linen [20]. Many fibrous materials are not suitable for fiber making like corn silk or wood slivers as they must have suitable properties to withstand harsh conditions during manufacturing process [21].

3. REQUIRED PROPERTIES FOR TEXTILE BASED ENERGY STORAGE DEVICE

The most important property of a fiber or yarn is its mechanical strength, also termed as tenacity, and defined as force per unit linear density necessary to break a fiber. Industrially, it is expressed in gram/denier or gram/tex [22]. (Both denier and Tex are the units of linear density). However, when measured in force per unit area it is termed as tensile strength and measured in KPa or MPa. (In the field of textile batteries, most researchers report the strength of their fiber in this unit). Traditionally, a single fiber strength of 5 g/denier is considered suitable for most textile applications, although some fibers with strengths of 1g/denier have been found suitable for various textile applications [21]. A fiber must be sufficiently flexible to go through repeated bending without significant strength deterioration or breakage of the fiber. Without adequate flexibility, it would be impossible to convert fibers into yarns and fabrics, since flexing and bending of the individual fibers is a necessary part of this conversion. As far as dimensions are concerned, fibrous materials must have sufficient length so that they can be made into twisted

<table>
<thead>
<tr>
<th>Anode</th>
<th>Cathode</th>
<th>Thickness</th>
<th>Capacity and Cycles</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li-Metal Fiber</td>
<td>CNT/MnO₂ Fiber</td>
<td>20 to 30μm CNT/MnO₂</td>
<td>218.32 mAh g⁻¹ at 5 x 10⁻⁴ mA for 100 Cycles</td>
<td>[28]</td>
</tr>
<tr>
<td>Li-Metal Fiber</td>
<td>MWCNT/Si Fiber</td>
<td>30 to 60 μm MWCNT/Si</td>
<td>3,537 mAh g⁻¹ for 50 Cycles</td>
<td>[29]</td>
</tr>
<tr>
<td>CNT-Si/CNT Fiber</td>
<td>CNT/LMO Fiber</td>
<td>2 mm (Full battery)</td>
<td>106.5 mAh g⁻¹ at 1C for 100 cycles</td>
<td>[30]</td>
</tr>
<tr>
<td>CNT/LTO Fiber</td>
<td>CNT/LMO Fiber</td>
<td>130 μm LMO and 70 μm LTO</td>
<td>138 mAh g⁻¹ at 0.01 mA for 200 Cycles</td>
<td>[31]</td>
</tr>
<tr>
<td>Planner polyester/CNT/LTO</td>
<td>Planner polyester/CNT/LFO</td>
<td>600 μm each</td>
<td>160 mAhg⁻¹ at 1C for 30 Cycles</td>
<td>[37]</td>
</tr>
<tr>
<td>Planner Li-Metal</td>
<td>Planner carbon cloth/ ZnCo₉O₄</td>
<td>N/A</td>
<td>1,300 mAh g⁻¹ for 40 Cycles</td>
<td>[38]</td>
</tr>
<tr>
<td>Li₄Ti5O₁₂ (LTO)/GF</td>
<td>LiFePO₄ (LFP)/GF</td>
<td>800 μm (Full battery)</td>
<td>143 mAhg⁻¹ at 0.2 C for 100 cycles</td>
<td>[40]</td>
</tr>
<tr>
<td>Polyester yarn/Ni/LTO</td>
<td>polyester yarn/Ni/LFP</td>
<td>N/A</td>
<td>100 mAhg⁻¹ at 85 mA g⁻¹ for 30 Cycles</td>
<td>[41]</td>
</tr>
</tbody>
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yarns. Importantly, diameter of fibers should be 1/100th of its length for further processing like yarn formation and weaving [20]. Porosity, is another important property of the textile that can be useful for high mass loading of active material. Therefore, researchers have used cotton and nylon as a substrate for high mass loading, which will be discussed later in this review.

4. TEXTILE/FIBER BASED LITHIUM ION BATTERIES

Lithium ion battery is pack of multiple lithium ion cells connected either in series or parallel depending to its final application. (Due to excessive use of the term ‘battery’ instead of ‘cell’ in literature, we, in this review, will continue to call lithium ion cell as lithium ion battery). Each cell consists of cathode and anode separated by an electrically insulative polymer soaked in an electrolyte.Conventionally, lithium metal oxides such as LiCoO$_2$, LiFePO$_4$ and LiMn$_2$O$_4$ and carbonaceous materials such as graphite are used as the cathode and anode materials, respectively [23–25]. Inside the cell, discharging occurs when Li$^+$ ions are removed from the anode, transferred into the electrolyte and inserted into the cathode, along with the electrons flowing from the anode to the cathode at the external circuit (Figure 1). The above process is reversed during charging [26,27].

