Invited paper

Zhibin Yang*

High performance fiber-shaped solar cells

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Abstract: This short review summarizes our recent progress in fiber-shaped solar cells based on carbon nanomaterials. Highly efficient fiber-shaped solar cells based on graphene/platinum composite fibers were developed with a certified power conversion efficiency of 8.45 %. Furthermore, stretchable fiber-shaped solar cells were realized by designing elastic conducting multi-walled carbon nanotube fibers with a novel rotation-translation method. These solar cells were further integrated with fiber-shaped supercapacitors to simultaneously achieve energy conversion and storage. These fiber-shaped energy devices can be woven into textile as next-generation power source for various portable electronic devices.

Keywords: carbon nanotubes; energy conversion; energy storage fiber; graphene; IUPAC-SOLVAY International Award for Young Chemists; solar cell; supercapacitor.

Introduction

Integration, miniaturization, light weight and flexibility are the mainstream direction for portable and wearable devices [1–5]. Currently, the traditional silicon-based solar cells and other inorganic or organic solar cells generally present in a planar format [6, 7], which cannot fully satisfy the ever-growing requirement for mobile devices and wearable electronics. Fiber-shaped solar cells emerged as a promising solution in recent years [8–15]. Compared with planar solar cells, they are, flexible, lightweight, highly integrated, and provide all-around surface available for illumination. Furthermore, they can be woven into textiles using mature textile technology just like conventional chemical fibers.

However, the poor performance has always been a bottleneck for fiber-shaped solar cells, which generally exhibit much lower power conversion efficiency compared with conventional planar solar cells. The commonly used fiber electrodes including metal wires, carbon fibers and modified polymer fibers are unable to fully meet the strict requirements of fiber-shaped solar cells, including high flexibility, strength and conductivity, as well as complex interface. In addition, all the fiber-shaped solar cells are not stretchable, which cannot afford deformation during use. Therefore, it is urgent to fabricate high performance fiber electrodes to simultaneously satisfy the above requirements.

Carbon nanomaterials, like multi-walled carbon nanotubes (CNTs) and graphene, shows exceptional mechanical and electronic properties including high tensile strength, electrical conductivity and catalytic activity, flexibility and transparency [16–19]. Most importantly, they can be assembled into macroscopic fibers with their excellent properties well maintained.

Therefore, based on these carbon nanomaterial fibers, we have designed and developed highly efficient, flexible and stretchable solar cells, as well as their integrated device to simultaneously achieve energy conversion and storage in a single fiber.

Article note: A collection of peer-reviewed articles by the winners of the 2015 IUPAC-SOLVAY International Award for Young Chemists.

***Corresponding author: Zhibin Yang,** State Key Laboratory of Molecular Engineering of Polymers, Department of Macromolecular Science and Laboratory of Advanced Materials, Fudan University, Shanghai, China 200438, e-mail: zbyang@uw.edu.
http://orcid.org/0000-0003-4036-9446

Highly efficient fiber-shaped solar cells

To fabricate highly efficient fiber-shaped DSCs, graphene fibers were fabricated via a wet spinning method [20], followed by electrochemically depositing platinum nanoparticles onto them to serve as the counter electrode (Fig. 1a and b), which showed a strength of 10^2–10^3 MPa and an electrical conductivity of 10^2–10^3 S cm^{-1}. On the other hand, dye-absorbed titanium wires with perpendicularly grown titania nanotubes arrays served as the working electrode. The above two electrodes were further twisted together, followed by the introduction of liquid electrolyte and encapsulation to form a fiber-shaped dye-sensitized solar cells (Fig. 1c). After optimizing the length of titania nantubes in the working electrode and the content of platinum in the counter electrode, the resulting solar cells showed a certified power conversion efficiency of 8.45 % (Fig. 1d). For these fiber-shaped solar cells, the effective area is defined as the projected area along the light illuminating direction. The high photovoltaic performance was attributed to a uniform dispersion of platinum nanoparticles on graphene fibers, due to the stronger synergetic effect between them, resulting a high surface area for catalysis and a high conductivity. These improved properties can effectively facilitate charge separation and transfer during photovoltaic conversion.

