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Research of Flexible and Wearable Solar Cells

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Abstract. Solar power has been widely acknowledged to be the purest and most economical power in the 21 st century. Flexible wearable solar cells are becoming the first choice for power generation because of their high power to weight ratio, stable mechanics, affordable and practical applications. Additionally, the rapid advancement of wearable devices and transport has created a need for flexible and portable power sources with adequate mechanical stability to support such advanced technologies. Flexible, wearable PV devices provide the perfect way to solve the problem. This paper gives a summary of recent studies and advances in the area of flexible wearable solar cells. I classify the PV modules into 5 categories – fiber, organic, GaAs, perovskite-based, and metal-dichalcogenide, and discuss their mechanism, operating principle, optics, and latest developments. In the end, I give an overview of the techniques and suggest their possible use in the future.

Keywords: Flexible wearable solar cells; Power generation; Mechanical stability.

1. Introduction

Since the two industrial revolutions, natural gas and other fossil fuels like coal and oil have been extensively utilized in various facets of production and everyday life. As society and the economy continue to develop and human civilization progresses, the demand for energy has surged rapidly. However, the limitless needs of humanity are at odds with the finite reserves of these non-renewable energy sources. Moreover, the combustion of coal, oil, natural gas, and other fossil fuels releases substantial amounts of carbon dioxide, contributing to the greenhouse effect and accelerating global warming. This poses a significant threat to the survival of humans, animals, and plants alike. Additionally, the widespread use of these non-renewable energy sources leads to environmental pollution and ecological degradation. Consequently, there is a growing consensus on the necessity for alternative energy sources that are renewable, clean, and abundant.

Due to rapid advancements in solar cell technology and increasing environmental concerns, solar energy has garnered significant attention. Solar energy offers several advantages over other energy sources: it is abundant, universally available, clean, non-polluting, and economical. Figure 1 illustrates the comparison of non-hydro renewable energy capacities among countries in 2012. Approximately four million exajoules (1 EJ = 10^18 J) of solar energy reach the Earth annually, with around 5 × 10^4 EJ being easily harvestable [1]. However, the practical application of solar energy remains limited due to challenges such as low conversion efficiency and insufficient mechanical stability.

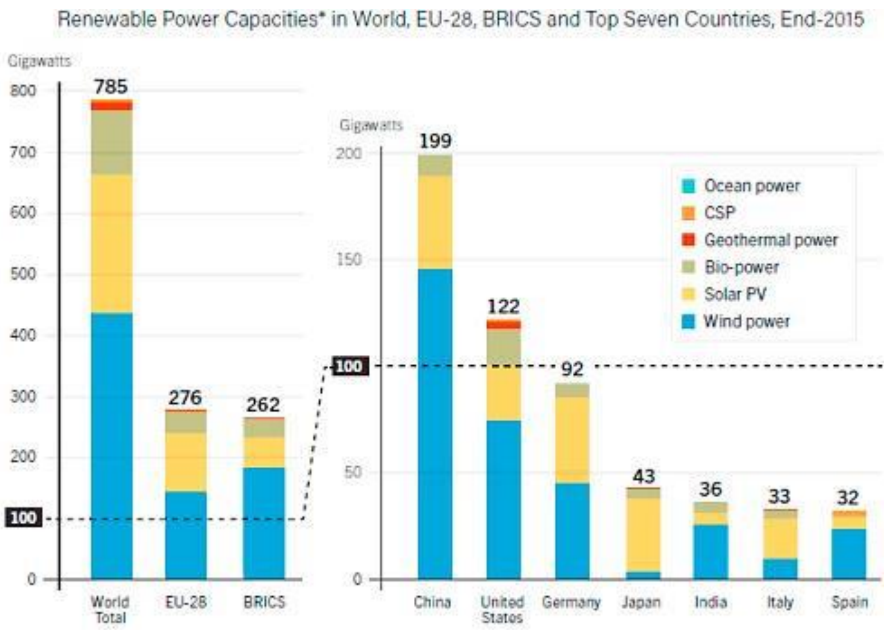

Figure 1. Comparison of non-hydro renewable energy capacities between countries [2].

Among devices designed to harvest sunlight, flexible and wearable solar cells have emerged as ideal choices for developing practical photovoltaic solutions due to their lightweight design, portability, durability, ease of installation, and versatility. To establish a scientific protocol for accurately measuring flexibility, it is essential to precisely define what constitutes a flexible photovoltaic device. Typically, electronic devices that are twistable, bendable, or even stretchable and are fabricated on flexible substrates such as polymers are classified as flexible electronic devices [3].