Among the various components of a cell, electrodes are considered to be the back bone of lithium ion cells and fabricating a one-dimensional fiber shaped electrode is the main challenge in realizing a flexible miniaturized battery for future generation applications. In pursuit of a flexible light weight fiber based electrode, Ren et al. [28] used aligned carbon nanotubes fibers prepared from the spinnable CNT array and coated MnO$_2$ nanoparticles using electrochemical deposition for enhancing the faradaic capacitance. The diameter of the fiber can be controlled from 20 to 30µm, which enables high tensile strengths up to 1.3 GPa and high electrical conductivities of $10^3$ S/cm. Without using any current collector or binder CNT/MnO$_2$ composite fiber was intertwined on a metallic lithium wire acting as anode (Figure 2). As prepared lithium battery with electrolyte consisted of 1 mol L$^{-1}$ of LiPF$_6$ in a mixture solvent of ethylene carbonate, diethyl carbonate, and dimethyl carbonate (weight ratios of 1/1/1) showed specific capacity was 109.62 mAh cm$^{-3}$ or 218.32 mAh g$^{-1}$ based on the whole CNT/MnO$_2$ electrode at 5 x $10^{-4}$ mA. At an elevated current, the specific capacity endured a slight decrease to 94.37 mAh cm$^{-3}$ or 174.40 mAh g$^{-1}$) at 2 x $10^{-3}$ mA. The discretion of fiber-based batteries lies in its flexibility and endurance, which, nevertheless, is weakened with the presence of lithium metal in lithium ion batteries. Therefore, the concept of incorporating silicon based fiber as anode have been tested where they used aligned multiwalled carbon nanotube (MWCNT)/Si composite fiber anodes for flexible, wire-shaped lithium-ion batteries [29]. Instead of electrochemical deposition, electron beam evaporation technology was used to vaporize the silicon, which

![Figure 1](image-url): (a) Charging (b) Discharging of a full lithium ion cell using graphite and LiCoO$_2$ electrode.
then was deposited onto the CNT sheet, an aligned two-dimensional film that had been drawn from the spinnable CNT array and paved on a substrate (Figure 3). Then the composite films were twisted into CNT/Si composite fiber, with diameter size from 30 to 60 µm. The twisted aligned MWCNT/Si composite fiber was flexible and could be made into various structures such as a knot, and the twisted structure had been well maintained during deformation. Both bare silicon and MWCNT/Si composite fibers were tested against lithium metal fiber as a reference electrode where bare silicon gave high capacity of 3,537 mAh g⁻¹ in the first cycle, which, nevertheless, decayed to 46.6 % after 30 cycles. On the other hand, CNT/Si composite fibers exhibited a capacity retention of 58 % over 50 cycles. The CNT/Si hybrid fiber exhibited flexibility that enables itself to sustain repeated bending for 100 times without sacrificing its electrochemical performance. In another method, Weng et al. [30] reported a prototype of coaxial, fiber-shaped full LIB by winding two aligned CNT composite yarns (CNT/Si as anode while CNT/LMO as cathode) onto a cotton fiber. Due to less volumetric change in LMO, particles of lithium manganese oxide (LMO) were directly deposited on aligned CNT sheets (Figure 4) followed by scrolling to form CNT/LMO composite yarn cathode while the anode was prepared using the same method discussed in reference [29]. It was observed that CNTs and coaxial CNT/Si nanotubes remained highly aligned in the CNT-Si/CNT and CNT-Si composite yarns as aligned structures are critically important for the composite yarns to form the desired hybrid layered structure. Initially, half-cells were used to investigate the electrochemical property of the composite yarns that acted as an electrode with a

Figure 2: (a) Schematic illustration of fiber-shaped lithium ion battery with lithium wire as anode and CNT/MnO₂ composite fiber as cathode (Reproduced from Ref. [28]) by permission of John Wiley & Sons Ltd). Charge-discharge curves of (b) bare CNTs fiber and (c) CNT/MnO₂ composite fiber

