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Research Progress of Flexible Perovskite Solar Cells

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Abstract: Since the perovskite material achieved 9.7 % energy conversion efficiency in solid-state sensitized batteries in 2012, its excellent photoelectric performance has quickly attracted global attention. In just 12 years, the efficiency of perovskite photovoltaic devices has jumped to 25.6 %, surpassing that of traditional thin film solar cells. With the development of flexible electronic technology, flexible perovskite solar cells (F-PSCs) have become a research hotspot, but their efficiency (currently up to 24.90 %) is still slightly lower than those of rigid devices, and facing many challenges. This paper reviews recent progress in enhancing the Power conversion efficiency (PCE) and flexibility (mechanical stability) of F-PSCs. It focuses on advancements in the development of flexible transparent metal oxide electrodes (TMOEs), optimization of charge transport layers, low-temperature fabrication techniques for thin film materials, grain control, and grain boundary modification. The aim is to facilitate performance improvements and promote the widespread application of F-PSCs.

Keywords: F-PSCs, PCE, flexible transparent metal oxide electrodes, low-temperature fabrication techniques, grain control, grain boundary modification

1. Introduction

Under the background of global climate change and increasing environmental pressure, the development and utilization of new energy sources has become the spotlight of the international community. As an abundant and clean energy source, the efficient conversion technology of solar energy, especially the large-scale development of solar cell technology, is of great significance to the realization of this goal. Solar cells, as the core devices for converting solar energy into electricity, have evolved to include various types such as monocrystalline silicon, polycrystalline silicon, thin film solar cells, and novel perovskite solar cells. Research efforts are focused on exploring new materials and structures that offer higher efficiency, lower costs, and broader adaptability to enhance the performance and application potential of solar cells (SCs).

Perovskite solar cells have rapidly emerged as a research hotspot in the field of solar energy due to their exceptional photoelectric conversion efficiency and straightforward fabrication processes. In 2012, Kim, Hui-Seon 's team used perovskite materials in solid-state sensitized batteries to achieve an Power Conversion Efficiency (PCE) of 9.7 %, [1] which sparked widespread interest among researchers in perovskite materials. Perovskites possess several advantages, including a high light absorption coefficient, long carrier diffusion lengths, and tunable band gaps. In just 12 years of development, photovoltaic devices based on perovskite materials have reached the PCE of 25.6%, [2] surpassing the PCE of thin film crystalline silicon (21.2%), copper indium gallium selenide thin film

SCs (23.35%), and cadmium telluride thin film SCs (21.0%). This advancement marks significant progress in the efficient conversion and utilization of solar energy resources [4].

At present, with the rapid development of flexible electronic technology, the demand for deformable solar cells capable of bending and folding is increasing. Researchers have combined perovskite materials with flexible substrates to develop flexible solar perovskite cells (F-PSC). Flexible solar perovskite cells not only inherit the efficient photoelectric conversion performance of perovskite materials, but also have good mechanical flexibility [5], low processing energy consumption [6] and high economic effect [7]. Flexible perovskite solar cells can adapt to a variety of complex and changeable installation environments, such as curved buildings, wearable devices, portable electronic products, etc. This innovation not only broadens the application field of solar cells, but also provides new possibilities for the widespread popularization and efficient use of solar energy.

Although flexible perovskite solar cells have a broad application prospect, there is still a gap in PCE and stability compared with rigid perovskite solar cells. In addition, new low-temperature processing technologies need to be explored in the production process due to the limitation of processing temperature by the choice of substrate flexible materials. At present, the highest PCE of PCS is 25.6 % [2] while the highest PCE of F-PSC is 24.90 % [3] which is mainly due to the different physical and chemical properties of plastic substrates and glass substrates. Plastic substrates have certain limitations on processing temperature, and it is difficult to prepare high conductivity transparent metal oxide electrodes (TMOEs) and charge transport layers by conventional high-temperature annealing methods. The optical transmittance of plastic substrate is lower than that of glass substrate, which also affects the PCE of F-PSC. In terms of environmental stability, plastic substrates are not fully resistant to water and oxygen penetration, which can cause irreversible damage in long-term operation under atmospheric conditions. Therefore, there is an urgent need to find ways to improve their photoelectric conversion and stability.

