Materials for Flexible Photovoltaic Textiles: Principles and Applications

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Abstract. This paper discusses the advancements in flexible photovoltaic technologies, with a specific focus on organic solar cells and perovskite solar cells. With the increasing global demand for renewable energy, these technologies present viable alternatives to traditional silicon-based solar panels. The principles of the photovoltaic effect are explored in detail, highlighting the mechanisms of light absorption, exciton generation, and charge separation that occur within these materials. Recent developments in material efficiency, stability, and production methods are reviewed, revealing the potential applications in smart clothing, portable devices, and building-integrated photovoltaics. While challenges remain in terms of performance and long-term durability, ongoing research and innovation promise to enhance the commercial viability of flexible photovoltaic technologies. This paper aims to provide insights into how these advancements can contribute to a more sustainable energy future, addressing both environmental concerns and the growing energy needs of society. Overall, flexible photovoltaic technologies represent an exciting area of research and development in the renewable energy landscape.

Keywords: Flexible Photovoltaics; Organic Photovoltaics (OPV); Perovskite Solar Cells (F-PSC).

1. Introduction

The global demand for clean and renewable energy is a critical prerequisite for achieving a sustainable society. With rising concerns over atmospheric contamination and greenhouse gas (GHG) emissions, it has become increasingly urgent to transition away from finite fossil resources and diversify energy sources, particularly with renewable energy technologies [1]. Presently, a significant portion of the world's population remains without access to electricity, while developed nations disproportionately consume the majority of global energy production [2]. The rapid growth in energy demand, particularly from emerging economies, emphasizes the need for the development of renewable energies, with solar photovoltaic (PV) power being a key contender [3].

Solar energy is a type of clean energy that we should be focusing on. PV cell is a type of technology that directly converts sunlight to electricity. The principle of PV cells is based on the photovoltaic effect which was first suggested by French scientist Edmond Becquerel.

This paper will focus on flexible photovoltaic technologies, particularly organic solar cells, which offer the potential for low-cost production and flexible applications. The development of flexible solar panels, which are lightweight, bendable, and easy to install, represents a promising direction for overcoming the limitations of traditional rigid silicon-based panels. This paper aims to explore the materials, manufacturing processes, and potential market applications of flexible photovoltaic technology, with a specific emphasis on organic solar cells and their future potential.

2. Materials

2.1. Perovskite flexible solar cells (F-PSCs)

In just seven years, perovskite solar cells (PSCs) have made remarkable progress, achieving a power conversion efficiency (PCE) of 24.2%. This efficiency surpasses that of several traditional solar technologies, including multi-crystalline silicon (22.3%), thin-film crystalline silicon (21.2%), copper indium gallium selenide (CIGS) (22.6%), and cadmium telluride (CdTe) thin-film solar cells (22.1%) [4].

2.1.1. Advantage of F-PSC

Perovskite flexible solar cells (F-PSCs) have achieved significant efficiency improvements in recent years. The introduction of the heterojunction structure enabled the efficiency to reach 21.73%, and the initial efficiency of 95% was retained after 1,000 bends. By passivating the surface with histamine diiodate (HADI) additive, a record efficiency of 22.4% was achieved. Going a step further, through organic molecular cross-linking technology and optimized perovskite crystal growth, the latest efficiency record reached 23.4%. F-PSCs have excellent mechanical flexibility and can withstand multiple bending cycles while maintaining high efficiency. For example, cells using the new perovskite material can maintain more than 90% of their initial efficiency after being bent 1,000 times [5]. Due to its lightweight and high power-to-weight ratio, F-PSC can be widely used in wearable devices, portable power supplies, building-integrated photovoltaic (BIPV) systems, and even for energy supply in military exploration and aerospace vehicles [6].

2.1.2. Disadvantage of F-PSC

Perovskite flexible solar cells have poor near-infrared responsiveness: Pb-based perovskite devices have low spectral response in the near-infrared (NIR) wavelength region, which limits their light conversion efficiency. Although perovskite flexible cells maintain high efficiency under multiple bending, their long-term mechanical durability remains a challenge. As the number of bending increases, the performance of the device may gradually decline. Perovskite materials are less stable in the presence of moisture and oxygen, which affects long-term stability. More advanced packaging and material optimization techniques are needed to address this issue.

