Miniature wire-shaped solar cells, electrochemical capacitors and lithium-ion batteries

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It is critically important to develop miniature energy harvesting and storage devices in modern electronics, for example, for portable and foldable electronic facilities. In this review article, novel miniature solar cells, electrochemical capacitors and lithium-ion batteries as well as their integrated devices are carefully summarized. Particular emphasis has been paid to wire-shape energy devices that exhibit unique and promising advantages such as being lightweight and weaveable compared with the conventional planar architecture. Recent new materials and attractive designs are highlighted for these wire-shaped energy devices.

Introduction

Electronic products ranging from cell phones and laptops to the electronic systems in spacecraft must be small, lightweight and flexible. To this end, on one hand, a lot of effort has been made toward discovering new materials that meet the above requirements [1–8]; while on the other hand, it is also critically important to produce matching energy harvesting and storage systems to power them. However, conventional silicon wafer-based photovoltaic technologies cannot fully satisfy these requirements. Therefore, there is increasing interest in developing next-generation photovoltaic devices, including dye-sensitized and polymer solar cells that can be made into flexible structures [9–16]. In the case of the storage systems, electrochemical capacitors [17,18] and lithium-ion batteries [19–21] have been the most extensively explored. For these widely studied energy harvesting and storage devices, they mainly appear in a relatively heavy planar or box format. In addition, it remains difficult to practically apply them in miniature electronics.

One general and effective method has recently been found to overcome the above difficulties in both energy harvesting and storage. These energy devices were successfully made into a new wire shape [22–24] that simultaneously enables them to be small, lightweight, flexible and foldable. In addition, they could be easily scaled up for industrial production by the well-developed textile technology. In this review, we will briefly describe the main areas of progress in these miniature wire-shaped energy devices, including dye-sensitized solar cells (DSCs), polymer solar cells (PSCs), electrochemical capacitors, and lithium-ion batteries, as well as integrated cells that may convert solar energy to electric energy and simultaneously store it.

Miniature solar cells

Inorganic solar cells

Over decades of the photovoltaic industry, crystalline silicon has remained the primary photovoltaic materials in commercial modules due to high efficiencies and natural abundance [25,26]; though the high cost in producing Si wafers has largely limited their use in the future. Therefore, a lot of effort has been made toward developing an ultrathin silicon film (thicknesses of 5–50 μm) as an active photovoltaic layer [27]. For instance, Rogers and co-workers [28] fabricated microcells from single-crystalline silicon (Fig. 1a), which could be further printed onto flexible substrates such as poly(dimethylsiloxane) (Fig. 1b). Here, an individual microcell was composed of phosphorus-doped,

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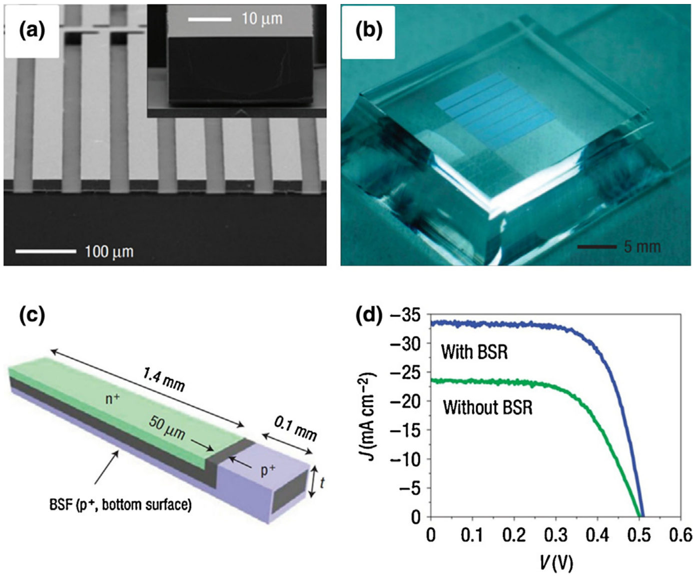

FIGURE 1

Silicon-based solar microcells. (a) SEM image of an array of microcells on a source wafer. (b) Optical image of an array of microcells on an elastomeric polydimethylsiloxane substrate. (c) Schematic illustration of a microcell, BSF, back-surface field. (d) Representative *J–V* curves of a microcell with and without a white diffusing backside reflector (BSR) under AM 1.5 illumination of 1000 W/m^2 condition. Reproduced with permission from Ref. [28]. Copyright 2008, Nature Publishing Group.

boron-doped and un-doped regions (Fig. 1c). The energy conversion efficiency achieved 11.6% with a white backside reflector under AM 1.5 illumination (Fig. 1d). The main limitation of these ultrathin silicon cells was that the absorption of photons was reduced greatly due to the very thin active material, which lowered the device performance. To this end, some modifications were made to improve the light trapping in ultrathin silicon solar microcells [29,30], for example, nanostructured relief features [31] were introduced to the surface of the device to enhance the light absorption through scattering or diffraction and passive concentration [32] through the luminescent waveguide. Both incident and diffusing photons from the bottom and sidewall could be harvested.

To meet the miniature requirement of modern electronics, some nanodevices have also developed for inorganic solar cells. Lieber and co-workers [33,34] fabricated single *p*-type/intrinsic/*n*-type (*p*-i-*n*) coaxial silicon nanowire solar cells that mainly consisted of a *p*-type silicon nanowire core, intrinsic polycrystalline silicon layer and *n*-type polycrystalline silicon sheath (Fig. 2a and b). The coaxial silicon nanowire solar cell exhibited an energy conversion efficiency of 3.4% and served as an independent power source to drive a silicon nanowire pH sensor. A nanowire-based AND logic gate and large loads were further driven by interconnecting the cell in series and in parallel (Fig. 2c and d).