The degree of flexibility is often gauged using the index of curvature radius, where bendability plays a crucial role. According to available reports, flexibility can be categorized into two levels based on performance. Devices termed "flexible" retain 80% of their initial properties when bent with curvature radii ranging from 10 cm to 1 mm. If the curvature radius can be reduced further to 1 mm or even less, these devices may be classified as "ultra-flexible" [3].

Since they are highly efficient in comparison with their extremely small weight, excellent mechanical stability and low production cost, they are a useful substitute for conventional power generation devices. The utility model can be applied to the textile platform such as the tent, the curtain, the garment, so as to provide the user with more convenience and energy saving. It can also supply power for various locations and conditions. In this paper, this paper will look back on the newest research results and make a summary of the recent advances in this area. This paper deals with the application of the organic solar battery, the GaAs solar battery, the perovskite-type solar battery and the metal-dichalcogenide solar battery.

2. Flexible and Wearable Solar Cells

2.1. Highly Efficient Fiber-Shaped Organic Solar Cells Toward Wearable Flexible Electronics

In this paper, this paper propose an effective fiber type organic solar battery (FOSCs) using a nonfullerene-acceptor (NFAs) as a light harvesting material, and to examine the outside factors affecting its properties. Flexible fibre type solar battery (FSCs) is able to produce electrical power and is easy to incorporate into the cloth. Nevertheless, the effectiveness of different FSCs, especially FOSCs, is still quite low, around 2 percent because of the constraints on the quality of the material and the light-absorbing properties.

Their properties are critical to FOSCs' efficiency. Previous FOSCs have used a polymer based donor and a fulleren-based acceptor as a light absorber, which limits the absorption of light into the visual field and makes them inefficient. In this paper, an NFA-based organic semiconductor is proposed to be a light collector. Additionally, the substrate and core electrode are crafted from low-cost industrial stainless-steel wire. The opposite electrode is made of a CNT (CNT) thread or a silver thread, which is wound on the main electrode. A solution-treated perylene diimide-derived interlayer material is employed to generate the electron-transfer layer.

Figure 2 illustrates the architecture and optical microscopic images of the FOSCs. The authors employ a programmed slide-coating system to manufacture the devices, with all preparations conducted under open-air conditions. The power conversion efficiency (PCE) of this FOSC reaches up to 9.40%. However, it is important to note that even a slight increase in humidity during the preparation process can lead to a significant decline in device performance.

FOSCs can be applied in many fields such as textile drives, FOSC bundles, the red LEDs and the mini fans [4].

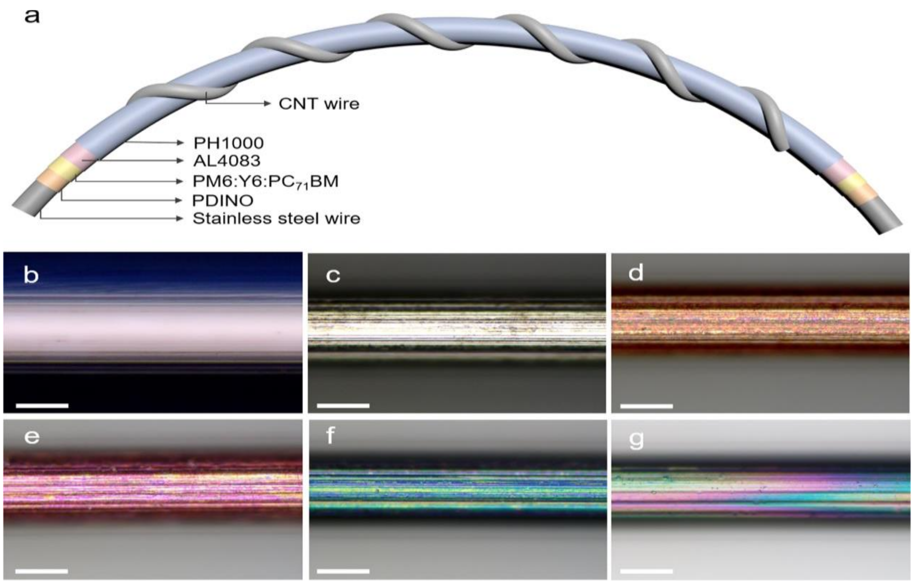

Figure 2. Illustration of the fiber-shaped organic solar cell (FOSC) [4].

