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Research on wearable flexible solar cells

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Abstract. With the continuous development of various new energy sources, flexible solar cells have attracted much attention as a renewable and clean energy source. Compared with rigid solar cells, flexible solar cells have the characteristics of bendability, flexibility, and portability. Choosing the right material and manufacturing process can get twice the result with half the effort in the research of flexible solar cells. This article aims to review the research progress of wearable flexible solar cells, analyze the materials and preparation technologies used in flexible solar cells at this stage, and discuss the influence of some materials and processes on the photoelectric conversion efficiency and flexibility of flexible solar cells. In addition, this paper also discusses the future development prospects and some existing problems of flexible solar cells. With the continuous development of wearable technology, the research of flexible solar cells must be one of the development priorities in the future.

Keywords: solar cells, wearable devices, flexible devices.

1. Introduction

With the continuous development of science and technology, traditional energy sources are being continuously consumed. Gases emitted during the use of energy sources such as coal and oil have caused a lot of pollution to the earth's atmosphere, leading to global warming and many other problems. In order to solve the problems of limited traditional ore energy and environmental pollution, research on renewable energy is urgent and has become a hot research direction that has attracted much attention in the world. Among the many research on new energy sources, solar energy, as a clean and renewable energy source, is an energy source with great potential for development, and has received widespread attention in the world. One problem with traditional solar cells is that they occupy a large area and may lose some energy due to energy conversion efficiency issues [1].

At the same time, wearable electronic products have attracted more and more people's attention in recent years, and have been applied in many fields, bringing many changes to people's lives. However, it is worth noting that these wearable electronic products usually require a portable and stable energy supply device to ensure battery life, and the traditional batteries currently used cannot meet the flexibility and portability required by smart textiles, and the battery life is poor [2]. Therefore, a portable wearable device is needed to power these electronic devices to ensure their better operation.

By combining flexible wearable solar cells with wearable electronics, a self-powered system is created to provide portable and stable energy to keep other electronic devices running and provide them with endurance. People can get rid of the dependence on traditional charging methods and charge the electronic devices they carry with them anywhere that have incident light, avoiding the problem that some daily electronic devices are out of power but cannot be charged due to insufficient conditions. However, conventional solar cells have deficiencies in flexibility and portability, making it difficult to meet the needs of wearable devices. Therefore, the development of flexible solar cells that can be in contact with the human body and fit the surface of the human body and can be fully bent and deformed has become a current research hotspot and challenge.

There are still many problems in realizing the application of wearable solar cells, including the selection of materials, the power conversion efficiency of solar cells, design methods, manufacturing methods, safety performance and stability, etc. Therefore, a comprehensive review of the research and development of wearable flexible solar cells is helpful to analyze the current progress, existing problems and future development directions of the research, and can better provide ideas for future research.

The structure of this review paper is as follows: First, this paper will discuss in detail the selection of materials commonly used in wearable flexible solar cells and analyze the impact of different materials on the battery performance and flexibility properties. Next, this article will discuss the preparation technology and process of wearable flexible solar cells. Finally, this article will discuss the applications of wearable flexible solar cells in wearable devices, smart textiles, and other fields, and look forward to their future development directions.

This paper aims to analyze the research progress of wearable flexible solar cells, comprehensively analyze and compare the effects of different materials, design methods and preparation technologies on battery performance and device flexibility and look forward to its future development. By reading this review paper, readers will gain an understanding of the field of wearable flexible solar cells and understand their latest research progress and application prospects.

