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Effect of different materials on the performance of flexible organic solar cells

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Abstract. In recent years, in order to solve the shortage of energy resources, organic solar cells have developed rapidly, and the photoelectric conversion efficiency has exceeded 16%. The development of organic solar cells is of great significance to the development of portable devices and the large-scale use of solar power generation in the future. The research of new materials is the key factor in the development of flexible organic solar cells. To develop large-area flexible organic solar cells, it is necessary to develop materials with better comprehensive performance. Now, new progress has been made in new flexible organic materials, which further improves the efficiency of flexible organic solar cells. This review mainly focuses on the analysis of the impact of representative flexible organic solar cell materials on the various of performances of photovoltaic cells in recent years and the prospects for the development of high-efficiency organic solar cells and the main research directions in this field in the future.

Keywords: Organic solar cell, flexible OSCs, flexible electrode, flexible organic material.

1. Introduction

In recent years, the rate of exploitation of fossil fuels in the world has increased day by day. The use of solar energy as a renewable energy is the best way for human’s sustainable development. The energy supply of the sun is large and stable. If solar energy can be utilized efficiently, the burden of human energy can be greatly reduced. Although the inorganic solar cells prepared with silicon as the main material have been put into use in large quantities, there are still many shortcomings in this kind of solar cells. Flexible organic solar cells have many advantages in addition to inorganic solar cells. Compared with inorganic solar cells, organic solar cells have the advantages of more environmental friendliness, more available fields and lower costs. Due to its excellent properties, the research on new flexible solar cells is growing day by day.

After decades of research, researchers have made considerable progress in the efficiency of organic solar cells. In 1956, Tang used phthalocyanine and perylene imide to prepare a double-layer organic solar cell with a photoelectric conversion efficiency of 1%, taking the first step in the research and preparation of organic solar cells [1]. The Nobel laureate Heeger designed the polymer-fullerene system using polyphenylacetylene (MEH-PPV) and fullerene derivatives ($PC_{61}BM$) in 1995, which was widely used in the preparation of organic solar cells [1]. So far, the photoelectric conversion efficiency of polymer organic photovoltaic cells has exceeded 16% [2]. Such polymer materials can be roughly divided into polystyrene (PPV), triphenylamine (TPA), benzodithiophene (BDT) and pyrrolidine dione (DPP). In addition, a new type of flexible electrode: silver nanowire flexible transparent electrode has become one of the most ideal transparent electrode materials for flexible organic solar cells (FOSC) constructed on plastic substrates due to its excellent conductivity, transparency and excellent mechanical flexibility [3]. Because FOSC has excellent flexibility, it can be integrated with wearable devices to provide energy for small electronic devices and use photovoltaic power generation in a wider range of fields [3].

Although the research on the manufacturing materials of flexible organic solar cells has developed steadily, which has gradually improved the efficiency of organic solar cells, there is still a certain gap in the photoelectric conversion efficiency compared with the relatively mature monocrystalline silicon solar cells, and there are still many immature technologies in the preparation of materials, structural stability, mass production. Even so, flexible organic solar cells are still an important research object for researchers in the field of photovoltaic power generation. This paper reviews the effects of different substrate materials, different electrode materials and different active layer materials on the properties of organic solar photovoltaic cells.

2. The history and development of flexible organic solar cells

Solar cell-related research can be traced back to as early as the 1950s and has continued to evolve and change since then. Now, this research is more commonly used in silicon-based solar cells, but such cells must be processed into hard, slab-like panels, which are not convenient for application in many conditions, so people will turn to the development of FOSCs. Research into organic polymer solar cells emerged in the 1960s, and flexible organic solar cells are a type of thin-film solar cell and are technologically advanced, high performance, cost effective and versatile. Flexible organic solar cells have broad application prospects in wearable electronic devices as well as photovoltaic building integration because of their high efficiency, light weight, foldability and rich colour [4].

3. The basic principle of flexible organic solar cells

The basic working principle of flexible organic solar cells is almost the same as that of ordinary organic solar cells, both of which are semiconductor devices that convert light energy into electricity according to the photovoltaic effect, thus realizing solar power generation, and their basic working principle is shown in Figure 1 [5]. The general principle is described below. When receiving light, the donor material absorbs photons and undergoes electron transition, i.e. electrons leap from the HOMO orbitals to the LUMO orbitals. After the electron transition, the HOMO orbitals holes bound with the electrons in the LUMO orbitals to produce excitons, and then the excitons diffuse and separate at the donor/acceptor junction to produce free charge electrons, i.e. positive and negative carriers. Finally, the positive and negative carriers are transported to the cathode and anode respectively, and are collected by the electrode to produce current.