Comprehensively, this paper explores the flexible scheme of TMOEs, the structural optimization of carrier transport layer and the low temperature improvement strategy from the perspective of improving the PCE and flexibility of F-PSC.

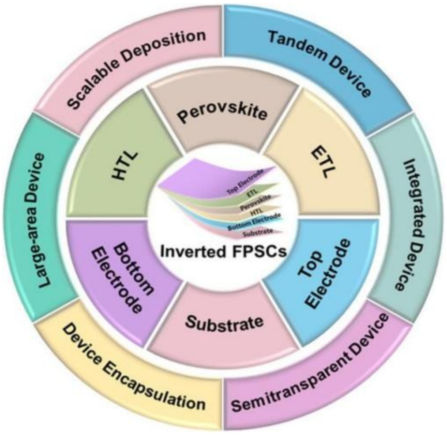

Figure 1: The functional layers of flexible perovskite solar cells [8]

2. Challenges for F-PSC

The basic structure of PSC consists of substrate material, bottom electrode (transparent conductive layer), electron transport layer (ETL), perovskite photoactive layer, hole transport layer (HTL), top electrode (The ETL and HTL positions of the p-i-n structure are opposite to those of the n-i-p, as shown in Figure 1). To complete the conversion of PCE from rigid to flexible to achieve a broader application scenario and field, this process faces many important challenges.

When considering the conditions that need to be met by each part of the F-PSC, it is necessary to make the six components of the F-PSC flexible, i.e., to achieve bending and stretching, which leads to the concepts of bending and tensile stability, where the material itself does not suffer from damages and failures, such as cracks and breaks, and maintains the respective functions of each part after multiple bending and stretching. Many F-PSC structures contain inorganic materials, including TMOEs, ETL, and HTL, as well as perovskite films, which are not conducive to achieving stable flexibility. To realize the transition from rigidity to flexibility, there are two ways to achieve it. The first way is to excavate new materials with flexible properties as the structural layer of PSCs (e.g., development of polymer materials), and the second way is to improve the structure of the original functional materials through the optimization of the preparation process, so as to make them flexible while possessing the original functions.

Consider the challenges of achieving overall device flexibility for F-PSCs. First of all, the limitations of the overall preparation process due to changes in the physical and chemical properties of the materials during their modification should be considered. In the preparation process, the commonly used F-PSC substrate materials, PET and PEN, have good ductility and high chemical stability, but their Tg temperatures are low and cannot be higher than 150 °C during the entire preparation process. The electrical properties of TMOEs (such as ITO) are closely related to the substrate deposition temperature. The microstructure of ITO without high-temperature heat treatment is usually amorphous or partially crystallized, so the electrical properties are poor. Therefore, it is necessary to find a solution to prepare transparent conductive materials at low temperatures or to replace them with new materials that can be prepared at low temperatures and have similar functions. Secondly, the problems caused by changes in the conditions of use should be considered. Under the action of bending stress and tensile stress, the stress distribution between the various bending layers of the device is different, and the degree of stretching is also different. This requires different parts to have different requirements for ductility and flexibility, and to match each other to ensure that the articulation between the layers.

3. Research progress of F-PSC

In the following, the research progress in recent years in improving the PCE and flexibility (mechanical stability) of F-PSC thin film materials will be introduced from three aspects: the flexible scheme of TMOEs, the structural optimization and low temperature improvement strategy of carrier transport layer and the grain regulation and grain boundary modification of F-PSC thin film materials.

3.1. The flexible scheme of TMOEs

Its excellent transparency and conductivity are widely used as transparent electrode materials for PSC. However, due to the traditional ITO itself is an inorganic material, poor ductility and flexibility, it is difficult to be directly applied to flexible electronic devices; at the same time, the conductivity of ITO is affected by the precipitation temperature, the F-PSC flexible substrate processing temperature Tg limitations make ITO cannot be prepared through high-temperature precipitation process to obtain excellent electrical conductivity, which seriously affects the device's PCE. Therefore, it has become a mainstream research direction to find a flexible transparent electrode (FTE) with excellent conductivity, light transmission and flexibility, and low cost to replace ITO materials. These new types of FTE include metal substrate [9], carbon-based materials (carbon nanotubes (CNT) and graphene),[10] conductive polymer (CP),[11] composite,[12] etc. The metal-based materials inherently have good conductivity and processability, and the metal preparation processes are usually straightforward and mature, facilitating large-scale production and cost control. The following will focus on such material.