2. Effect of different materials in solar cells

2.1. GIGS thin film solar cells

CIGS thin-film solar cells are composed of four chemical elements, Cu, In, Ga, and Se, and belong to direct bandgap semiconductors. Compared with traditional silicon-based solar cells, CIGS solar cells have better flexibility. Cu, In, Ga, and Se compounds are usually deposited on flexible substrates, which have better bendability and plasticity. The efficiency of CIGS thin-film solar cells is closely related to the energy band structure of the material, and has the ability of broad-spectrum absorption, which enables CIGS cells to efficiently convert light energy into electrical energy. Its light absorption coefficient can reach $10^{\wedge 5}$ cm-1, and the battery absorption thickness can be reduced to between 1 and 2 μm. Among them, the power conversion efficiency (PCE) of flexible substrate CIGS thin film solar cells can reach 20.4%, which has very broad application prospects. CIGS thin-film solar cells not only have high PCE under direct sunlight, but also have weak light characteristics, so that their photoelectric efficiency exceeds other solar cells in places where solar radiation is weak. When the solar radiation intensity is 0.1 mW/cm^2, the photoelectric conversion efficiency is 3.12%, when the solar radiation intensity is increased to 1.0mW/cm^2, the photoelectric conversion efficiency is 7.25%, and when the solar radiation intensity is increased to 10.1 and 100 mW/cm^2, the photoelectric conversion efficiencies are 11.26% and 14.24%, respectively [3].

2.2. PEDOT: PSS effects on solar cells

PEDOT is a kind of conductive high polymer with excellent conductivity, which can be used in the transparent electrode layer in thin film solar cells. It has good flexibility and great potential in the field of wearable solar cells. PEDOT: PSS exhibits low charge transfer resistance with high room temperature conductivity and remarkable stability. Using the flexible electrode developed by it can ensure the stability of the device and provide better processing performance for materials such as perovskite. It can greatly improve the hole injection ability and thus improve the short-circuit current. A large number of experiments have proved that. Adding PEDOT: PSS to the original electrode can achieve a PCE of about 3% [4]. PEDOT: PSS can be deposited on a flexible substrate to make it have better flexibility, and it can still maintain good efficiency after bending hundreds of times, which is better than metal electrodes, so it can be used as platinum and other noble metal electrode substitutes [5].

PEDOT: PSS has a good energy band matching with other photosensitive materials, which is conducive to the effective separation and transmission of electrons and holes, which can improve the efficiency of the battery, and has an excellent performance in smoothing the electrode interface and extracting holes. Hole transport layers have many advantages. After further modification of PEDOT: PSS by doping and other methods, its electrical conductivity is further improved, and it also has strong optical transmission performance, which enables the device performance to ensure high energy conversion efficiency. And it has the characteristics of solution processing, and can use spin coating, inkjet printing, screen printing, slot die coating and other methods to form a smooth and uniform conductive film, so that it can meet the conditions of mass production [5].

2.3. Gallium arsenide thin film solar cell

Gallium arsenide thin-film cells are a high-efficiency solar cell technology with excellent cell performance. Gallium arsenide thin-film cells have a high light absorption coefficient, can efficiently absorb energy in the solar spectrum, provide high photoelectric conversion efficiency, and have adjustable band gaps, which can be close to the theoretical Shockley-Queisser limit. It has a broad spectral response and can absorb light energy in the visible and infrared ranges, enabling it to maintain high efficiency in low-light conditions. Its high-temperature performance is also very good, and it can still guarantee high battery efficiency in high-temperature environments and can adapt to high-temperature areas and high-concentration light environments [6]. In terms of flexibility, although gallium arsenide thin-film batteries are more fragile than other flexible solar cell materials, they still have a certain degree of flexibility and can adapt to a certain degree of bending, but generally speaking, they are not as good as CIGS and other solar cells.

GaAs-based thin-film photovoltaic cells can be produced by an epitaxial lift-off (ELO) process, which separates the active layer from the substrate by desiccating a sacrificial layer. This enables the dummy substrate to acquire the active layer on the growth substrate without degrading the separation substrate, so that the expensive GaAs substrate can be reused, thereby effectively reducing the manufacturing cost. Moreover, GaAs thin-film photovoltaic structures with back reflectors have the better optical advantage of compensating for the optical confinement of thin absorbing layers that reabsorb reflected light in the back reflector. This type can reduce manufacturing costs and minimize growth time and material quantity. Therefore, gallium arsenide thin film-based photovoltaic cells are suitable as auxiliary power sources for personal and portable electronic devices because of their superior material properties [6].