Figure 3: (a) Preparation method for CNT/Si hybrid fiber. (b) Schematic illustration of fiber-shaped lithium ion battery (c) Charge-Discharge curve of bare MWCNT and MWCNT/Si. (Reproduced from Ref. [29]) by permission of John Wiley & Sons Ltd.
lithium wire as the counter electrode. A high delithiation capacity of 2240 mAh g\(^{-1}\) (or 3521 mAh g\(^{-1}\) based on the Si) was obtained at the first cycle with 88% retention after 100 cycles for the CNT-Si/CNT composite yarn. In contrast, only 42% capacity was retained for the CNT-Si composite yarn under the same condition. On the other hand, CNT/LMO gave initial lithiation capacity of 100 mAh g\(^{-1}\) with columbic efficiency of 92%, and the capacity was maintained by 94% after 100 cycles at 1 C. Finally, a coaxial fiber full Li\(_{2}\) was finally fabricated based on the CNT-Si/CNT and CNT-LMO composite yarns as the anode and cathode, respectively. The CNT-LMO and CNT-Si/CNT composite yarns were sequentially wound onto the cotton fiber while separated with a gel electrolyte. Full Li\(_{2}\) yarn of 2 mm diameter showed a tensile strength reaching 250 MPa along with moderate initial capacitance of 106.5 mAh g\(^{-1}\) with 87% retention for 100 cycles, proving high stability of the CNT-Si/CNT composite yarn anode.

Based on all electrode material, the volumetric energy density was found to be 99.3 mWh cm\(^{-3}\). Despite of high theoretical capacity of silicon as an active material, its fragile performance and laborious preparation weaken the endurance of the battery. On this account, already commercialized anode material like Li\(_{4}\)Ti\(_{5}\)O\(_{12}\) was used as anode active material to reduce volumetric expansion produces in the case of silicon [31]. Typically, LiMn\(_{2}\)O\(_{4}\) and Li\(_{4}\)Ti\(_{5}\)O\(_{12}\) nanoparticles were dispersed in N, N-dimethylformamide (DMF) to form uniform suspensions. Then, two CNT sheets drawn out of the CNT array were stacked and subsequently immersed into the as-prepared nanoparticle suspensions. These CNT sheet anchoring LiMn\(_{2}\)O\(_{4}\) and Li\(_{4}\)Ti\(_{5}\)O\(_{12}\) nanoparticles were rolled to prepared fibers with diameters 130 and 70 µm, respectively. As-prepared LMO and LTO hybrid fibers were first tested in half-cells with the lithium metal as counter electrodes showing specific capacities of 60 and 150 mAh g\(^{-1}\), respectively. After running for 200 cycles, both of the half batteries retained their capacities above 80 %, much higher than the silicon anode-based fiber-shaped batteries. Finally, the fiber-shaped LTO/LMO full battery had a specific capacity of 138 mAh g\(^{-1}\) at 0.01 mA (specified to the weight of the CNT/LTO fiber). It also delivered a volumetric energy density of 17.7 Wh L\(^{-1}\) and power density of 560 W L\(^{-1}\) based on the volume of anode and cathode. Besides, the capacity retained by 85 % after 100 cycles at 0.05 mA, with columbic efficiency over 80 %. For real life application, a 10 cm charged fiber-shaped battery was constructed to power nine red light emitting diodes (LEDs) for at least one minute (Figure 5) and an energy fabric was woven from fiber-shaped lithium ion batteries, which was then integrated into a cloth. In another similar work, super-stretchy, fiber-shaped lithium-ion batteries with a strain up to 600% were developed with remarkable electrochemical properties [32]. Two aligned multi-walled carbon nanotube (MWCNT) composite fibers incorporated with active materials including LTO and LMO were first synthesized with fiber diameters of 160 and 130 mm, respectively showing high mechanical strengths, electrical conductivities and electrochemical activities. Typical voltage profiles with increasing cycle numbers at a current density of 0.1mA cm\(^{-2}\) showed initial discharge capacity of 91.3 mA h g\(^{-1}\) based on the entire negative electrode. These Fiber-shaped batteries can be easily scaled up with an applicable length and woven into textiles with different shapes such as a bracelet and knitted sweater to achieve better adaptability to the movement of the body. Authors claimed that these
fiber-shaped batteries can be easily scaled up with an applicable length and woven into textiles with different shapes such as a bracelet and knitted sweater.

