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Introduction

1.1 Development of Wearable Solar Cells

Wearable devices can be worn close to the human body, have a good fit on irregular body surfaces, and perform ideal functions when worn. They are considered to be the next-generation electronic devices with broad applications. They thus enable a variety of desirable and unfulfilled functions, including but not limited to energy harvesting, storage, sensing, display, and actuation in a wearable format, which can reshape our traditional lifestyle [1]. Wearable solar cells, an important branch of wearable devices, can convert light into electric energy, namely the photovoltaic conversion process, in a wearable format and can be readily integrated with other wearable devices such as supercapacitors, batteries, sensors, displays, and actuators [2, 3]. These appealing features and potential applications have greatly facilitated the development of wearable solar cells in the past decades.

Although thin-film solar cells have been investigated as potential candidates in wearable applications, their limited flexibility generally results in inferior interfacial stability that severely degrades their photovoltaic conversion performance under large deformation in wearable applications [4]. More importantly, the two-dimensional configuration sacrifices breathability and cannot meet the requirements for breathability and comfortability. Therefore, the emergence of fiber-shaped solar cells has offered a promising approach to realizing fully wearable solar cells [5]. In 2002, a pioneering work reported a fiber-shaped dye-sensitized solar cell (DSSC), in which the photoactive materials were layer-by-layer coated on a metal wire, shedding light on the feasibility of fiber-shaped solar cells with promising wearability [6]. This also inspired the production of a fiber-shaped polymer solar cell five years later, which consisted of photoactive materials coaxially incorporated into an optical fiber [7]. In 2014, the first perovskite solar cell in a fiber format was developed with all-solid-state characteristics, which were highly appealing for the requirement for practical applications [8]. Over the past twenty years, a variety of exciting progresses has been achieved in device structure, fiber electrode, photoactive material, and electrolyte, as well as the functionalization, integration, weaving, and application of the obtained fiber-shaped and textile solar cells. These will be mainly introduced in the other chapters of this monograph with more details.

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1.2 Characteristics of Fiber-Shaped Solar Cells

As mentioned above, wearable solar cells in the fiber format can afford a variety of attractive characteristics that benefit wearable applications. For instance, fiber-shaped solar cells generally demonstrate excellent flexibility owing to their unique one-dimensional configuration, which can tolerate multiple deformations such as bending, twisting, and even stretching with specific device design [9]. This overcomes the long-standing bottleneck for traditional silicon-based solar cells, which are highly rigid and cannot fully meet the requirement of flexibility for wearable applications [10].

For instance, fiber-shaped solar cells can absorb light from all directions, recognized as the three-dimensional light harvesting capability originating from the unique one-dimensional configuration of the device. For traditional solar cells, such as Si-based solar cells, the power conversion efficiencies (PCE) are highly dependent on the incident light angle. In contrast, fiber-shaped solar cells can harvest light from all directions without significant performance fluctuation. This is an attractive feature for practical indoor applications in which scattered light is highly abundant. This unique feature allows rational device design to further improve the photovoltaic conversion performance toward practical applications.

The weavability of fiber-shaped solar cells represents another key advantage relevant to their production and application. Ideally, fiber-shaped solar cells can be woven into various forms, such as clothing, curtains, and tents, either alone or with other common fibers through proven textile manufacturing techniques such as knitting and weaving [11]. The weavability is highly dependent on the strength and flexibility of the fiber-shaped solar cells as the basic building blocks, which play a key role in the continuous weaving process. The resulting fabrics and textiles can not only inherit the flexibility of the fiber devices but, more importantly, show breathability different from all their bulky and planar counterparts, which provides the best wearability for the resulting devices. This allows for producing wearable solar cells with the best flexibility and breathability that cannot be easily achieved for state-of-the-art solar cells.

Despite the above advantages, fiber-shaped solar cells still suffer from several disadvantages that hinder their practical production and application [12]. For instance, the electrical resistance of fiber-shaped solar cells generally rises when the fiber length increases, which requires the use of highly conductive fiber electrodes. In addition, the light shielding issue based on either twisting or coaxial structure remains a general challenge for fiber-shaped solar cells. These should be taken into serious consideration and will be introduced in more detail in the corresponding chapters.