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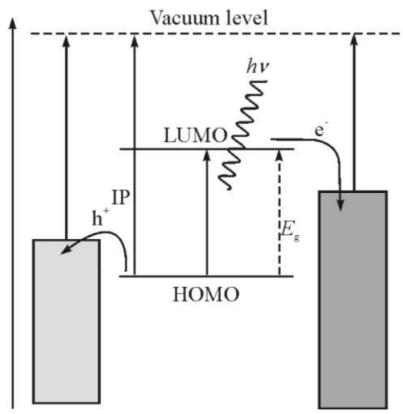

Figure 1. The basic physical process of the flexible organic solar cell.

4. The structure of flexible organic solar cell

The structure of a flexible organic solar cell is also consistent with that of a normal organic solar cell, as shown in Fig. 2, where the FOSC usually consists of a transparent encapsulation layer, anodes and cathodes, an electron transport layer, an active layer, a hole transport layer and a flexible substrate [6]. It is worth mentioning that the encapsulation layer, the anodes (for inverted structure) and the flexible substrate are generally made of materials with high light transmission, which results in a higher light absorption and a lower light loss rate. Commonly used transparent flexible substrates include metallic substrates and plastic flexible substrates. ITO electrodes, which are commonly used in solar cells, are not that commonly used in flexible organic solar cells because of poor flexibility and high brittleness higher cost and lower efficiency. As a result, FOSC electrodes are generally made from highly corrosion-resistant transition metals, or even anodes made from non-metallic transparent materials such as carbon nanomaterials.

Currently, the laboratory focuses on optimising the performance of FOSCs by optimising the materials used to produce the cell substrate, anode, cathode and the active layer. The main objective is to improve the conversion efficiency and enhance the stability of the FOSC, as well as to achieve higher production efficiency so that better performing FOSC devices can be mass production and put into use. The following discussion focuses on the impact of the materials used in the various FOSC structures on the performance of the devices themselves.

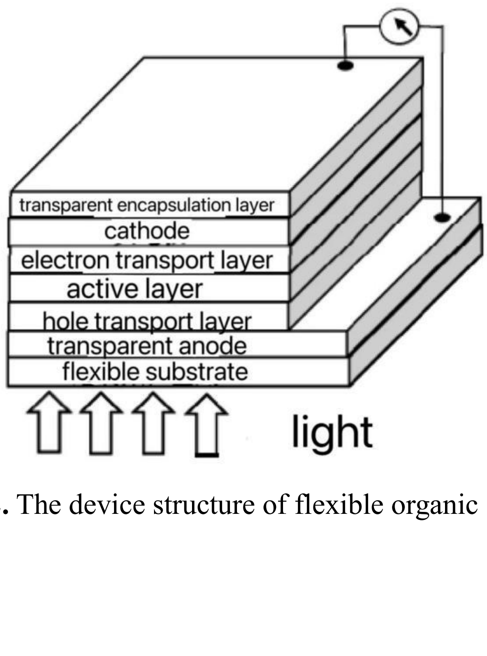

Figure 2. The device structure of flexible organic solar cell.

5. Influence of different substrate materials on the performance of FOSCs

The choice of material for the flexible substrate has a significant impact on the performance of the FOSC. The commonly used substrate materials are flexible metals and organic polymer materials (e.g. polyethylene terephthalate (PET), polyethylene terephthalate (PEN), etc.). Moreover, the flatness and temperature resistance of the material will directly affect the compatibility between the substrate and the electrodes. And when the compatibility is poor, it can reduce the performance of the cell or even make the whole device fail [6].

Unlike dye-sensitised solar cells (DSSCs) with conductive glass substrates, flexible dye-sensitised solar cells (FDSSCs) with conductive plastic substrates or metal substrates have certain advantages in terms of weight, size, transportation, mounting and production in roll-to-roll processes, i.e. a wider range of applications and suitability for large-scale continuous production [7]. FDSSCs with conductive plastic substrates are more likely to produce photovoltaic effects due to their high light transmission, low surface resistance and good chemical stability [7]. Metal substrates, on the other hand, can be sintered directly to the electrode material, thus increasing the bonding between the substrate and the electrode, and commonly used metal substrates, such as metallic titanium foil, have low resistance and good electron collection capability, thus increasing the conversion efficiency, but the widespread use of such substrate materials is limited by their high price.