Contrary to fiber-based lithium ion batteries, another strategy of realizing a textile based lithium ion battery is to use a very simple two-step fabricating process. 1) Coating a conductive layer on a ready-made textile like cotton or nylon 2) Deposition of active material onto the surface of conductive composite textile for higher capacities. Both steps can be performed using various depositing strategies which already exists in textile industry [33]. The first step of this approach is crucial due to the fact that conductance of the composite textile is proportional to the nature of deposited layer and its thickness [34] while the ability of conductive composite textile to load high mass of active material is proportional to capacity of final energy storage device [35]. It differs from fiber based approach in a way that it does not require the tedious and complex process of conductive fiber/yarn formation and uses already braided, knitted or woven textile as a low density current collector when coated with a conductive material. Moreover, the intrinsic rough surfaces of textiles is ideal for many energy devices in which large surface roughness is actually preferred. The concept was first surfaced by Yi Cui Lab of Stanford University when they introduced textile based energy storage device and designed a supercapacitor using highly conductive single wall carbon nanotube (SWCNT) coated textile fiber [36]. Later they extended their work to lithium ion batteries, where they developed [37] a Li-ion battery based on the conductive textiles with a mass loading of \( \sim 168 \text{ mg cm}^{-2} \) with a thickness of \( \sim 600 \mu\text{m} \). Authors claimed that the mass loading is 8–12 times higher of those on metal collector. A polyester textile was dip coated with CNTs to achieve a conductive textile current collector with a thickness of \( \sim 2 \text{ mm} \) and surface conductivity of \( \sim 1300 \text{ S/cm} \). Slurries of \( \text{Li}_4\text{Ti}_5\text{O}_{12} \) and \( \text{LiFePO}_4 \) were dip coated on conductive textile to fabricate electrode and used in a coin cell formation using 1 M solution of \( \text{LiPF}_6 \) in ethylene carbonate (EC)/diethyl carbonate (DEC) (1:1 vol/vol; Ferro) as electrolyte. A full cell based on conductive textile gave specific capa-
citance of 160 mAh/g with a Columbic efficiency of 95% for 30 cycles, however, when Li4Ti5O12 based conductive textile was tested against lithium counter electrode, the capacities reached at 180 mAh/g and maintained for 350 cycles with columbic efficiency of 95%. Authors concluded that 3D textile current collectors not only provide an extremely simple method for increasing the mass loading of the electrode materials, but also lead to much better performance in terms of device over potential and impedance. In another method [38], hierarchical three-dimensional ZnCo2O4 nanowire arrays were hydrothermally synthesized on a carbon cloth as anode which was paired with LiCoO2/Al cathode and sealed in a flexible plastic package. Typical ZnCo2O4 nanowires have uniform diameters of about 80–100 nm and lengths of about 5 µm. The flexible battery outputs a voltage of 3.4 V and a stably going reversible capacity of 1,300 mAh g⁻¹ for 40 cycles. These rudimentary flexible batteries, however, still used liquid electrolyte, making them less adaptable for application. Therefore, solid-state electrolyte like lithium phosphorus oxynitride electrolyte (LiPON) was introduced, which even made the metallic lithium anode compatible to flexibility [39].

Using a different approach, Li et al. [40] used a graphene foam (GF) consists of a 3D interconnected networks of high-quality chemical vapor deposition-grown graphene. This kind of 2D-platform, like textile, can be used as a fast transport channel of charge carriers with electrical conductivity of ~1,000 S/m. Moreover, the GF is extremely light (~0.1 mg/cm² with a thickness of ~100 µm) and flexible. It possesses a high porosity of ~99.7% with high specific surface area and can be bent to arbitrary shapes without breaking. Using the GF network as both a highly conductive pathway for electrons and ions and a 3D interconnected current collector, they developed a thin, lightweight, and flexible LiFePO4 (LFP)/GF and Li4Ti5O12 (LTO)/GF electrodes by in situ hydrothermal deposition of active materials on GF followed by heating in an argon atmosphere. Electrochemical behavior of both electrodes were tested separately against lithium metal and found remarkable lithium insertion/extraction properties. In comparison, charge and discharge capacities of LTO and LTO/GF hybrid material showed similar behavior. However, at higher charge/discharge rates (1 C, 30 C and 200C) LTO/GF showed a specific capacity of about 170, 160 and 135 mAh/g, respectively (Figure 6) while bare LTO electrode at 200 C showed zero capacitance. In case of lithium iron phosphate cathode, the specific capacity of the LFP/GF electrode at 50-C discharge rate was 98 mAh/g. Finally, a flexible LFP/GF cathode and LTO/GF anode with a thickness of ~100 µm were first laminated onto the both sides of a polypropylene separator and then sealed with ~250-µm-thick poly (dimethyl siloxane) (PDMS) in an Ar-filled glove box using LiPF6 in ethylene carbonate/dimethyl carbonate as an electrolyte. The total thickness of this flexible full battery was less than 800 µm showing initial discharge capacity of ~143