Besides silicon, group III nitrides [35] have also been studied as photovoltaic materials to fabricate nanowire devices, for example, *n*-GaN/i-$In_xGa_{1-x}N$/*p*-GaN that was highly robust and showed a J_{sc} value of up to 390 mA/cm^2. However, the energy conversion efficiencies were lower than their silicon counterparts [36]. Li and co-workers [37] also developed single organic/inorganic p–n junction nanowires based on the inorganic semiconductor cadmium sulfide and conducting polymer polypyrrole, and the energy conversion efficiency remained very low, for example, 0.018%. More effort should be paid to improve the efficiencies in such nanodevices.

Wire-shaped dye-sensitized solar cells

DSCs are generally made into a planar structure. A transparent fluorine-doped tin oxide glass that is coated with a thin layer of sensitized-porous semiconductor metal oxide such as TiO_2 is used as a photoanode, another conductive glass coated with platinum serves as the counter electrode, and the redox electrolyte is incorporated between the two electrodes [38–41]. Recently, wire-shaped DSCs had been explored by replacing the planar electrodes with fiber electrodes. Fig. 3a and b shows a typical wire-shaped DSC with stainless steel wire and Pt wire as the working and counter electrodes, respectively [42]. For the twisted wire-shaped DSC, the energy conversion efficiencies were independent on the angle of incident light. A limitation for the twisted DSCs was that the fiber counter electrode shadowed some of the incident light with low efficiencies. To this end, three-dimensional, wire-shaped DSCs were developed to more effectively take advantage of the incident light [43]. As one example, Wang and co-workers [44] reported a DSC based on an optical fiber with zinc oxide nanowire arrays that enhanced the contact area between the light and dye molecule (Fig. 3c and d). In addition, the internal reflection of the light trapped in the optical fiber could increase the light absorption. As a result, an energy conversion efficiency of 3.3% was obtained under illumination along the fiber axis, and it was four times that of the same device when the light was illuminated from outside. For another example, Liu and co-workers [45] reported the use of a spiral-shaped titanium wire working electrode with a platinized titanium wire inserted as the counter electrode (Fig. 3e). As a result, the working electrode was not shielded by the inner counter electrode.

The fiber counter electrode also plays a critical role in enhancing the photovoltaic performance of the wire-shaped DSC. It is required to be flexible, electrically conductive and highly catalytic. Besides platinum, carbon-based fibers [46–51] such as commercialized carbon fibers, carbon nanotube (CNT) fibers and graphene fibers have mainly been explored. Zou and co-workers [49] fabricated DSCs by twisting a platinized carbon fiber counter onto a Ti wire modified with porous TiO_2 film with efficiencies up to 5.8%, compared with 4.75% of a platinum wire. Cao and co-workers [50] further introduced a platinum nanoparticle-absorbed CNT fiber as the counter electrode, and the resulting DSCs also exhibited higher efficiencies than the Pt wire-based counterpart. Here the platinum nanoparticles showed large surface areas with high electrocatalytic activities. Recently, a graphene fiber deposited with platinum nanoparticles [51] was studied as the counter electrode to achieve efficiencies of up to 8.45%, the highest efficiency reported to date. The formation of uniform and small platinum nanoparticles on graphene sheets was the key to the high performance. Recently, the high-performance counter electrode without the use of platinum that has a limited source has also been described. A carbon fiber coated with poly(3,4-ethylene dioxythiophene):poly(styrene sulfonate) exhibited an efficiency of 5.5% [52].

The metal-based working electrode can be also replaced by the carbon-based fiber such as CNT fibers. We recently fabricated wire-shaped DSCs by using a TiO_2-loaded CNT fiber as a working