2.2. Organic flexible solar cell

Organic photovoltaics (OPVs) have attracted much attention over the past decade because of their potential to address energy demands and environmental issues caused by the burning of fossil fuels. The development of OPVs has resulted in a significant increase in power conversion efficiency (PCE), from around 3% to over 15%. This improvement has been driven by a better understanding of photovoltaic mechanisms, including advances in chemical structural patterns and device architecture [7].

2.2.1. Advantage of organic flexible solar cell

Semi-transparent and flexible OSCs have been developed quickly. Thus far, the maximum energy conversion efficiency of semi-transparent OSCs has been 7.7%, while the maximum energy conversion efficiency of flexible OSCs has exceeded 10%. Additionally, the average visible light transmittance of these OSCs is 37% [8]. Therefore, organic materials have high light absorption capacity and can effectively absorb sunlight at a thin layer thickness, improving energy conversion efficiency. Besides, it has a low-cost manufacturing process since organic photovoltaic cells are usually manufactured using a low-temperature solution method, which is suitable for large-scale production, especially the roll-to-roll (R2R) process, which reduces production costs [9]. By changing the chemical structure of organic materials, their band gap can be adjusted, the light absorption range can be optimized, and the optoelectronic properties can be enhanced.

3. Principle of photovoltaic

3.1. Inorganic Photovoltaic Panel

There are four main steps in the inorganic photovoltaic effect: Photon absorption: when sunlight strikes a semiconductor, the energy from the photon will be absorbed by the electrons in the semiconductor. Electron excitation: the electrons will jump from the valence band to the conduction band after they absorb energy which must be greater than the band gap energy of the semiconductor, and create electron-hole pairs. Charge separation: the electrons separated from their holes in the P-N junction(the region between the P-type and N-type materials) of the material. Current generation: the electrical field pushes the electrons toward the negative side and the holes to the positive side. After connecting these two sides to an external circuit, the electrons start to flow in the circuit and the current is generated.

3.2. Organic Potovoltaic Panel

In organic photovoltaic cell, there are Highest Occupied Molecular Orbital (HOMO) and Lowest Unoccupied Molecular Orbital (LUMO) instead of the valence band and conduction band. The mechanism of the organic PV cell is quite similar to the traditional silicon-based PV cell. It will also go through the process below. Light absorption: when the light hits the organic active layer of the OPV cell. The molecules will be excited leading to the formation of excitons which is bound electron and hole pairs. Exciton diffusion: the excitons generated in the active layer will diffuse to the interface between donor material and acceptor material. Charge separation: the excitons are split into free electrons and holes. The doner material donates the elections and leaves a hole behind. The acceptor material will accept the electrons. Current generation: the free elections and holes are collected by the electrodes after passing through different layers, creating an electric current.

3.3. Molecular Orbital theory

The photovoltaic effect involves several key steps, beginning with photon absorption in a material, such as an organic semiconductor. When light strikes the material, electrons are excited from the Highest Occupied Molecular Orbital (HOMO) to the Lowest Unoccupied Molecular Orbital (LUMO), creating electron-hole pairs (excitons). These excitons need to be separated to generate an electric current [10]. At the donor-acceptor interface, the difference in energy levels between the donor's HOMO and the acceptor's LUMO helps drive charge separation. The electron moves to the acceptor, while the hole remains in the donor. This movement of charge carriers creates an electric field, allowing for current generation. The efficiency of this process is influenced by factors such as the material's band gap and how well the charge carriers can be transported without recombining. In organic semiconductors, the HOMO represents the highest energy state that an electron can occupy, and the LUMO is the lowest state an electron can move to after excitation. The energy difference between these two levels determines the band gap and impacts photon absorption. Once separated, the electrons and holes must travel to their respective electrodes. The mobility of the charges, their ability to move without recombining, and the interface quality between the organic material and electrodes are crucial for the efficiency of a solar cell.