Stretchable fiber-shaped solar cells

Although high performance fiber-shaped DSCs have been realized, they are easily broken during bending or stretching when integrated with other wearable electronic devices. Thus, fabricating stretchable solar cells is of extremely importance for practical application. To this end, we developed an elastic conducting fibers that were prepared by winding aligned carbon nanotube sheets on rubber fibers through a rotation-transla-

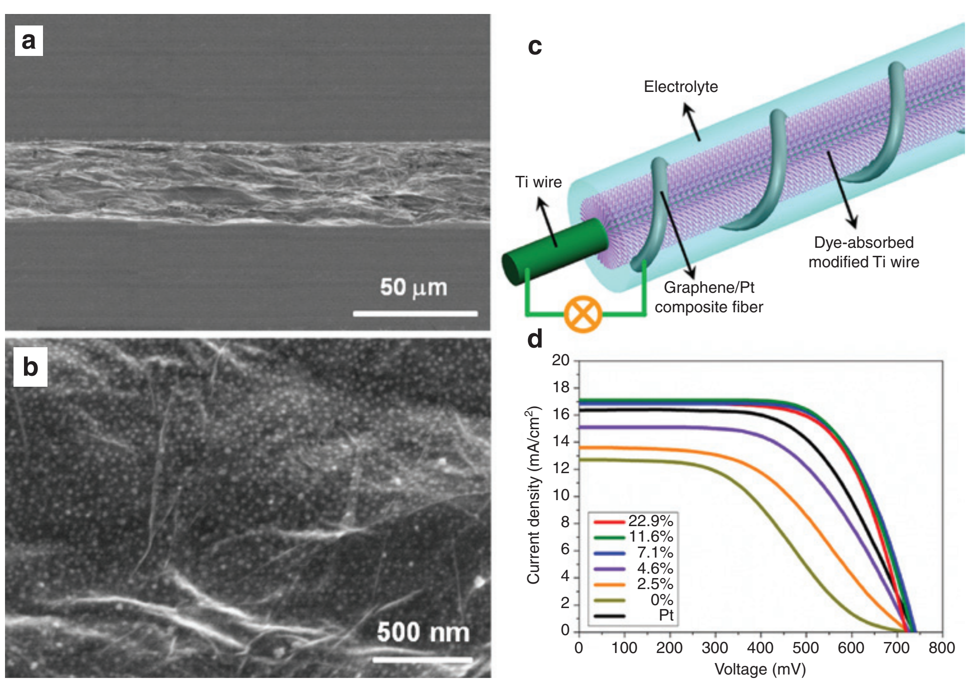

Fig. 1: (a) and (b) Scanning electron microscopy (SEM) images of graphene/Pt composite fibers with different magnifications. (c) Schematic illustration of a fiber-shaped DSC fabricated by using a graphene/Pt composite fiber as the counter electrode and a Ti wire impregnated with TiO_2 nanotubes as the working electrode. (d) Photovoltaic performance of the fiber-shaped solar cells with graphene/Pt composite fibres (different Pt content) as counter electrodes under AM 1.5 illumination. Adapted from ref. [20]. Copyright John Wiley and Sons (2013).