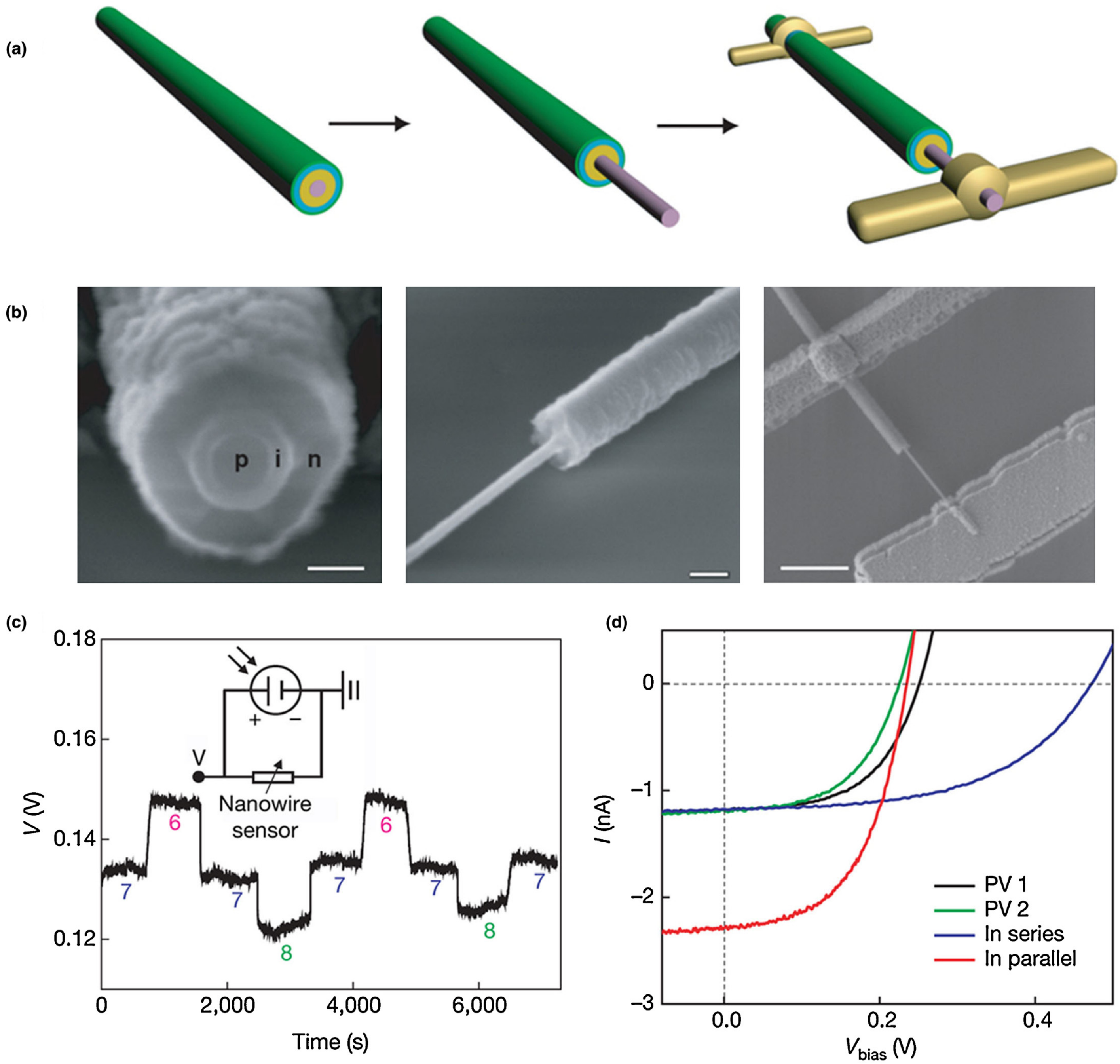

FIGURE 2

Coaxial Si nanowire photovoltaics. (a) Schematics of the device fabrication. Left part: pink, yellow, cyan and green layers correspond to the *p*-core, *i*-shell, *n*-shell and SiO_2, respectively. Middle part: selective etching to expose the *p*-core. Right part: metal contacts deposited on the *p*-core and *n*-shell. (b) SEM images corresponding to the three steps at (a). Scale bars are 100 nm (left), 200 nm (middle) and 1.5 μm (right). (c) In situ detection of the voltage drop across an aminopropyltriethoxysilane-modified Si nanowire at different pH values under 8-sun illumination. The inserted graph schematically shows the corresponding electric circuit. (d) *I–V* curves of two nanowire cells individually and their connections in series and parallel. Reproduced with permission from Ref. [33]. Copyright 2007, Nature Publishing Group.

electrode [53] and a bare CNT fiber as the counter electrode (Fig. 4a). Due to the large surface area of nanostructured CNT fibers, the TiO_2 nanoparticles could be effectively incorporated into the CNT fiber. In addition, the CNT fiber was highly flexible and had been stably twisted together. Therefore, a stable efficiency of 2.94% was well maintained during bending, and these DSCs were further woven into flexible electronic textiles (Fig. 4b).

Besides the twisted structure, the wire-shaped DSCs have been also made with a coaxial structure [54,55]. For instance, a highly aligned CNT sheet that was flexible, transparent and conductive has been wound onto a Ti wire working electrode to form the core-sheath structure (Fig. 4c and d). The resulting DSC exhibited a maximal efficiency of 4.1%, higher than the twisted structure under the same conditions [55]. The superior contact between