Metals (such as gold, silver, etc.) exhibit exceptional electrical conductivity, making them among the most widely utilized materials in the realm of electronic devices. However, their lack of transparency hinders the entry of light. A certain degree of transparency can be obtained by reducing the thickness of the metal electrodes, but their conductivity and the transparency of the thin-film metal electrodes are constrained by each other. By designing their arrangement, metal nanowires can make the electrodes conductive in one direction and transparent in the other, as well as giving the electrodes a degree of flexibility. It has become one of the most likely materials to replace ITO, and silver nanowires have also been rapidly developed. [13]

The length of metal nanowires (MNWs) synthesized by chemical methods is typically less than 50 mm, and there are residual surfactants and impurities present during the synthesis process. These problems hinder charge transfer and limit the conductivity of MNWs based TCEs.[14] To enhance the performance of silver nanowire (AgNW) networks, various strategies have been implemented. These include increasing the length of the nanowires to extend the transmission distance, reducing their diameter to minimize light scattering, and annealing the nanowire junctions to decrease electrical resistance. In addition, the adhesion between these nanowires and the substrate is usually insufficient.[15] Although thermal annealing, electric laser welding,[16] plasma welding,[17] both chemical welding and mechanical pressing techniques [18] can be employed to decrease the contact resistance at the cross junctions and enhance the adhesion of the nanowires to the substrate. N. Burak Kiremitler. Nanofibers (NFs) were prepared on glass substrates by electrospinning a polymer solution composed of polyethylene oxide (PEO), polyvinylpyrrolidone (PVP) and particle-free silver ink (PEO/PVP-Ag). After annealing at 300 °C for 30 seconds, the synergistic combination of PEO and PVP achieves a high conductivity junction-free AgNFs network, which can produce a high-performance TCE with a sheet resistance of 1.9 V/sq and a transmittance of 90 % (Figure 2).[19] Liwen Zhang prepared ultra-fine and ultra-long Ag/CNFs by electrospinning as a new type of conductive material, and partially replaced AgNWs to prepare hybrid transparent conductive films (TCF).[20] When the fiber diameter of Ag/CNFs is about 30 nm, when the degree of substitution is 28.3 %, the sheet resistance of the prepared TCF is 83.0 Ω/sq, and the transmittance is 87.5 %. Following adequate heat treatment and acid leaching processes, the conductivity can be further enhanced to reach a value of 50.0 Ω/sq. In addition, the prepared hybrid TCF has good flexibility, strong adhesion, good high temperature resistance and strong acid resistance. Using $AgNO^3$-doped polyvinylpyrrolidone (PVP) composite nanofibers as raw materials, AgNFs were synthesized by calcination reduction method using gas-assisted solution spinning method.[21] The AgNFs has a length of more than 2 mm and a diameter of nearly 200 nm.[22] The material possesses a small diameter and a high aspect ratio, making it suitable for large-scale synthesis of high-quality continuous silver nanofibers (AgNFs) as well as the production of 2D and 3D flexible conductors. There is a melting junction between the nanofibers. The AgNFs network as a transparent electrode exhibits high transparency, low sheet resistance (6 Ω sq-1 at 97 % transparency), and high flexibility.