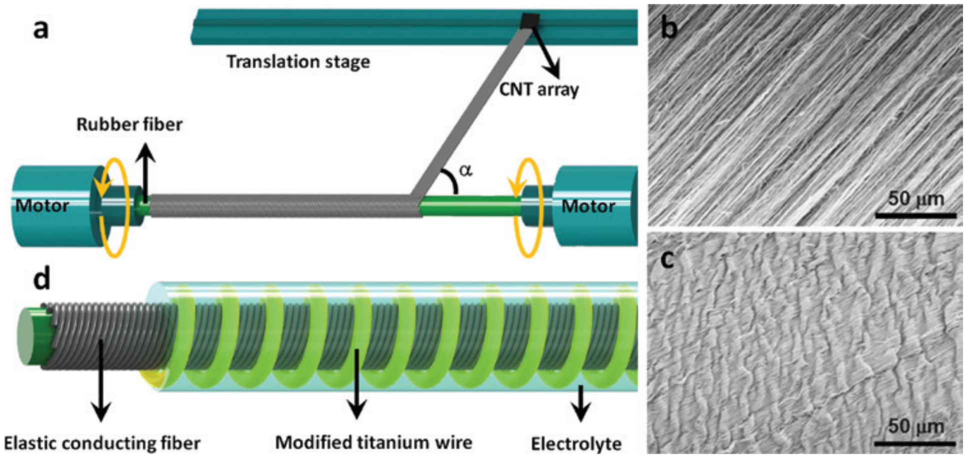

Fig. 2: (a) Schematic illustration to fabricate an elastic conducting fiber. (b) and (c) A top SEM view of the elastic and conducting fiber before and after stretching. (d) Schematic illustration of a stretchable DSC. Adapted from ref. [21]. Copyright John Wiley and Sons (2014).

tion method (Fig. 2a) [21]. The as-prepared fibers showed high and stable electronic properties even under stretching with a strain of 100 %. This amazing property can be mainly attributed to the formation of wrinkle structured CNTs during stretching process (Fig. 2b and c). More importantly, the conductivity of the elastic conducting fibers can be accurately controlled by tuning the helical angle and the thickness of the CNT layer. Then, the elastic conducting fiber was inserted into a long and spring-like modified Ti wire (working electrode) to construct a stretchable fiber-shaped DSC (Fig. 2d). A high power conversion efficiency of 7.13 % had been achieved and well maintained under a strain of 30 %.

Stretchable integrated devices

For the fiber-shaped solar cells, the generated electricity from solar power should be stored for further outputting when necessary. Generally, external batteries were connected to solar cells for electricity storage, which was less efficient and inconvenient. Therefore, it is necessary while challenging to fabricate a stretchable fiber-shaped device that can realize both energy conversion and storage.

Herein, a stretchable fiber-shaped supercapacitor was integrated with a fiber-shaped DSC to simultaneously realize energy conversion and storage in a single fiber. As shown in Fig. 3a, a stretchable fiber-shaped supercapacitor was fabricated through the rotation-translation method with specific capacitance of ~19.2 F/g that can be maintained under stretching by a strain of 75 % [22]. Then, a stretchable fiber-shaped DSC was integrated with the supercapacitor based on a coaxial structure as shown in Fig. 3b [23]. The inner supercapacitor can be photocharged when its two electrodes are connected with the photoanode and cathode of the outer DSC, respectively. Then the stored electrical power can be output after the supercapacitor was fully charged. The entire energy conversion and storage efficiency of the integrated fiber device reached 1.83 % and can be maintained after 50 cycles of stretching.

These fiber-shaped energy devices can be further woven into flexible and stretchable textiles (Fig. 4a and b) [21]. The output currents and voltages of the derived photovoltaic textiles can be tuned by parallel and series connections, respectively. For instance, the output voltage increased from 0.71 to 3.31 V once five fiber-shaped solar cells were connected in series, while the photocurrent increased from 1.19 to 4.27 mA when five cells were connected in parallel. In addition, the performance of these energy textiles can be well maintained after 50 cyclic stretching (Fig. 4d).

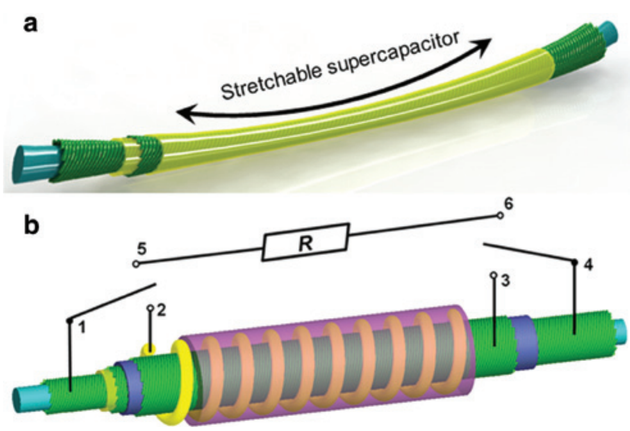

Fig. 3: (a) Schematic illustration to a stretchable supercapacitor. (b) Schematic illustration to a stretchable energy conversion and storage integrated device with a coaxial structure. Figure 3a and b is adapted from ref. [22] and [23], respectively. Copyright John Wiley and Sons (2013, 2014).