![Figure 6](image_url)
mAh/g with a coulombic efficiency of 98% at a 0.2-C rate while the energy density of this light-weight battery was ~110 Wh/kg based on the total mass of the LTO/GF anode and LFP/GF cathode. As a complete integrated prototype of textile energy storage device powered by solar panel, Lee et al. [41] demonstrated a fully functional wearable textile battery by finding unconventional materials for all of the key battery components including Ni-coated polyester yarn as a current collector for efficient stress release, polyurethane (PU) binder for strong adhesion of active materials, and PU separator for superior mechanical, electrochemical, and thermal properties. Woven polyester yarn was selected as a textile substrate, and Ni was coated onto the surface of each yarn by the established electroless deposition method (EDM). The sheet resistance of the Ni-coated textile reaches 0.35 Ω sq⁻¹, which is as small as those of typical metal foils. Electrochemical performance of the wearable textile battery consisting of the LTO anode and lithium iron phosphate (LFP) cathode showed gravimetric capacitance of around 100 mAh g⁻¹ 85 mA g⁻¹ for 100 cycles with 80% of coulombic efficiency. Inspired by Lee’s work, Kim et al. [42] extended their concept of wearable energy storage devices for real world application and expanded textile batteries into large area multi-stacked platforms to cover emerging outdoor, building, and military applications. To construct such battery, polyester textile was dip coated with Nickel sulfate solution to obtain a conductive textile. The typical sheet resistance of the Ni-coated textile was 0.35 ohm sq⁻¹, which is approximately 2–3 orders of magnitude lower than those based on the widely adopted dip coating of carbon based material. Using doctor blade, slurries of lithium iron phosphate (LiFePO₄ or LFP) and lithium titanium oxide (Li₄Ti₅O₁₂ or LTO) as cathode and anode active material were coated on conductive textile. Electrochemical testing was performed by preparing aluminum pouch with 1 M lithium hexa-fluorophosphate (LiPF₆) dissolved in a mixture of ethylene carbonate (EC) and dimethyl carbonate (DMC). Multi-stacked platform was constructed by joining 16 cell in series. Based on the active materials (LFP and LTO) chosen, each single-cell delivers 1.8 V, and the entire module consisting of 16 single-cells thus delivered 28.8 V (Figure 7) with capacitance of 25 mA h for the given area of 5 x 5 cm² and retained 93.4% of

**Figure 7:** (a) A schematic representation of a rollable display supported by a multi-stacked textile battery underneath. (b) A schematic illustration of the large area textile battery module. The single-cells with 1.8 V and 25 mA h are connected in series. The partial module (green area) consisting of 4 single-cells delivers 7.2 V and 25 mA h, and the entire module consisting of 16 single-cells delivers 28.8 V and 25 mA h. Photographs of multi-stacked textile batteries attached onto (c) an outdoor tent and (d) a roller blind on a building window. (e) Charge discharge curves of full lithium ion battery with (f) cycling performance. (Reproduced from Ref. [42] by the permission of Royal Society of Chemistry).
this initial capacity after 30 cycles. Finally, authors suggested that flexible LIBs could find a broad range of unique applications once the cells are designed carefully from each component in a single-cell to a module assembly.

5. CONCLUSIVE REMARKS

Research in textile energy storage is an exciting field presenting viable solutions for wearable devices in an array of applications. They have potential to transform the rigid electronic devices into flexible counterparts, which open new doors in electronic and textile industries. However, it is clear that much work has yet to be done to refine the fabrication processes and material selection before textile energy storage can become widely available. One of the key challenges to the field is creating scalable materials while maintaining the mechanical properties required while processing the textile fabric. We also observed that number of research articles on textile/fiber based supercapacitors are exponentially higher than textile-based lithium ion battery. The main reason lies in the active material used in lithium ion battery which in one end useful for high capacity but on the other hand makes the device mechanically unstable for long term cycling.

REFERENCES