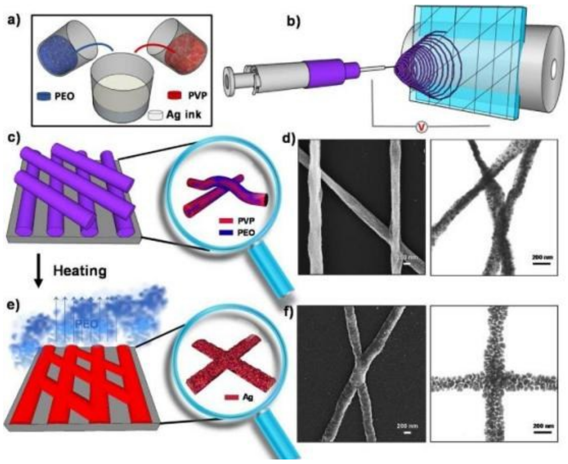

Figure 2: Fabrication of transparent electrodes using electrospun nanofibers (NFs) embedded with reactive silver inks. The process is illustrated as follows: a) preparation of the solution, b) electrospinning onto a glass substrate attached to a rotating collector, c) resulting NFs containing silver ink and a blend of PEO/PVP, d) SEM (left) and STEM (right) images of the NFs prior to annealing, e) removal of PEO from the NFs, leading to the formation of junction-free and continuous silver NFs through thermal annealing, f) [19]

Despite their advantages of low resistivity and straightforward preparation, metal nanowires face numerous challenges, including a trade-off between conductivity and transmittance, poor mechanical properties, weak adhesion to the substrate, high haze, and elevated nodal resistance.[23] Li combined Ag mesh with PEDOT : PSS, which can increase the conductivity of transparent electrodes and improve the adhesion to the substrate, which makes the PCE reach 14 %.[24] In addition, this flexible SC has excellent flexural durability, with the PCE value remaining above 95.4% even after 5,000 full flexural cycles at a radius of curvature of 5 mm.

3.2. Low temperature preparation strategy of carrier transport layer

3.2.1. Low-temperature

ETM. In general, n-type materials that can be used as ETLs in PSC are organized into two categories: organic and inorganic. Organic ETMs have the advantages of low temperature, flexibility and large-area fabrication process. Organic n-type materials such as fullerene[25], graphene[26], graphyne[27] and their derivative [28] have been widely developed as ETLs. However, they generally exhibit weak environmental, thermal, and mechanical stability. To address this, inorganic n-type materials, particularly inorganic metal oxides (MOs) like TiO2, ZnO, and SnO2, are frequently utilized as cost-effective electron transport layers (ETLs), which exhibit excellent electronic properties, versatility, high stability and outstanding device performance.[29]

At present, PSC mainly has mesoporous structure and planar structure (Figure 3).[30] The mesoporous TiO_2 (mp-TiO_2) layer was first used as a scaffold in PSCs, and then other MOs (including Al_2O_3, [31] ZrO_2 [32], ZnO [33], SnO_2[34]) were developed to replace TiO_2. In mesoporous-structured perovskite solar cells (PSCs), mesoporous n-type metal oxide (MO) electron transport layers (ETLs) not only function as structural scaffolds but also play a crucial role in the efficient extraction and transportation of charge carriers. To date, optimization of charge transport layers and perovskite absorbers has been pursued through compositional design, morphological control, and interfacial engineering. Commercial anatase TiO_2 nanoparticles (20 ~ 50 nm) have been widely used in DSSCs due to their mesoscopic structure. However, the phase transition from amorphous titanium dioxide to anatase phase can only be achieved by a warm sintering process (~ 500 °C), which greatly limits their application on flexible plastic substrates.

The first planar PSC was constructed by the Snaith team, who removed the mesoporous structure from the typical mesoscopic superstructure PSC, vapor deposited perovskite on the dense TiO_2 ETL as the absorption layer, and successfully fabricated a complete planar PSC with 15.4 % high PCE. It has been demonstrated that perovskite absorbers can achieve peak efficiency in a streamlined device architecture, obviating the need for intricate nanostructures.[35]

The existing low-temperature synthesis methods can be categorized into two distinct groups. [36]: a) Solution treatment, which involves the use of precursors and colloidal dispersions for deposition through methods like spin coating, printing, and chemical bath deposition. b) Vapor deposition, which utilizes solid or liquid precursors or target materials and encompasses techniques such as atomic layer deposition (ALD), magnetron sputtering, and electron beam evaporation.