In the case of flexible chalcogenide solar cells, when plastic (mainly PET and PEN) is used as the substrate, the solar cell device has good light transmission and good chemical and thermal stability, but the plastic substrate itself is not conductive, so this type of substrate needs to be used together with conductive films [8]. When metal is used as the substrate, due to the nature of the metal itself, the flexible organic solar cell shows corrosion and high temperature resistance When metal is used as the substrate, flexible organic solar cells show resistance to corrosion and high temperatures and do not have a major impact on efficiency when bent, but such substrate materials have disadvantages such as high mass, poor plasticity, high partial efficiency and high price. In addition to the above two commonly used substrates, other materials with good flexibility and light transmission are also used as substrate materials, such as ultra-thin willow glass, which is used as a substrate for FOSCs with good resistance to high temperatures and a low coefficient of thermal expansion, in addition to the properties mentioned in the previous section (good light transmission) [8].

6. Influence of different electrode materials on the performance of flexible organic solar cells

Conventional inorganic solar cells often use ITO electrodes, but these electrodes are prone to peeling off during annealing and are more expensive, and the performance of the device will change after peeling, resulting in higher production costs and lower efficiency of the photovoltaic effect. Therefore, FOSCs usually do not use flexible ITO as electrodes, but other materials that are more suitable, such as graphene electrodes and nano-silver grid electrodes. Flexible organic solar cells tend to use electrode materials with good light transmission, because the higher the light transmission, more light will reach the active layer through the transparent material, which makes the light loss smaller and the conversion efficiency higher.

Professor Yongsheng Chen's team has used a one-step method to produce a flexible transparent electrode with a "lattice-like" structure of silver nanowires, which has excellent properties such as high conductivity, low square resistance, high light transmission, high stability and smooth surface. The photovoltaic efficiency of the flexible organic/polymer solar cell fabricated with this electrode has set a new record in the literature [9]. In addition, his team's research has shown that devices using the transparent electrode prepared by the team have comparable performance to devices using commercial ITO glass electrodes. In addition, the FOSCs using this electrode showed excellent mechanical properties, i.e. their efficiency remained above 95% of the initial efficiency after being bent several times in the experiment [9].

When using carbon nanomaterials such as graphene as the electrode material, F-PSCs based on flexible substrates also have a certain degree of bending resistance and higher photovoltaic performance due to the high transparency, flexibility and good electrical conductivity of the carbon nanomaterials themselves. However, graphene is generally prepared using chemical vapour deposition, which makes it more expensive. F-PSCs, on the other hand, have good electrical conductivity, optical transparency and stability when using metallic materials such as silver nanowires (Ag-NWs) as electrode materials [8][10], also due to the nature of the silver nanowires themselves. Some new flexible bottom electrodes (e.g. PEDOT: PSS with high electrical conductivity, high light transmission and high coverage [10]) of F-PSCs have good resistance to bending, but are susceptible to moisture erosion and are acidic, thus leading to poor device stability [11].

7. Influence of different active layer materials on the performance of flexible organic solar cells

In addition to the selection of the substrate and electrode materials will have an impact on the performance of the FOSC, the different properties of different active layer materials such as stability and energy level will also have an important impact on the performance of the FOSC. In other words, the use of suitable active layer materials plays a crucial role in improving the performance of the devices.

The active layer consists of a donor and an acceptor material. Conventional flexible organic solar cells generally use fullerenes as the acceptor material and poly-thiophenes as the donor material, which have a unique structure and photovoltaic properties. Fullerene materials can be classified into hollow fullerenes, fullerene derivatives and embedded metal fullerenes based on their structure [12]. Fullerene materials have high electron affinity and can therefore be used in quantum dot solar cells as p-type dopants to dope PTAA, effectively promoting hole extraction and improving device performance [13]. It has been shown that when fullerenes are used in chalcogenide solar cells (F-PSCs), their unique structure can prevent the ion migration of chalcogenide, thus facilitating the reception and transport of charge during the reaction, which in turn improves the photoelectric conversion efficiency and stability of the cell [14]. However, the energy level and chemical structure of fullerene-like molecules are not easily tunable and aggregation is strong, which also greatly limits the development of organic solar cells. In contrast, non-fullerene materials with low cost and flexible tunable molecular energy levels and chemical structures have received widespread attention. FOSCs with non-fullerenes (e.g. pyrroloxypyrrolidone (DPP), perylenediimide (PDI)) as active layer materials have higher photovoltaic conversion efficiencies compared to equivalently conditioned fullerene materials. In addition to the two materials mentioned above, organic small molecule photovoltaic materials are also often used as acceptor materials for FOSCs, which are lighter in weight and lower in cost, stable and easy to prepare, but have lower mobility and limited photovoltaic conversion compared to other materials. The high ductility of the film and the improved thermal storage stability of the device were achieved by introducing a polymer acceptor into the system, which has considerable practical applications in flexible organic solar cells. In 2022, Ge Ziyi, a researcher at Ningbo Institute of Materials, China, improved the fracture tensile strain of the active layer film by introducing polymer receptors into the system, making the film have high ductility, and improving the thermal storage stability of the device, which has quite practical applications in flexible solar cells [15].