2.2. Ultra-Flexible Organic Solar Cell Based on Power Source in Wearable Devices with Indium-Zinc-Tin Oxide Transparent Electrode

Ultra-Soft Organic Photovoltaic (UFOPVs) are being developed to supply power to wearable devices, which can be displayed in real-time, enabling rapid and accurate detection of biological signals. Parylene is employed as an ultra-flexible substrate, applied via chemical vapor deposition. Indium-Zinc Tin Oxide (IZTO) was produced as a transparent electrode by using a pulsed DC magnetron sputtering at room temperature to form an amorphous structure. To enhance the UFOPVs' performance, a 2D lattice is introduced into the photoactive layer by soft imprinting lithography. In this way, it is possible to reduce the device's dependence on incident light and to optimize its performance in different circumstances.

When the 1D mesh is used, the UFOPVs are 2 times less dependent on the UFOPVs at 80 °, as shown in Figure 3. The PCE of the manufactured device is 8.35%, which means an improvement of 13.6% compared to the ITO device shown in Figure 4. In addition, it offers a 30% improvement in the mechanical stability compared to the ITO transparent electrodes.

This new structure UFOPV can be applied in future photoelectric devices, wearable device and fabric platform such as clothes, tents, blankets and so on [5]. Data shows normalized values of PCE. Inset shows the illustration of incident angle of light [5].

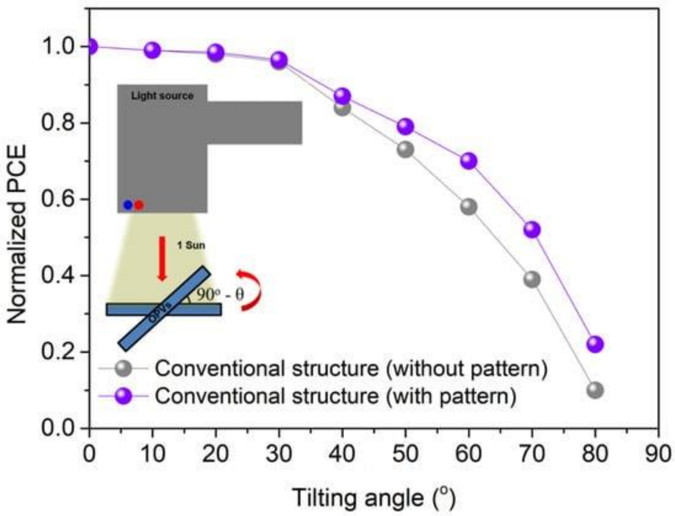

Figure 3. Incident angle dependence characteristics of with/without patterned ultra-flexible OPVs [5].

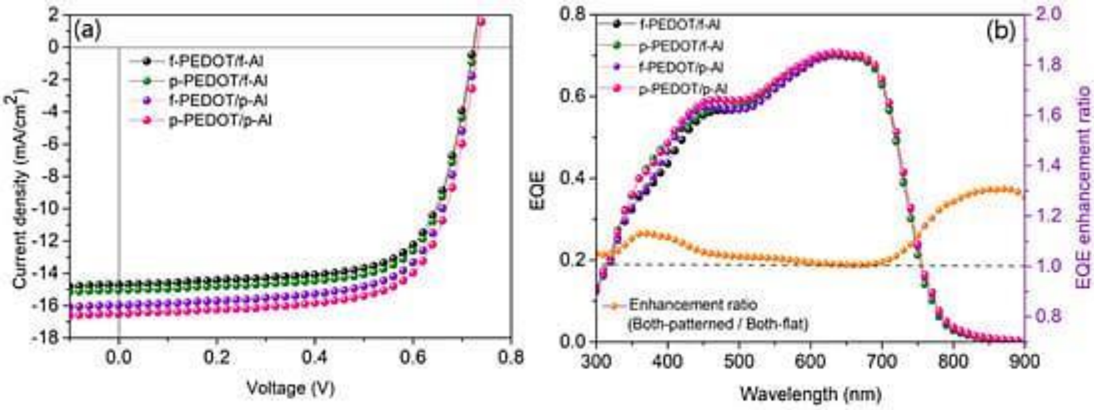

Figure 4. J-V characteristics of ultra-flexible OPVs based on PTB7:PC71BM BHJ [5].