The process also involves overcoming challenges such as recombination losses, where electrons and holes recombine before reaching the electrodes, reducing the cell's efficiency. The document discusses using techniques like bulk heterojunctions, which blend donor and acceptor materials to maximize the interface area for exciton dissociation, improving overall performance. [1]

In the molecular orbital theory, the electron is not orbiting the nucleus. In fact, it actually is the probability density of the electron appearing which is equals to the square of the wave function. The wave function has a positive or negative value, when two molecules combine together, the wave function for the elections will also combine which means that constructive interference happens when the values for both atoms are positive or negative and destructive interference happened when the values for atoms are inversed. In constructive interference, the probability density of the election will amplify. This orbital is called a bond molecular orbital. Vice versa, in deconstructive interference the probability density of the election will cancel out and form a node. This orbital is called an antibonding molecular orbital. The highest Occupied Molecular Orbital is the bond molecular orbital which has the highest energy. The lowest Unoccupied Molecular Orbital is the antibonding molecular orbital which has the lowest energy. The electrons in the HOMO level will jump to the LUMO level after being excited by the photon. Since the LUMO level is an antibonding molecular orbital which is very unstable, the electrons are willing to drop back to the HOMO level which is a bonding molecular orbital that is more stable. The stability of the molecular orbital is determined by the probability density of the electrons. In bond molecular orbital, the wave function will constructive interference with each other and amplify so the probability density of the electrons will increase. Therefore, forming a more stable orbital.

4. Applications

Integration into smart clothing and fitness trackers to provide renewable energy for powering sensors and devices so it is possible to provide lightweight solar chargers for smartphones, tablets, and other devices, ideal for outdoor enthusiasts and travellers [11]. For instance, the flexible photovoltaic cell can be used as the raw material of clothes or umbrellas, changing the portable device while the user is still moving. The technology has military applications such as Portable Solar Kits. The Kit can provided to soldiers so they can charge their communication equipment in the field without having to carry extra batteries [12]. Agricultural applications of the technology can be solar greenhouses. Greenhouses with flexible solar panels on roofs to power climate control systems and irrigation [12]. The flexible photovoltaic cell can be used as the material of construction. For example, Solar Windows and Solar Facades. The former can make the window glass generate electricity while allowing natural light, and the latter allows the architecture to pursue environmentally friendly clean energy and aesthetics at the same time [12]. The technology enables smart city infrastructure by building solar streetlights and bus stops. The street light is powered by flexible solar panels to illuminate public spaces sustainably. The bus stops provided temporary shelters equipped with solar panels to provide lighting and charge mobile devices for commuters.

5. Conclusion

Organic photovoltaics (OPV) and flexible perovskite solar cells (F-PSCs) still face challenges in long-term stability. Despite the portability of OPVs, their materials are sensitive to moisture and oxygen, resulting in performance degradation. F-PSCs, while making progress in efficiency (the highest efficiency is 19.11%), have also been shown to be less stable than rigid cells in humid environments. Besides, the highest conversion efficiency of OPV is usually between 10% and 15%, which is lower than the 19.11% of F-PSC and the 24.2% of rigid perovskite. In order to be competitive in the market, both OPV and F-PSC need to further improve their efficiency to approach the level of glass-based rigid cells.

In summary, both organic photovoltaics (OPV) and flexible perovskite solar cells (F-PSC) show great potential in technology. Despite the current challenges of efficiency, stability and manufacturing cost, these obstacles are expected to be overcome with the continuous development of materials and technologies. OPV shows good application prospects in portable and wearable devices due to its lightness and low cost, while F-PSC has important value in the wide application of building integration and renewable energy.

In order to promote the development of these two technologies, it is recommended that the government and scientific research institutions strengthen support for related research, and encourage innovation and technology transformation. At the same time, enterprises should strengthen cooperation and jointly promote the commercial application of technology to achieve the widespread popularization of renewable energy.

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