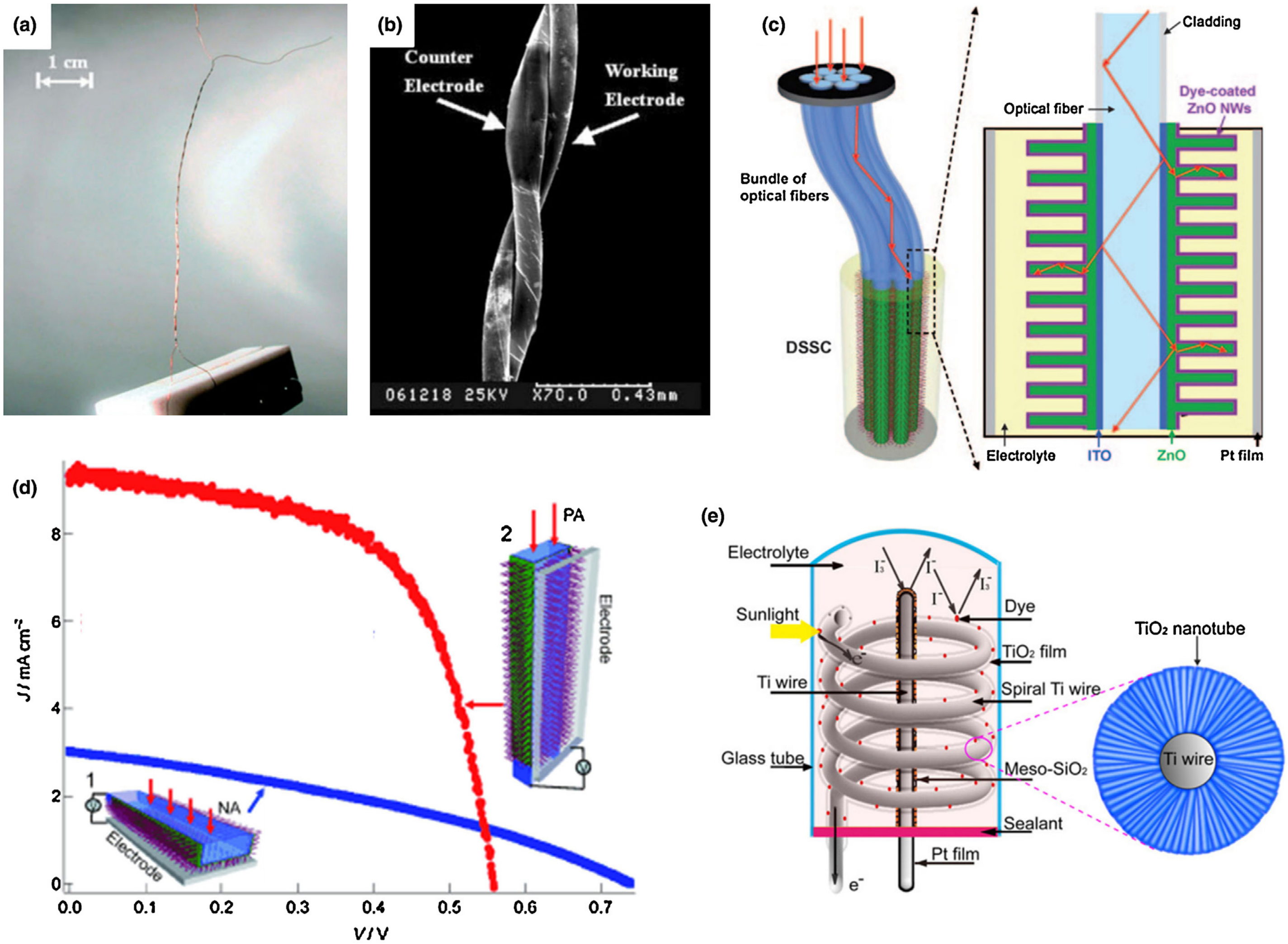

FIGURE 3

Wire-shaped dye-sensitized solar cells (DSCs) with three different structures. (a) and (b) Photograph and SEM image of a twisted wire-shaped DSCs, respectively. Reprinted with permission from Ref. [42]. Copyright 2008, John Wiley and Sons. (c) Schematic illustration of wire-shaped three-dimensional (3D) DSCs. (d) *J–V* curves of a rectangular optical-fiber-based 3D DSCs. Reprinted with permission from Ref. [44]. Copyright 2009, John Wiley and Sons. (e) A spring-structured wire-shaped DSC. Reprinted with permission from Ref. [45]. Copyright 2010, IOP Publishing.

the sheet and electrolyte was expected to favor the charge separation and transport.

Generally, liquid electrolytes are used for the DSCs. However, they easily leak and volatilize during use, which has largely limited their applications in many fields. It becomes more severe in the wire-shaped device as the sealing is more difficult for wire-shaped DSCs, several meters in length, compared with the planar structure. Recently, we developed eutectic melts of 1-ethyl-3-methylimidazolium iodide, ionic liquid of 1-propyl-3-methylimidazolium iodide, and iodine as a quasi-solid-state electrolyte to overcome the above challenge [56]. A modified Ti wire was coated with photoactive components and a quasi-solid-state electrolyte, followed by the winding of an aligned CNT sheet as the counter electrode. The highest energy conversion efficiency of 2.6% was achieved for the solid-state wire-shaped DSC. Some other functions have been also introduced to the wire-shaped DSCs. For instance, superparamagnetic metal oxide and metal nanoparticles (e.g., Fe_3O_4 and Ni) were incorporated into the counter electrodes, and the resulting DSCs exhibited a response to the magnetic field [57]. They could be easily attached or detached to the substrate through the use of a magnetic field.

Wire-shaped polymer solar cells

Compared with DSCs that often use liquid electrolytes, polymer solar cells (PSCs) can be made into all-solid-state devices. Therefore, it is particularly promising to develop wire-shaped PSCs for various electronic textiles. Similar to the DSCs, both twisted and coaxial structures have been studied for PSCs. For the twisted wire-shaped PSCs, two fiber electrodes based on metal wires and CNT-based materials have been extensively studied. For instance, a modified Ti wire that was coated with a photoactive layer of poly(3-hexyl-2,5-thiophene) (P3HT) and (6,6)-phenyl-C_{71} butyric acid methyl ester ($PC_{70}BM$) on the surface was twisted with an aligned CNT fiber. However, the energy conversion efficiency was relatively low [58] as the ineffective contact between the electrode and photoactive layer was not favorable for charge separations and