2.3. Flexible Fabric-Based Gaas Thin-Film Solar Cell for Wearable Energy Harvesting Applications

Well-known, GaAs PV cells have a lot of merits in terms of light-absorbing factor, flexibility, and high-PCE (29.1%, Alta Devices), so they can be extensively applied in the soft energy-collecting equipment. In order to overcome this problem, a thin film transfer technology has been reported. In this process, a double-layered sacrifice layer is proposed, the Au bonding method is employed, the Cr/Au double-layer is fabricated, and the Cr/Au dual layer is fabricated, and the Fast Epitaxial Deposition (ELO) is employed. In addition, a polyimide layer affixed at the bottom of a cloth base is used for protection of a weak epitaxy and for ease of side etching by self-bending.

The main benefit of this technique is that it can transfer high quality ultrathin film on a textile substrate with no loss in the quality of the crystal. The fabric based GaAs PV (PV) battery exhibits good PV performance, having an open circuit voltage (Voc) of 0.972v, short circuiting current density (Jsc) of 22.59 mA/cm2, and the charge ratio (FF) of 79.64% at AM1.5G lighting.

Additionally, the fabric-based GaAs PV cell exhibits remarkable mechanical flexibility. Even when subjected to a 7 mm radius mechanical curve bending test and 1000 machine bending cycles having a curvature radius of 10 mm, the PV properties are still stable and not affected. This paper presents a new kind of flexible material based GaAs PV battery, which can enhance the application of PLD and extend its application [6].

2.4. Wearable Perovskite Solar Cells Made from Aligned Liquid Crystal Elastomers

Perovskite-Type solar battery (PSCs) has a lot of merits, for example, PCE (more than 25%), lightweight, flexible, low-cost, advantageous photo-electric properties of the compound perovskite-type, and the like. But their commercialisation has been hindered by poor long-term operational stability and mechanical endurance, primarily due to interface flaws.

To address this issue, this paper have designed LCEs with well-aligned interlayer, which are formed by thiol termination LCE as a hardening charge transfer path between SnO2 and the perovskite membrane. The alignment of the interlayers guarantees good charge collection and minimizes charge recombination at the SnO2/perovskite interface. As a result, a solid PSC device reaches PCE of 23.26 percent, VOC 1.17 V and FF 0,803 with decreased hysteresis.

Moreover, the LCE interlayers can maintain the configuration integrity through enhancing ETL/perovskite-type interface and restraining the perovskite-phase segregation. Unpackaged equipment displays T80 life (when the power of the equipment drops to 80% of its initial value) over 1 750 hours on N2. Moreover, the flexibility PSCs which were altered using an LCE interlayer also demonstrated a high PCE of 22. 10 percent, VOC was 1.15 V. The apparatus has also demonstrated superior physical properties, maintaining 86 percent of its initial efficiency over 5000 bending cycles [7].

2.5. Flexible Transition Metal Dichalcogenide Solar Cells with High Specific Power

Semiconductive transition metal dichalcogenides (TMDs) have the characteristics of very high light absorbency, ideal band gap and self - passivating surface. Because of this, it will have a promising prospect in the area of PV with high flexibility. But the PCE of TMD is less than 2 percent. Furthermore, fabrication on a soft base can pollute or damage the TMD interface, thereby reducing the performance of the equipment.

To address this issue, this paper have adopted three techniques: (1) to facilitate Faraday level pinning with clear graphene contacts, (2) a way of passive, spray and reflective reduction by MoOx capping, and (3) a clear direct transfer procedure to manufacture an apparatus on a light elastic polyimide substrate with no injury, which leads to a PCE of 5.1%, a record of 4.4wg-1 for a flexible TMD (WSe2) solar battery, and an improvement in mechanical stability, offering unprecedented possibilities in many areas from aerospace to wearable and implanted electronics [8].

2.6. High Performance Flexible Perovskite Solar Cells Using Low-Cost Bottom Electrodes with Copper Top

The Perovskite Solar Battery (PSC) is expensive by using clear electrically conducting oxides (TCOs) and valuable metals (e.g., Au, Ag), and TCOs are so brittle that they cannot be applied in flexible applications. For the first time, Cu has been applied to FPSCs as a major conductive material for both transparent and opaque electrodes. In addition to the low material cost, Cu has been shown to be superior to silver and gold due to the fact that it does not diffuse to perovskite-type and has a relatively slow reaction with the perovskite-type composition. The substrate clear electrode was fabricated by means of mixed copper mesh on PET. A coating of polyethene (3 - 4 ethylene dioxythiophene) polystyrene-sulfonic acid (PEDOT: PSS) is also contained as PH1000. Then, a perovskite-type absorption device, an electronic transmission layer (ETL), and a hole-transfer layer (HTL) are spin-applied to a mixture of transparent electrodes in proper order. Lastly, to complete the process of manufacturing the device, a thin layer of copper is deposited over the opaque electrode. Inorganic Cu-doped NiOx nano-particles (Cu: NiOx NPs) are applied onto the PH1000 membrane so as to lower the manufacturing cost of the equipment, thereby achieving superior properties of HTL. As a result, FPSCs not only reach the maximal PCE of 13. 58 percent, but also have high VOC and FF levels. Importantly, FPSCs are also highly flexible in mechanics and are able to achieve over 90% of their original effectiveness at 1000 bending cycles at a small diameter of 5 mm. Excellent performance can be obtained in N2 environment with no packaging over 10 weeks, and it is easy to reproduce.