The key points of the method for preparing TiO2 ETL on a flexible plastic substrate at low temperature are: a) Low-temperature deposition using vacuum-based thin film deposition systems (e.g., evaporators, sputtering, ALD). b) Deposition of well-crystallized TiO2 colloidal particles followed by treatment (e.g., UV treatment, low-temperature annealing).[37,38]

ZnO boasts a superior electron mobility compared to TiO2, along with a favorable energy structure characterized by a conduction band minimum (CBM) of -4.17 eV and a band gap of 3.3 eV. These attributes facilitate efficient electron extraction and transmission. Moreover, ZnO is relatively easy to synthesize and well-suited for preparation at low temperatures.[29] ZnO can be directly prepared through solution-based and vapor deposition methods at relatively low temperatures. These methods include spin coating, electrodeposition, hydrothermal growth, and atomic layer deposition (ALD). Kumar[33] published the first article using ZnO. He employed a ZnO dense layer formed via electrodeposition and ZnO nanorods grown through chemical bath deposition (CBD) as the electron transport layer (ETL) to fabricate a flexible solid-state perovskite CH3NH3PbI3 solar cell at a low temperature. This resulted in a power conversion efficiency (PCE) of 2.62%.

SnO_2 materials have been studied in the field of PSC in recent years due to their excellent photovoltaic properties and stability. The wide band gap of 3.6-4.5 eV and the small reflectivity of 2 contribute to the transmission of light.[29] Its transmittance of visible light can reach more than 90% or even 95%[39], which enhances the light absorption ability of the lens material. At the same time, the deep levels of the conduction and valence bands satisfy the requirements of electron extraction and hole blocking. Subbiah 's team[34] used nitrogen plasma to treat sol-gel coated tin dioxide films at temperatures close to room temperature, maintaining material properties comparable to those of heat-treated tin dioxide and achieving a PCE of 18.1%.The advantages of low-temperature treatment greatly expand the range of applications for SnO2. The Wang [40] team used the ion-enhanced atomic layer deposition (PEALD) to reduce the deposition temperature of SnO_2 to 100℃.The flexible PVSC with the best performance achieved a conversion rate of 18.36 %. Attempts have been made to enhance the charge-transport property of SnO2 ETL by doping it with metal ions or mixing it with graphene oxide.[41,42]

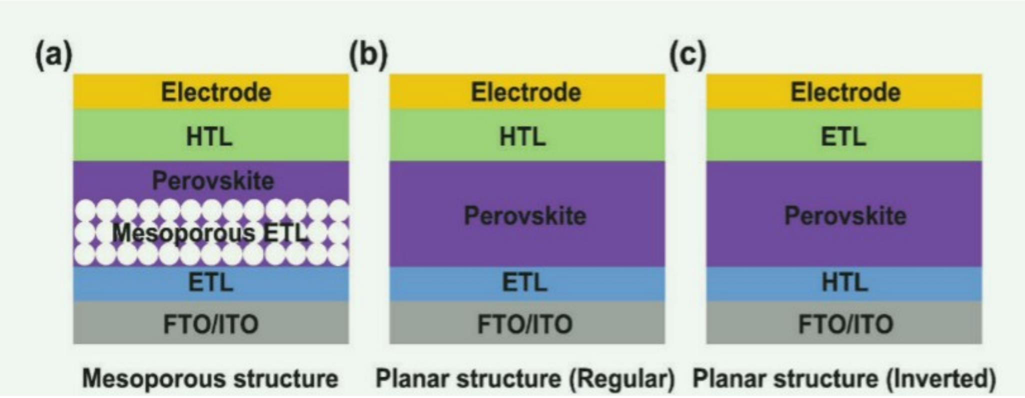

Figure 3: Typical structures of perovskite solar cells (PSCs) include: a) mesoporous structure, b) regular planar structure, and c) inverted planar structure [29]

3.2.2. F-PSC hole transport material

Effective hole harvesting avoids electron-hole pair recombination, thus ensuring high device performance. The amorphous organic small molecule Spiro-OMeTAD is widely used in the HTL of F-PSCs, which inherently has a low hole carrier mobility ($\mu \sim 1.69\times10^{-6}$ $cm^2 (Vs)^{-1}$) and conductivity. To enhance hole collection efficiency, Spiro-OMeTAD is typically doped with the p-type material, Bis(trifluoromethane)sulfonimide lithium salt (LiTFSI). This doping process increases its conductivity and facilitates hole transport through the oxidation of Spiro-OMeTAD.[43] Spiro-OMeTAD has the advantages of matching the band gap of perovskite materials and low temperature manufacturing, but spiro-OMeTAD is expensive, has a mediocre hole mobility, and has poor environmental stability.