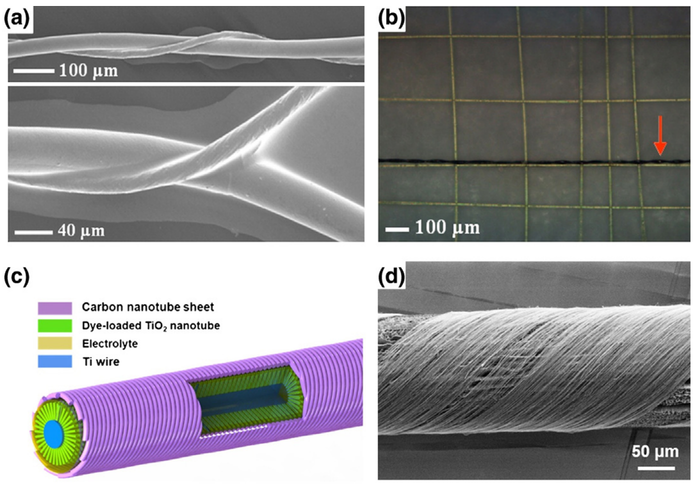

FIGURE 4

Wire-shaped DSCs based on aligned fiber and CNT film. (a) SEM image of a wire-shaped DSC with a twisted structure. (b) Wire-shaped DSC being woven into a flexible textile. Reprinted with permission from Ref. [53]. Copyright 2012, American Chemical Society. (c) and (d) Schematic illustration and SEM image of a wire-shaped DSC with a core-sheath structure, respectively. Reprinted with permission from Ref. [55]. Copyright 2013, The Royal Society of Chemistry.

transports. To this end, a thin layer of titania nanoparticles was incorporated between the fiber substrate [59] and photoactive layer (Fig. 5a–c). The titania nanoparticles were found to enhance the adsorption of photoactive materials and charge transport, which increased the energy conversion efficiency by 36% compared with the wire-shaped PSCs without the titania nanoparticles under the same condition.

For the twisted structure, the low contact area between two fiber electrodes may limit the charge separation and transport. As a comparison, a core-sheath structure [60,61] where the photoactive layer is sandwiched between two electrodes similar to the conventional planar structure will be useful for higher efficiencies. Shtein and co-workers [61] developed a core-sheath wire-shaped PSC with main components of Mg/Ag:Au/Au/CuPc/C_{60}/Alq_3/Mg:Ag/Ag, and the semitransparent Mg:Ag layer served as the outer electrode (Fig. 5d). An energy conversion efficiency of 0.5% had been produced, compared to 0.76% for the planar counterpart.

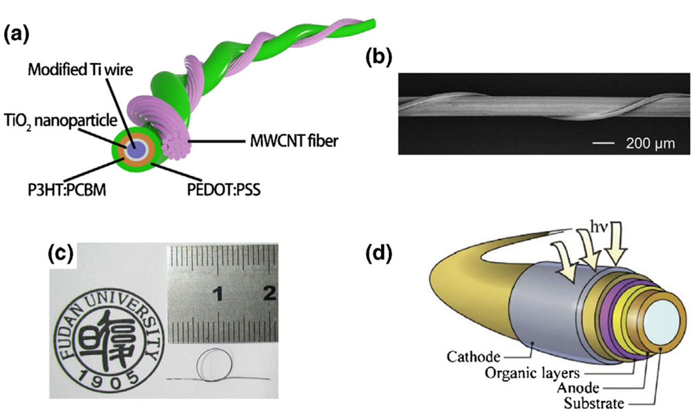

FIGURE 5

Wire-shaped polymer solar cells (PSCs). (a) and (b) Schematic illustration and SEM image of a wire-shaped PSC with a twisted structure, respectively. (c) A wire-shaped PSC with a twisted structure was tied a knot. Reprinted with permission from Ref. [59]. Copyright 2014, John Wiley and Sons. (d) Schematic illustration of a wire-shaped PSC with a core-sheath structure. Reprinted with permission from Ref. [61]. Copyright 2008, American Institute of Physics.

CNT sheets and graphene films have been recently explored as electrode materials in the core-sheath structure due to high surface areas and remarkable electrical, mechanical and thermal properties [62–64]. For instance, metal substrates such as steel wires coated with zinc oxide nanocrystals were successively deposited with P3HT:PCBM and PEDOT:PSS layers, followed by wrapping with a CNT sheet. An energy conversion efficiency of 2.31% had been previously obtained [62]. Compared with the CNT sheet, the graphene film could be more closely wrapped on fiber substrates. As a result, the efficiencies were maintained and varied less than 5% in air for days [64]. In addition, the planar structure of graphene favored the deposition of second phases such as metal nanomaterials for higher performances, for example, the use of Au-doped graphene film enabled an efficiency of 2.53%.

For the wire-shaped PSCs, it is a challenging requirement to simultaneously make thin and continuous photoactive layers on fiber substrates. This technical challenge becomes even more severe when aiming for large-scale production, and more effort is necessary to develop new fabrication methods. Wire-shaped PSCs, typically with lengths of several centimeters, have mainly been reported. For the core-sheath structure, it is also highly desirable to obtain transparent and continuous conducting films as outer electrodes. The current materials such as semi-transparent carbon nanostructured films decrease the light absorption.

The differences among these miniature wire-shaped solar cells are further summarized below. Wire-shaped inorganic solar cells have mainly been made from crystalline silicon and showed higher energy conversion efficiencies than the wire-shaped DSCs and PSCs. It remains difficult to continuously make wire-shaped inorganic solar cells, while the wire-shaped DSCs and PSCs can be continuously fabricated through neat and efficient solution processes. Inorganic solar cells have been produced at the nanoscale, compared with DSCs and PSCs which are micrometer-sized in diameter, so the inorganic solar cells would be generally used for various electronic nano-devices, while the wire-shaped DSCs and PSCs may be scaled up for practical applications in portable and wearable electronics using well-developed weaving technology.