The technology can be applied to low-cost, flexible photo-electronic devices that do not require TCO [9].

2.7. A Low-Bandgap Organic Bulk-Heterojunction Enabled Efficient Flexible Perovskite Solar Cells

As a result of the outstanding solution and low-temperature technology, the lead halide perovskite and organic solar battery (PSCs, OSCs) have become very important in the field of clean energy nowadays. But because of the loss of light in NIR (NIR), and the comparatively big photo-voltage deficiency, they are not suitable for high-performance solar cells.

To overcome this problem, this paper have designed an HSC with an extension of the photoreaction beyond 950 nm by adopting polyphase compound as BHJ. The CH1007 NFA was employed as an efficient NIR photon collector with a redshifted absorbance of approximately 60 nanometers in comparison with Y6. Moreover, a PCBM with excellent carrier mobility was used in order to improve electronic transmission. Furthermore, in order to improve BHJ's exciton dissociation property and its stability, a little PM6 has been applied. As a result of this progress, the authors have successfully produced an HSC with a PCE rate of 23 - 80% and a very sustainable facility. Flexible HSCs exhibit superior mechanical elasticity and a high PCE (21. 73%) owing to low-temperature treatment.

These Flexible Perovskite Solar Cells are available for real-time monitoring of a temperature-sensing device for wearable devices [10]. Graphene Transparent Anode Based on Layer Number and Dopant in High Efficiency Flexible Organic Solar Cells

For OSC (Organic Solar Cell) to function effectively, at least one electrode must be optically clear in order to allow the passage of light. In general, InIntin Oxide (ITO) is employed as the transparent conducting electrode (TCE). But because of its fragile nature, low NIR transparency, the fact that indium is diffused in the active layer, as well as the increasing cost and shortage of indium, there is a need to look for an alternate electrode for flexible and compatible OSCs. Due to its flexibility, constant transmissivity (Tr), and its excellent chemical stability, graphene films have been proposed as potential TCEs for next-generation PV systems.

A significant milestone for TCEs has been to develop a wide range of high-quality graphene thin films on a flexible polymeric base by CVD (CVD) and then post transport. Even so, OSCs with graphene TCEs remain sub-optimal in PCE, and the number of OSCs that are reported to have restricted activity regions.

OSC structure including a thick poly-photo-active layer and a benzimidazole (BI) doped graphene as a clear anode is shown. A PPDT2FBT: PC71BM photo-active layer contributes to the smoothness of the TCE surface, while BI doping decreases the resistance of the paper (Rsh) with minimal loss in Tr, and also makes the graphene anode smooth. The relationship between PV characteristics (JSC, VOC, FF, PCE) and average SR of BI doped graphene TCE-based cells have been investigated. The 3-layer (3L) graphene TCEs provide optimum performance in cell design, with PCEs of up to 6.85 percent per 0.2 cm ^{2} cell. Furthermore, they were able to generate 1.6 cm ^{2} OSCs by combining a dense photo-active layer with an optimal 3L BI doped graphene TCE.

The results show that the development of TCEs is very important as the next generation of flexible, wearable optics [11].

3. Conclusion

In this review, I review the progress of flexible wearable solar cells, discussing their variety, materials used, and design standards. The research focuses on key elements, including the flexibility and mechanical stability of the solar cells. This paper classifies flexible solar cells into five categories: fiber, organic, GaAs, perovskite-type, and metal-dichalcogenide solar cells. In each section, this paper explore the mechanism, the principle of operation, and the key design elements of each type of solar cell. In addition, the latest benefits of individual solar cells and their essential optical properties are investigated and reported.

The information gathered highlights the great potential of these photovoltaic devices in predicting the next generation of wearable electronics, and provides valuable information and advice for future researchers.

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