Poly (3,4-ethylenedioxythiophene)/poly (styrenesulfonate) (PEDOT: PSS) as high electrical conductivity, can be processed into polymers in low-temperature solutions, and has good mechanical flexibility, which is widely used in flexible perovskite HTLs. The You[44] team constructed the structure of substrate/ITO/PEDOT : PSS/$CH_3NH_3PbI_{3-x}Cl_x$/PCBM/Al with PEDOT : PSS as HTL by low temperature (< 120 °C) solution treatment. A power conversion efficiency (PCE) of 11.5 % was achieved in a rigid substrate (glass / ITO), and a PCE of 9.2 % was achieved for a PET / ITO flexible substrate. PEDPT: PSS is often used in inverted flexible solar cells. The li[24] team used PEDOT : PSS as HTL and PCBM as ETL to fabricate inverted flexible solar cells using a hybrid electrode. Its PCE on Ag / conductive polymer flexible substrate can reach 14 %, and it can still maintain more than 95 % of the original efficiency after 5,000 times of complete bending. Acidic PEDOT: PSS corrodes indium tin oxide (ITO) and decomposes perovskites, leading to poor device stability. Hou [45] adopts MoO_3 / PEDOT: PSS bilayer structure. The insertion of a MoO_3 layer between the ITO and PEDOT: PSS not only enhances the hole extraction efficiency from $CH_3NH_3PbI_3$ to the ITO electrode but also eliminates any direct contact between the ITO and PEDOT: PSS. As a result, the maximum power conversion efficiency (PCE) of the obtained device reaches 14.87%. After being stored in dark ambient conditions for 10 days, the device retains 93% of its initial PCE.

Inorganic hole transport materials, characterized by their high mobility, low fabrication costs, and excellent chemical stability, have been employed as an alternative to the PEDOT: PSS layer in inverted perovskite solar cells. The Choy [46] team applied NIOx to the flexible substrate for the first time, so that the power conversion efficiency (PCE) of the device can reach 14.53 % without significant hysteresis. They realized the preparation of NIO_x HTL at room temperature by spin-coating NiO_x NC water-based ink onto a pre-clean ITO substrate and drying it naturally at room temperature to obtain nanostructures.

3.3. High quality perovskite film of F-PSC

Producing high-quality perovskite films on plastic flexible substrates that exhibit large grain size, low trap density, high coverage, and high crystallinity poses a significant challenge. The quality of perovskite films deposited on flexible substrates suffers due to the plastic substrates' characteristics of low surface energy, inadequate wettability, and propensity to wrinkle. Hence, the development of an appropriate perovskite precursor is imperative to enhance the quality of perovskite films deposited on flexible substrates. The morphology of the ABX_3 film plays a crucial role in achieving high-performance PSCs, and the adoption of a two-step deposition technique is advantageous for enhancing the morphology of the perovskite (ABX3) layer by promoting superior crystallization.[47] The primary two-step deposition techniques utilized for the fabrication of F-PSCs are spin-coating and spin-dipping. Specifically, the spin-spin deposition method involves initially spin-coating a BX_2 solution, followed by the spin-coating of an AX solution onto the BX_2 layer. [48] The spin-dipping deposition method entails immersing the pre-spin-coated BX_2 layer into an AX solution, facilitating a solid-liquid reaction to obtain the ABX_3 perovskite layer [49]. Liu [50] prepared $CH_3NH_3PbI_3$ layers using a two-step process. This includes spin-coating a PbI_2 layer on the ZnO surface and then immersing the substrate in a CH_3NH_3I solution. The $CH_3NH_3PbI_3$ tetragonal phase with a microcrystalline size of more than 75 nm was obtained. The large microcrystalline size can be used to increase the carrier mobility in the $CH_3NH_3PbI_3$ layer and reduce the recombination from defects and trap states. The flexible perovskite solar cell (F-PSC) fabricated using this perovskite achieved a notable power conversion efficiency (PCE) of 10.3%, accompanied by a photovoltage (Voc) of 1.03 V, a photocurrent density (Jsc) of 13.4 mA/cm², and a fill factor (FF) of 73.9%. In contrast, its glass-ITO-based counterpart exhibited an even higher PCE of up to 15.7%.