1.3 Functionalization and Integration

Functionalization and integration have been widely recognized as an important branch for fiber-shaped solar cells, which accommodate complex and harsh applications. For instance, fiber-shaped devices are required to be remotely controlled when a physical detachment is not available in aerospace, which gives birth to a novel magnetic response fiber-shaped solar cell [13]. The Fe_3O_4 nanoparticles were incorporated into multi-walled carbon nanotube (MWCNT) fiber via a dry-spinning method, offering a high saturation magnetization of 17.9 emu/g. With the above Fe_3O_4/MWCNT hybrid fiber as the counter electrode and a modified Ti wire as the working electrode, the obtained fiber-shaped solar cells could be reversibly attached to and detached from a substrate controlled by a magnet. This work also sheds light on smart wearable solar cells through rational material design for practical applications.

The safety issue of fiber-shaped solar cells is very important because they are closely attached on the human body. This inspires the development of safe materials to promote device safety. For instance, a polymer-ionic liquid (IL) gel electrolyte was developed to replace the flammable carbonate and ether solvents, which significantly improved the safety and long-term stability of the obtained fiber-shaped solar cells [14]. Hydrophobic polyvinylidene fluoride-hexafluoropropylene copolymer and 1-butyl-3-methylimidazolium bis(trifluoromethanesulfonyl) imide (BMImTFSI) IL served as the gelata and solvent, respectively, which could maintain the quasi-solid state from room temperature to 300 °C. The resulting fiber-shaped solar cells thus exhibited improved safety and long-term stability and could retain 90% of the original PCE after 30 days.

Efficient integration of fiber-shaped solar cells for enhancement of wearable applications also represents an important direction for real-world applications of fiber-shaped solar cells. To simultaneously realize energy harvesting and energy storage, Bae et al. integrated nanogenerator, supercapacitor, and DSSCs into a single fiber, which could convert the mechanical and optical energies into electric energy and store it in the supercapacitor [15]. Specifically, ZnO nanowires decorated with Kevlar fiber served as a common electrode, and the transparent graphene on Cu mesh was wound around the common electrode as another electrode. Although the total PCE of the integrated device was only 0.02%, this pioneering work showed the feasibility of rational integration of fiber-shaped electronics, which opens a new avenue for further improvement.

1.4 Applications of Wearable Solar Cells

The unique characteristics of fiber-shaped solar cells have made them promising candidates in a broad range of wearable applications, including but not limited to consumer electronics, the Internet of Things (IoT), and smart healthcare, which promise to innovate the conventional function paradigm. Their unrivaled flexibility enables the incorporation of irregular devices and substrates and provides a reliable power supply to diverse electronic devices with high performance.

For instance, wearable solar cells can power consumer electronics in a novel and fascinating way. Owing to their high flexibility and wearability, they can be easily integrated onto the surface of electronic devices without compromising their original flexibility and functionality. In addition, they can significantly extend the life span of consumer electronics as a secondary power source. They can form self-sustaining electronics, for example, a self-powered sports sensor that can generate electric power from outdoor or indoor light, which could overcome the bottleneck of wearable power supplies.

The IoT has been rapidly growing in the past few years, which can realize the connection of numerous electronic devices (e.g. wireless sensors, actuators, transmitters, and wearable devices) for efficient information interaction. All these devices require a stable power supply, which demands self-sustainable power sources such as wearable solar cells [16]. Therefore, fiber-shaped solar cells can be ideal candidates to support the IoT in a highly flexible and portable way. To achieve this goal, the power conversion efficiency, lifetime, and integration of fiber-shaped solar cells should be taken into serious consideration. Overall, fiber-shaped solar cells can significantly contribute to the development of IoT and open a new avenue to achieve the goal of "Internet of Everything" for sufficient information interaction and usage.

Another promising application of fiber-shaped solar cells lies in smart healthcare, such as wearable medical devices. For example, a wearable health monitoring device equipped with a fiber-shaped solar cell panel can continuously track the heart rate, blood pressure, and oxygen levels. It can potentially avoid replacing energy storage devices such as batteries to reduce the infection risk during surgery. Therefore, they can be potentially used to power implantable devices such as pacemakers, defibrillators, or neural stimulators [17]. Of course, there are still some concerns, such as toxicity, biocompatibility, and device stability for implementable applications. This interdisciplinary and innovative direction has attracted broad attention in recent years, which may create a brand new "wearing" way to extend the application of fiber-shaped solar cells.

In summary, we introduce the development of wearable solar cells, particularly in a flexible fiber format, which demonstrates a variety of appealing advantages such as high flexibility, wearability, and weavability. The exploration of functionalization and integration has made them promising candidates in a variety of applications, including consumer electronics, IoT, and smart healthcare devices. We will introduce more details on the background and progress of wearable solar cells in the other chapters of this monograph, providing a comprehensive view of this emerging and highly promising field.

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