Five main types of donor materials are often used: oligothiophenes, polyphenylene vinylenes (PPVs), triphenylenes (TPAs), benzodithiophenes (BDTs) and pyrroloxypyrrolidines (DPPs). This paper focuses on the influence of the first three materials on the performance of FOSC. Oligothiophenes are one of the most commonly used donor materials for solar cells because of their superior electronic properties and chemical stability, as well as their simple structure and ease of synthesis, which facilitates mass production. Oligothiophene-based materials have been making breakthroughs in performance, and in 2021 Hou et al. presented one of the highest values obtained for devices based on oligothiophene receptors [16]. Early OSCs used PPV-like materials as donor materials, but research on this class of materials entered a trough because of the material's inherent disadvantages of narrow absorption range and wide band gap, resulting in low energy conversion efficiency and no possibility of improvement for the time being [17]. TPA materials with a unique helical structure are characterised by their ion transport efficiency and therefore POSCs with TPA as a donor material have excellent photovoltaic performance, while BDT materials have a symmetrical spatial structure and are large in size, thus improving charge migration efficiency. Therefore, the conversion efficiency of FOSC can be improved. DPP materials have excellent photovoltaic properties due to their high light absorption efficiency, good ageing resistance and improved exciton migration [17].

In addition to the above materials there are a large number of new materials that have been developed, but the development and development of photovoltaic devices must take into account the photoelectric conversion efficiency and cost, inexpensive, efficient, and can be put into mass production and use of materials is the ideal material people pursue. For some of the new materials that have not been used in practice and are not widely recognised, they are not discussed in detail in this paper.

8. Conclusion

Flexible organic solar cells have many advantages, such as lighter weight and wider application. In recent years, the research on organic solar cells with different materials has significantly improved the efficiency of small area organic solar cells. This paper mainly reviews the different properties of organic solar cells made of different materials, and finds that the different materials have a certain impact on their application fields and photoelectric conversion efficiency. The summary is as follows:

1. Substrate material: FOSC needs substrate material with high flatness and temperature resistance to maintain stable performance.

2. Electrode materials: graphene and nano-silver grid electrode are more suitable electrode materials for manufacturing FOSC than ITO electrode due to low light loss and high flexibility.

3. Active layer materials: FOSC using non-fullerene materials has higher power conversion efficiency. Organic small molecular photovoltaic materials have the advantages of high quality, low cost and high stability. As for different donor materials, oligothiophene materials have excellent performance and are conducive to large-scale production; TPA has unique structure and high ion transfer efficiency; BDT material can improve charge transfer efficiency, while DPP material has high light absorption efficiency and better exciton transfer performance.

Although the research on flexible organic solar cells has received extensive attention and in-depth research from researchers around the world in recent years, and the maximum efficiency of organic solar photovoltaic cells has also been continuously improved, the application of flexible solar cells is still in the small device. There are still many aspects to be studied in order to make it more widely used and truly commercialized. In this regard, this paper puts forward several main research directions in the future:

1. Deeper research on the durability of materials. It has been mentioned many times above that the performance of some materials will be reduced by different degrees in the face of environmental effects such as high temperature. Therefore, more stable transport layer materials need to be invented in the future to improve the stability of photovoltaic cells.

2. Cost reduction of materials as much as possible. The polymer materials mentioned above are often complex in process and low in yield, resulting in high cost and difficult to realize large-scale preparation. Therefore, new organic materials with simpler structure and easier preparation need to be developed in the future to reduce manufacturing costs.

3. Optimization of preparation method. At present, many cutting-edge high-efficiency flexible organic solar cell materials are prepared by spin-coating method, which cannot meet the large demand for solar cells today. In the future, the processing technology needs to be optimized to support large-scale production.

To sum up, flexible organic solar cells in the future are expected to overcome the above-mentioned obstacles to large-scale application, successfully realize real large-scale commercialization, and make unparalleled contributions to human energy supply and natural protection.

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