2.4. Dye-sensitized solar cells

Dye-sensitized solar cells (DSSCs) have attracted much attention because of their low manufacturing cost, good conversion efficiency under low-light illumination, and their ability to change color in combination with the dyes used. DSSC can use spectral light-absorbing dyes to absorb sunlight and convert it into electrical energy and can achieve high photoelectric conversion efficiency at room temperature. Its weak light responsivity is good, and it can generate electricity under low light conditions, so that it can also work indoors and in cloudy environments and generate a certain amount of electricity. DSSC has a good low photothermal effect, and has a lower temperature rise than other solar cells under high light conditions, which reduces the negative impact of the photothermal effect on cell efficiency. DSSCs can spatially separate the photoanode and counter electrode through electrolyte embedding, which greatly reduces the possibility of short circuits. By combining this approach with the concept of core-integrated DSSCs to achieve paper-based TCO-free DSSC9, devices using DSSCs for textile-based solar cells are proposed. DSSC has certain flexibility characteristics, and its sensitive layer can be prepared in the form of a flexible film, or it can be deposited on a flexible substrate, so that it can adapt to a certain degree of bending deformation. Compared with rigid and brittle conductive glass-based

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DSSCs, flexible DSSCs have the advantages of bendability, light weight, and compatibility with roll-to-roll fabrication techniques [7].

2.5. Fabric-type perovskite solar cells

Flexible perovskite solar cells refer to perovskite solar cells based on flexible substrates. Because of their low cost, easy processing, excellent mechanical properties, and convenient transportation and storage, they have become one of the focuses in the development of photovoltaic devices and are expected to be applied to in large-scale production. Perovskite materials can absorb a wide range of spectra, including visible light and near-infrared light, and can perform energy conversion under different lighting conditions and have high energy conversion efficiency. The photoelectric conversion efficiency of this type of cell is relatively high among all current materials. The efficiency has exceeded 20% [8]. Fabric-type perovskite cells can be integrated into textiles, which have good flexibility and can adapt to the softness and deformability of fabrics, ensuring comfort and wearability. Compared with traditional solar cells, they are lighter and thinner and will not add too much weight to the textile, which is conducive to maintaining the lightness and flexibility of the textile.

3. Fabrication technology and process of flexible solar cells

3.1. Fabric-based gallium arsenide thin-film photovoltaic cells

At present, part of the preparation technology and process of a gallium arsenide photovoltaic cell is as follows. First, the substrate is prepared. To prevent the chemical etchant from causing unpredictable transformation and corrosion during the manufacturing process of the solar cell, a Ni-Cu-plated polyester-based conductive fabric carrier is conducive to the expansion of the platform and assists in providing better photovoltaic performance and integrates the gallium arsenide thin film onto the fabric platform. In order to better protect the surface quality of the epidermis, the protective layer is designed for selective etching in acidic solutions and is compatible with the GaAs substrate. Therefore, in the epitaxial lift-off (ELO) process, the epitaxial structure of the AlAs sacrificial layer with the protection layer is grown first. Through Au-Au mechanical bonding and the ELO process, the fabric support replaces the GaAs substrate as the second epitaxial support layer after metal-organic chemical vapor deposition (MOCVD) growth. During the bonding process, high-quality gallium arsenide epitaxial layers are transferred to the fabric carrier to optimize the bonding conditions, preventing the fabric carrier with a highly rough surface from being weaker than the ordinary carrier with a flat surface due to the limited bonding plane. After the bonding process is completed, the AlAs sacrificial layer is etched in an HF-based etchant in order to peel off the GaAs outer film on the GaAs substrate bonded to the fabric carrier. During this process, the device performance is adversely affected due to surface roughness and various defects due to long-term exposure to HF solution or bending stress exceeding its limit. Therefore, Maintaining the crystalline quality of epitaxial layers is an effective approach to fabricating high-performance and stable photovoltaic cell fabric platforms. In addition, a polyimide layer with good flexibility properties can be used to maintain the crystal quality and prevent the transfer of cracks in the outer layer to the extremely rough fabric carrier. The combination of these technologies enables the transfer of wafer-level high-quality thin films onto fabric substrates without loss of crystal quality [6].