Electrochemical capacitors

Electrochemical capacitors have attracted a great deal of attention due to their higher power densities, excellent reversibility and long cycle life than conventional capacitors and batteries [65]. Based on the energy storage mechanism, electrochemical capacitors are classified as either electrical double layer capacitors (EDLC) (where the capacitance stems from ion adsorptions at electrode/electrolyte interfaces) or pseudo-capacitors (where the capacitance comes from reversible redox reactions between electrolytes and electroactive species) [66].

Most effort has been concentrated on synthesizing new materials and designing novel structures for high electrochemical properties, though increasing interest has recently been paid to the unique wire shape to meet the mainstream direction in portable electronic devices [67–76]. For instance, a wire-shaped EDLC was fabricated by twisting two aligned CNT fibers with a specific capacitance of 4.5 F/g at 2 A/g (Fig. 6a). Furthermore, the specific capacitance had been improved by incorporating second phases such as conducting polymers into aligned CNTs [77,78]. A high specific capacitance of 274 F/g or 263 mF/cm at 2 A/g was achieved from CNT/polyaniline composite fibers (Fig. 6b) [79]. As expected, these wire-shaped EDLCs were also flexible and could be easily bent without obvious fatigues in structure. Compared with the as-fabricated device, the specific capacitances were slightly decreased by less than 3% after bending for 50 cycles. The capacitances have also been increased by depositing metal oxide nanomaterials [80] on the CNT fiber to enhance the pseudo-capacitance. For the MnO_2 nanoparticles [81], the resulting wire-shaped EDLC exhibited specific capacitance of 0.014 mF/cm at 2×10^{-3} mA.

Currently, the two twisted fiber electrodes were found to be separated from each other during bending, and the stability needed to be further increased by synthesizing new materials and optimizing structures. In addition, it is desirable for these wire-shaped storage devices to be deformable as well as flexible during use. Recently, a core-sheath wire-shaped EDLC [82] was explored by scrolling an aligned CNT sheet onto the CNT fiber, and a gel electrolyte functioned as a conducting media as well as supporting material to provide the stretchability (Fig. 6c). The CNTs were kept highly aligned in both CNT sheet and fibers with the gel electrolyte filler among and between them based on the