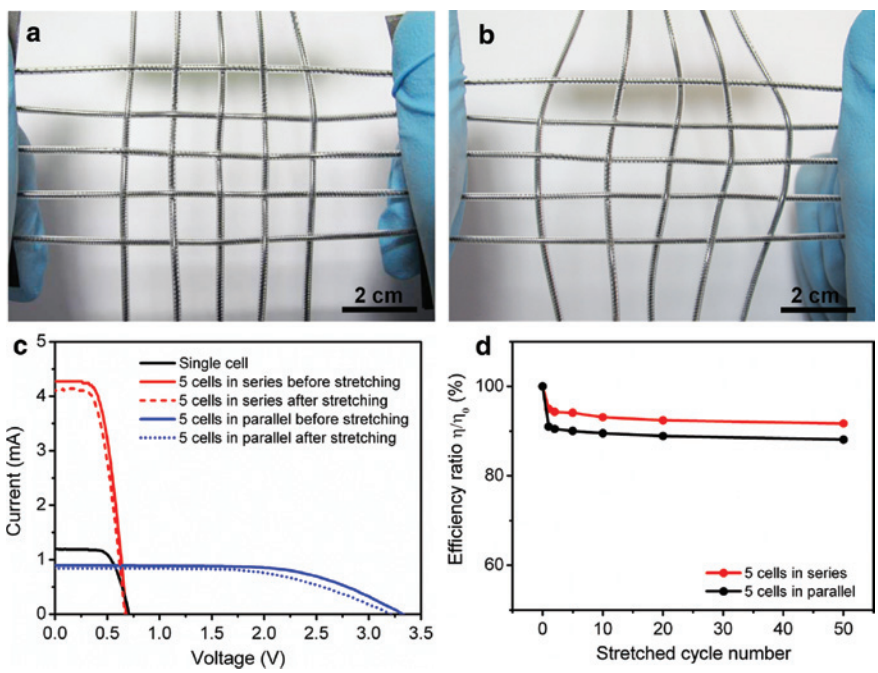

Fig. 4: (a) and (b) Photographs of a flexible and stretchable photovoltaic textile before and after stretching, respectively. (c) J-V curves of the photovoltaic textile in series and parallel connections before and after stretching. (d) Dependence of energy conversion efficiency on stretched cycle number at a strain of ~20 %. η_0 and η correspond to energy conversion efficiencies before and after stretching, respectively. Adapted from ref. [21]. Copyright John Wiley and Sons (2014).

Summary and perspective

In summary, we have developed a novel family of fiber-shaped DSCs based on carbon nanomaterials, which are highly efficient, stretchable and integratable. The rapid charge separation and transport at the interface of carbon nanomaterials are carefully studied to elucidate the high photovoltaic performance. The fiber-shaped DSCs have been further integrated with supercapacitors to simultaneously store the generated electric energy with high efficiency. Both fiber-shaped DSCs and integrated devices can be woven into flexible and stretchable self-powered textiles that may solve the energy bottleneck in the wearable electronics as well as many other related fields.

Despite of the exciting results achieved, there are still many challenges to be overcome to meet practical applications. First, the efficiencies of fiber-shaped DSCs are still too low for practical applications. Recently, the solution processable perovskite solar cells have boasted the efficiencies above 20 % in several years, which represents a promising direction for further improvement of the performance of fiber-shaped solar cells. Second, the capacity of the energy storage parts in integrated devices are too low compared with the energy converted by the photovoltaic conversion part, which generally demonstrates an ultra-fast charging process. A possible solution lies in the replacement of supercapacitor with other devices that have higher energy densities, such as lithium-ion battery or lithium-sulfur battery. Overall, there is much space to further improve the performances of fiber-shaped solar cells and integrated devices.

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