3.2. Perovskite solar cells

Perovskite solar cells are usually composed of Fluorine-doped Tin Oxide (FTO) conductive glass substrate, charge transport layer, perovskite light absorbing layer and bottom electrode. At present, there are mainly two types of regular N-I-P and inverted P-I-N, and according to the different structures of the bottom charge transport layer, the device can be further divided into the planar structure and mesoporous structure, forward N-I-P type perovskite solar cells and dye-sensitized. The battery structure is similar, and TiO2 materials are mostly used as the bottom transport layer and mesoporous support layer, which can play the role of transporting electrons and blocking holes and helps to regulate the deposition and crystallization of perovskite films. Most of the efficiency records and high-performance devices adopt this N-I-P mesoporous structure. However, TiO_2 usually needs to be combined with a high-temperature sintering process to ensure its high crystallinity, low defects and good charge extraction ability, which requires high energy consumption and is not suitable for large-area preparation processes. In this regard, a planar N-I-P device structure has been proposed. This structure discarded the mesoporous layer, and developed N-type inorganic semiconductor materials that can be prepared at low temperatures except TiO2 as an alternative electron transport layer. The process is simple and flexible Roll-to-roll continuous preparation of titanium ore photovoltaic devices is developing rapidly. However, it should be noted that although the removal of the mesoporous structure simplifies the process, it is not conducive to the controllable preparation of high-quality perovskite films. In addition, the repeatability and stability of the device also deteriorate, and the current and voltage hysteresis phenomenon Obviously, additional methods such as interfacial modification and material doping are generally required to ensure performance [2,8,9].

4. The future of wearable solar cells

Until today, the research technology of smart textiles has been gradually improved, and various wearable flexible devices have gradually entered the public's field of vision, such as rollable displays, electronic paper, flexible sensors, etc., and are now widely used in various fields. Therefore, higher requirements are put forward for its power supply equipment [9]. However, the current energy storage system cannot meet the performance requirements of high battery life, high energy storage efficiency, high current tolerance range and high safety. At the same time, the electrochemical performance of flexible and portable micro energy storage devices is difficult to guarantee [1]. For future wearable flexible solar cells, their energy conversion efficiency should be enhanced. They can better collect, store and utilize solar energy, and can produce more electricity for equipment used at the same time, so as to achieve long-term power. At the same time, its flexibility and bendability should be enhanced to apply to various shapes and curved surfaces. At the same time, we should also pay attention to the size and storage capacity of the energy storage equipment, as well as the aesthetics and comfort of the entire equipment.

In the development of solar cells, there are still some great challenges, and further efforts are needed to realize the development of wearable flexible solar cells. Many of the materials used are synthetic materials, such as carbon nanotubes, graphene, metal oxide nanoparticles, metal-organic frameworks (MOFs), etc. These materials face complex synthetic processes, low yields, environmental pollution and many other issues. Secondly, the test results of individual components are good, but when the overall test is used, it is not as good as expected. Third, safety is a crucial issue for wearable flexible solar cells, especially under some extreme conditions, it is also necessary to ensure that it will not pose a threat to the human body [10]. Finally, new materials can be continuously used, or the original materials with good performance can be continuously studied, and the material preparation method and the entire device assembly method can be improved to achieve performance improvement and large-scale production. With the continuous development of science and technology, portable flexible solar cells will change people's way of life soon.

5. Conclusion

This paper lists the performance and flexibility of CIGS thin film solar cells, gallium arsenide thin-film solar cells, dye-sensitized solar cells, and perovskite solar cells, as well as the fabrication of gallium arsenide thin-film solar cells and perovskite solar cells. Compared with traditional solar cells with rigid substrates, the research and development of flexible solar cells is more difficult. To improve the flexibility and photoelectric conversion efficiency of solar cells, continuous improvement of existing materials and research and development of new materials are essential. Secondly, the roll-to-roll, printing, packaging technology and other production processes of flexible batteries need to be developed and matured urgently. At present, most wearable flexible batteries are still in the experimental stage, and the cost is relatively high. However, with the continuous development of wearable technology and the increasing demand for environmental protection, although some technologies of wearable flexible solar cells are not mature enough, it is still a very promising research direction.

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