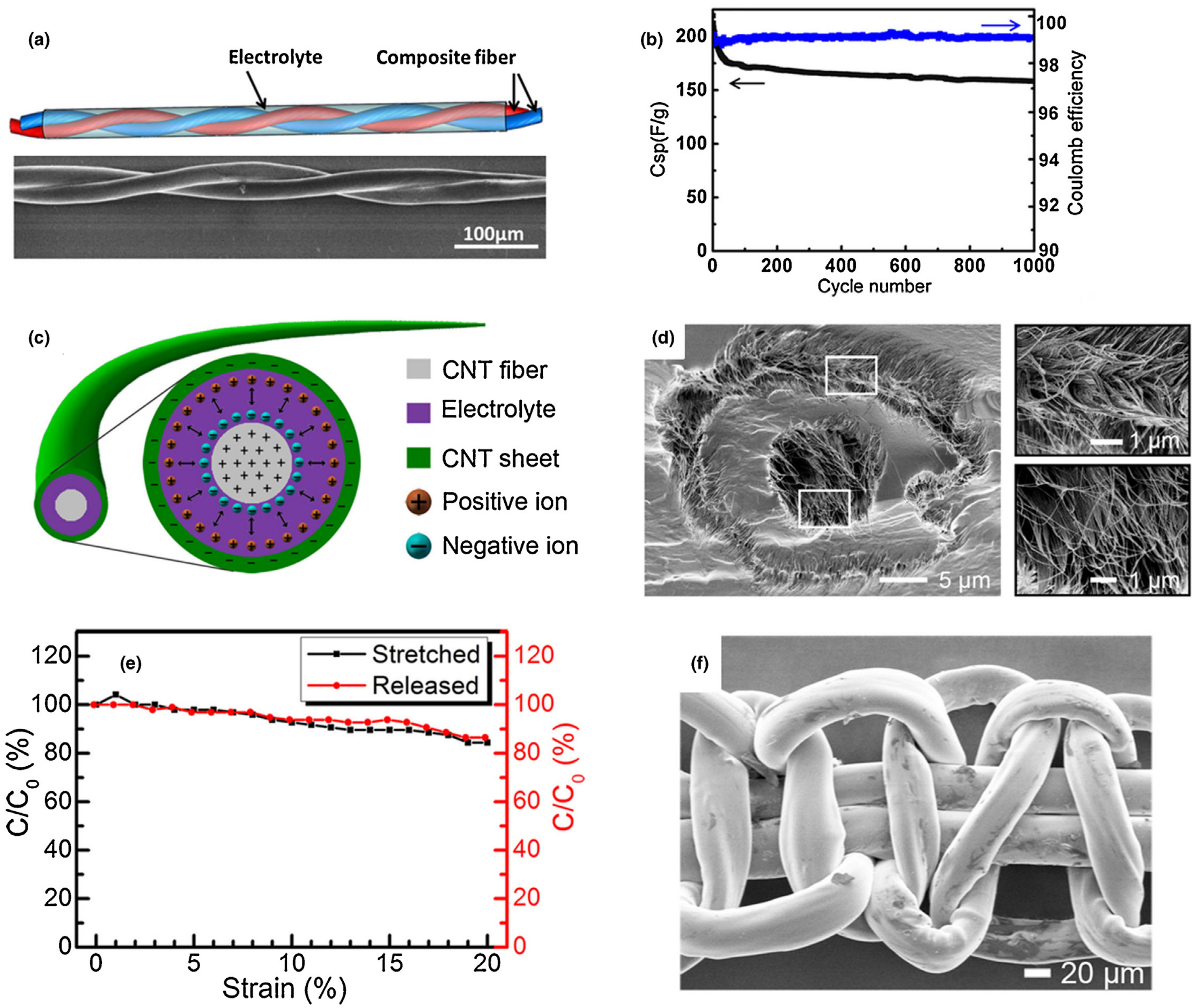

FIGURE 6

Wire-shaped electrochemical capacitors with two different structures. (a) Schematic illustration and SEM image of the wire-shaped electrochemical capacitors with a twisted structure, respectively. (b) Dependence of specific capacitance and coulomb efficiency on cycle number of the twisted electrochemical capacitors. Reprinted with permission from Ref. [79]. Copyright 2013, The Royal Society of Chemistry. (c) and (d) Schematic illustration and SEM images of a wire-shaped electrochemical capacitor with a coaxial structure. (e) Dependence of specific capacitance on strain in the coaxial electrochemical capacitors. (f) SEM image of several coaxial electrochemical capacitors being woven into a textile structure. Reprinted with permission from Ref. [82]. Copyright 2013, John Wiley and Sons.

cross-sectional SEM image (Fig. 6d), and the specific capacitances were also well maintained during the bending and unbending processes (Fig. 6e). These wire-shaped EDLCs could be woven into various structures such as powering textiles (Fig. 6f). Compared with the twisted structure, the coaxial EDLC also exhibited a much higher specific capacitance of 59 F/g as the coaxial structure had more effectively taken advantage of the large surface area of CNTs with lower internal resistance.

Lithium-ion batteries

Besides the conventional planar structure, increasing attention has been paid to developing lightweight and portable lithium-ion batteries. By rolling thin films into rod-shaped electrodes, miniature pin-type batteries have been fabricated, which exhibited a specific capacity of 37.5 mAh/cm^3 [83]. Recently, a cable-type lithium-ion battery [84] has been fabricated from a hollow, spiral core anode and a tubular outer cathode, and the two electrodes were separated by a poly (ethylene terephthalate) membrane. A specific capacity of 1 mAh/cm was produced from this novel cable structure. A flexible wire-shaped battery (Fig. 7a) was achieved with a specific capacity of $\sim$100 mAh/cm^3 by twisting an MnO_2-decorated CNT fiber and a Li wire (Fig. 7b) [81]. The electrochemical performances of these wire-shaped batteries were expected increase further by incorporating second phases such as $LiFePO_4$ [85] and Si [86] into CNT fibers.

The wire-shaped batteries may be also woven into textiles although the resulting power textiles have not been explored yet. Alternatively, a thin-film battery with a grid structure similar to the woven battery textile has been produced (Fig. 7c) [87]. $LiMn_2O_4$ nanorods and $Li_4Ti_5O_{12}$ nanopowders were used as cathode and anode materials, respectively. Here, a transparent gel electrolyte was used, which enabled the textile battery to also be transparent.

Integrated energy devices

To extend the practical application of wire-shaped solar cells and electrochemical storage devices, it is necessary to simultaneously realize the energy harvesting and storage, that is, self-powering energy systems. For instance, the wearable photovoltaic textiles woven from the wire-shaped solar cell were proposed to be used in the field working, but it remained challenging to store the generated electric energy. As a result, a lot of efforts have been put into integrating the solar cell and electrochemical storage functionalities in a single wire device and a few examples of integrating DSCs or PSCs and electrochemical capacitors exist [63,88]. In the case of the DSC and electrochemical capacitor, a twisted structure with two fiber electrodes has mainly been studied. Typically, a Ti wire is coated with photoactive materials to realize the photovoltaic conversion in some parts and a gel electrolyte to realize the energy storage in other parts; a CNT fiber is then twisted with both conversion and storage parts to produce an integrated wire-shaped device (Fig. 8a and b). The energy conversion efficiency was calculated to be 2.2% and the storage efficiency was found to be 68.4%. The integrated device thus demonstrated a complete photoelectric conversion and storage efficiency of 1.5% [88].

For the integrated wire-shaped device based on the PSC and electrochemical capacitors, a coaxial structure was recently realized [63]. A Ti wire that had been coated with a thin layer of photoactive P3HT/PCBM materials in some parts and gel electrolyte in the other parts was wrapped with a continuous, aligned CNT sheet to produce the integrated coaxial energy wire (Fig. 8c).

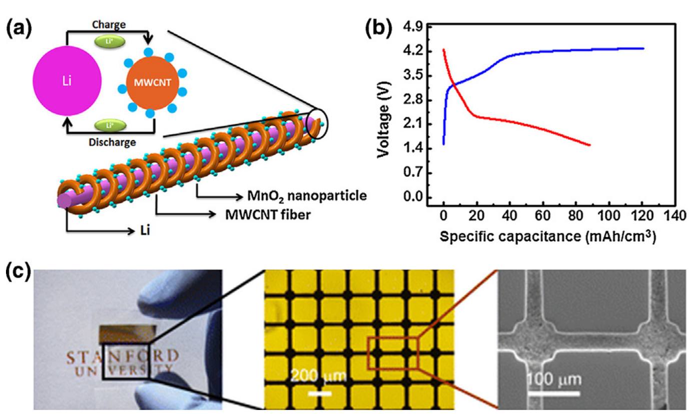

FIGURE 7

Lithium-ion batteries with different structures. (a) and (b) Schematic illustration and capacity of wire-shaped lithium-ion batteries, respectively. Reprinted with permission from Ref. [81]. Copyright 2013, John Wiley and Sons. (c) Transparent lithium-ion batteries realized by a grid structure. Reprinted with permission from Ref. [87]. Copyright 2011, National Academy of Sciences of the United States of America.

