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RESEARCH HIGHLIGHTS

Fiber-like solar cells

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The human habit of wearing fiber materials and interwoven fabric can be dated back to the prehistoric time. In recent years, efforts have been devoted to make flexible energy devices, e.g., solar cells, into fiber shape, further expanding the concept of fiber from cloth materials to modern on-body electronic devices. The evolution of device shape has not only made changes to the sandwich-like device structure, but also provided more alternatives to classical electrode materials like transparent conductive oxide. In 2008, a flexible dye-sensitized solar cell (DSSC) was invented by Zou *et al.*[1] *via* twisting two electrodes into one fiber-like device, as a breakthrough to the coaxial-type or planar-type device structure. The entire cell was a fine wire with diameters of ~200 μm. The working electrode was stainless steel fiber coated with a layer of dye-sensitized TiO_2, and the counter electrode was Pt wire. Positive charges from the photoanode can be transferred to counter electrode by either liquid electrolyte or all-solid hole-transport materials[1−3]. Thanks to the twisting structure, solar light can easily reach the working electrode from almost every direction, even though both electrodes are opaque. It completely got rid of transparent conductive oxide material for both electrodes. This work is a vital start, which enables weaving solar cells into any shapes, such as rope, bag, or clothing etc. After that, fiber-like solar cells with a twist structure have attracted increasing attentions. To realize high efficiency, low cost and wear comfort, a lot of works have been reported on the development of photoanode, counter electrode and photoactive materials (Fig. 1).

For the photoanode, Ti wire was first selected as an alternative for the stainless-steel wire by Zou *et al.*[4]. Electrochemical anodization was used to anodize a Ti wire into a TiO_2 nanotube (TNT) array anode for semi-solid and all-solid fiber-like DSSCs. The power conversion efficiency (PCE) of the semi-solid device increased from <1% to >1.5%. After years efforts, the PCE for Ti-based fiber-like DSSCs reached >10%[5], and the TNT photoanode currently becomes a standard anode. To reduce the weight of metal wire, various metals, e.g. Mn, Ni and Zn, were deposited onto polymer wires for photoanode assembling. Among them, a low-cost and lightweight PBT\Cu\Mn\ZnO photoanode was developed by Fan *et al.*[6], and exhibited special suitability for CuI-type all-solid DSSCs. Furthermore, all-carbon electrode-based fiber-like DSSCs were reported in 2012[7]. The devices had a carbon fiber/TiO_2 photoanode and gave a 1.9% PCE, with significantly reduced weight and cost. In 2014, vertically aligned TiO_2 nanowire arrays and hierarchical TiO_2 nanoparticle were successively deposited onto carbon fibers to form the anode[8]. The devices offered an apparent PCE of 4.18% due to 3D light-harvesting.

For the counter electrode, carbon-based materials were found very promising as a low-cost but effective alternative for the expensive Pt wire. In 2011, Zou *et al.* reported a transparent conductive oxide-less DSSC with Pt-plated commercial carbon fiber as the counter electrode, which gave a 5.8% PCE[9]. In 2012, a low-cost all-carbon counter electrode was further developed, i.e., a bundle of carbon fibers coated with commercial carbon ink[7]. The flexible conductive thread-like counter electrode was made by dip-coating PEDOT:PSS onto insulating commercial threads. PEDOT:PSS improved the conductivity and catalytic performance of the threads, and the fiber-like DSSCs gave a 4.8% PCE[10].

For the photoactive materials, semiconductive oxides of TiO_2, ZnO and SnO_2 were explored as the photoactive materials on the photoanode of DSSCs[11, 12]. Scientists also tried to apply perovskite materials into fiber-like solar cells. In 2019, Zou *et al.* reported fiber-like perovskite solar cells with a 10.79% PCE[13], which is the record PCE for fiber-like solar cells. To prepare a high-quality perovskite layer onto the fiber substrate, the vapor-assisted deposition method was performed.

Besides materials exploration, micro optical structures, like micro-reflectors, wave-guide concentrators and hierarchical light harvesters, were also designed and integrated into fiber-like solar cells, which can effectively capture diffuse light from all directions and significantly enhance the maximum power output[14, 15]. In addition, to provide an uninterrupted wearable power supply based on fiber-like solar cells, hybrid devices of energy harvest and energy storage were explored to realize a stable power output. In 2012, Zou *et al.* reported a fiber-like supercapacitor[16], and the low-cost commercial pen ink was directly used as the electrochemical material. The supercapacitor was then integrated with the fiber-like DSSC to form a new power fiber[17] with a ~2.1% PCE. Compared with traditional integrated power systems, the power fiber provided a lightweight, flexible, and inexpensive alternative for integrating with cloth. Similar integration strategy was applied in batteries to produce a sustainable power fiber[18].

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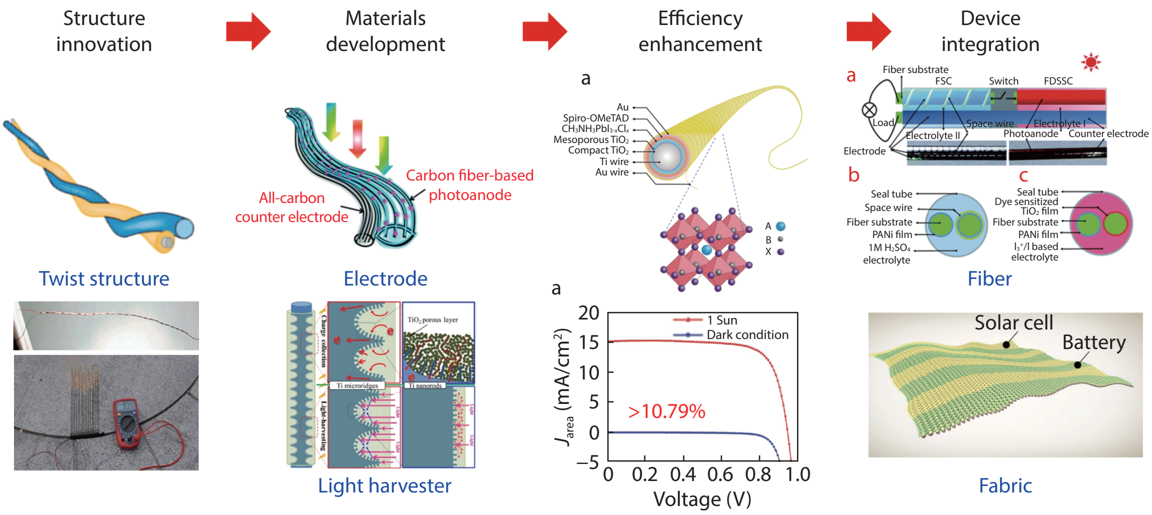

Fig. 1. (Color online) Fiber-like solar cells and applications. Reproduced with permission[1], Copyright 2008, WILEY-VCH. Reproduced with permission[7], Copyright 2012, Royal Society of Chemistry. Reproduced with permission[13], Copyright 2019, WILEY-VCH. Reproduced with permission[15], Copyright 2018, Elsevier. Reproduced with permission[16], Copyright 2012, WILEY-VCH. Reproduced with permission[17], Copyright 2013, Royal Society of Chemistry. Reproduced with permission[19], Copyright 2020, Elsevier.

Though there are challenges in PCE, lifetime, scalable fabrication and wearing comfort, fiber-like solar cells hold the advantages for being integrated with fiber-like energy storage devices and further being woven into clothes[19]. We believe that fiber-like solar cells will find applications in AI in the near future.

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