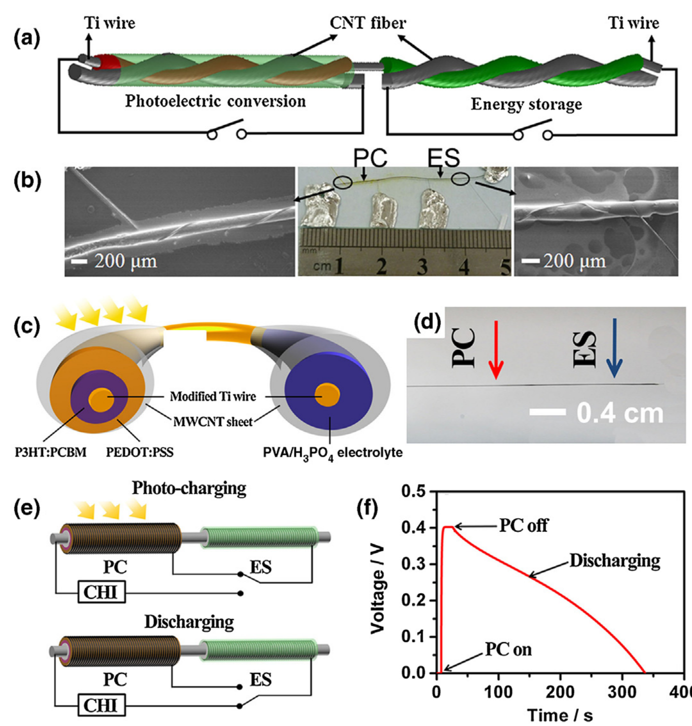

FIGURE 8

Integrated photoelectric conversion (PC) and energy storage (ES) devices with two different structures. (a) and (b) Schematic illustration and SEM image of the integrated wire-shaped device with a twisted structure, respectively. Reprinted with permission from Ref. [88]. Copyright 2012, John Wiley and Sons. (c) and (d) Schematic illustration and photograph of the integrated wire-shaped device with a coaxial structure, respectively. (e) The coaxial integrated device in the process of charging and discharging. (f) Charging–discharging curve of the coaxial integrated device with a current of 0.1 μA during the discharging process. Reprinted with permission from Ref. [63]. Copyright 2014, John Wiley and Sons.

Fig. 8d shows a photograph of a typical coaxial, wire-shaped integrated energy device that did not require sealing. Upon exposure to the light, the energy wire could be charged once the photoelectric conversion and energy storage parts have been connected; the stored electric energy is released to power the connected electric facility after disconnecting the two parts discussed above (Fig. 8e). The energy conversion efficiency was calculated to be 1.01% and the storage efficiency was found to be 81.2%, which produced an entire photoelectric conversion and storage efficiency of 0.82%. Fig. 8f shows a typical charging–discharging curve of the coaxial integrated device. Here, the charging process was very fast as the specific capacitance of the storage part was relatively lower. It remains challenging to explore new materials for the wire-shaped electrochemical capacitors to match the wire-shaped solar cell. Of course, additional formats of energy harvesting and conversion could be also integrated into a single device [71,89,90]. For instance, solar energy and mechanical energy were converted to electric energy that had been electrochemically stored at the same fiber.

Besides wire-shaped energy devices, flexible and stretchable planar miniature electronic devices, for example, electronic skins or e-skins that are also known as smart skins [91–93], have also been attracting increasing attentions. Such e-skins can be fabricated from intrinsically stretchable materials [94] or through designing wrinkled structures from conventional materials [95]. The e-skins are generally produced with tactile sensors, just like human skin. Besides the sensing properties, some other functions such as biocompatibility and biodegradability, self-healing and self-powering have also been integrated into e-skins [96,97].

Conclusion

Although miniature energy conversion and storage devices, particularly, wire-shaped solar cells, electrochemical capacitors and lithium-ion batteries, started to attract attentions just a few years ago, great advances have been already made in many aspects including the synthesis of functional materials, design of effective structures, improvement of electronic performances and development of promising applications. For instance, a high energy conversion efficiency of over 8% was achieved for the wire-shaped dye-sensitized solar cell. Despite obvious achievements in wire-shaped energy devices, there is still a long way to go in terms of their application due to several critical challenges that must be overcome. The efficiencies greatly decrease when increasing the length from centimeters to meters. It is highly desirable to develop general and effective methods to scale up the production of these miniature devices. Although the wire structure enables their use as flexible electronic clothes using well-developed textile technology, the connection of electrodes may prove very difficult.

To realize practical applications of these wire-shaped energy devices, it is highly desirable to develop new fiber electrodes with high electrical conductivities, so, with the increasing length, the increased resistances of the fiber electrode will not obviously decease their performance at the applicable scale. Wire-shaped energy devices have been widely proposed for portable and wearable electronics. To this end, it is also necessary for wire-shaped energy devices, as well as the resulting electronic devices, to be stretchable, so they will not break under stress during use.

Acknowledgements

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