The chemical formula for perovskite is typically denoted as ABX_3, in which A represents an organic cation, such as cesium, methylammonium, ethylammonium, formamidine, or phenylammonium; B is a metal inorganic cation, including elements like Ge, Pb, Sn, Sr, or Bi, and its size is generally smaller than that of A; and X stands for any halide element, specifically iodine (I), chlorine (Cl), or bromine (Br) [51]. Therefore, there are various choices of materials for the formation of perovskite materials. In the optimization of perovskite structure, composition engineering is a very useful strategy to regulate the crystallization process of perovskite by optimizing the required proportion of different precursors, so as to obtain high-quality perovskite structure. A mixed iodine-chlorine perovskite $CH_3NH_3PbI_{3-x}Cl_x$ layer was used by You [52], a carrier with a long lifetime and good electrical properties. They mixed $PbCl_2/CH_3NH_3I$ at a ratio of 1: 3, spin-coated onto the PEDOT: PSS layer at 1500 rpm, and then annealed at 90 °C for 2 hours to obtain a uniform 340 nm perovskite film with some pinholes. The wider thickness ensures sufficient light absorption. Finally, devices based on glass/ITO rigid substrates can reach a PCE of 11.5% and devices based on polyethylene terephthalate (PET)/ITO flexible substrates can reach a PCE of 9.2%.

The choice of solvents and additives also affects the formation of perovskite films. MAPbI3 p-i-n PSC perovskite film was prepared by a two-step continuous deposition method.[52] The precursor solution of methylammonium iodide was enriched with the hydrophilic fullerene derivative known as [6,6]-phenyl-C61-butyric acid-(3,4,5-tris(2-(2-(2-methoxyethoxy)ethoxy)phenyl) methanol ester, or PCBB-OEG. This additive facilitated the formation of a high-quality perovskite film on both the hydrophilic poly(3,4-ethylenedioxythiophene)/poly (styrene sulfonic acid) and the hydrophobic polytriarylamine (PTAA) hole transport layers. Notably, the film exhibited a top-down gradient distribution of PCBB-OEG, boasting high crystallinity, minimal trap states, and a uniform morphology with dense grains. The structure of ITO/PTAA/perovskite film containing PCBB-OEG/[6,6] -phenyl-C61-butyric acid methyl ester/Al was expected to achieve a power conversion efficiency (PCE) of 20.2 %, and showed excellent stability. After exposure to high humidity environment for 300 hours, it can maintain 98.4 % of its initial PCE.

According to the different constituent materials, perovskites can be categorized into organic-inorganic hybrid perovskites and all-inorganic perovskites. Organic-inorganic hybrid perovskite is currently the most studied solar cell material in the field of solar photovoltaic cells. It has excellent flexibility, machinability, photoelectric properties, and stability. Dong 's research group [53] introduced a multi-functional olefin monomer 2,4,6-trivinyl-2,4,6-trimethylcyclotrisiloxane (V3D3) in-situ polymerization into perovskite, and achieved monomer enrichment by solvent annealing to induce phase separation between grains and polymers, resulting in in-situ cross-linking reaction between elastic crystals GB and increased grain size, achieving a flexible perovskite film structure with “grain-elastic grain boundary-grain” regionalization. In the tensile state, the grain of the reference film is destroyed, while the perovskite film doped with V3D3 molecules still retains the original grain structure. After 300 hours of continuous illumination with maximum power point output testing, the flexible cell still exceeded 83% of its initial efficiency and maintained 73% of its initial efficiency after 10,000 small radius bends.

4. Conclusions and outlooks

F-PSC has a broad application prospect and development space due to its flexibility, light weight and portability. In the development from rigid PSCs to F-PSCs, the study of material selection and production process from the substrate to the top electrode, and how to ensure good resistance to various deformations, is crucial to fabricate F-PSCs for different applications. In this paper, the flexibility of transparent electrodes is realized from the flexibility scheme of TMOEs. Strategies for low-temperature preparation of carrier transport layers are discussed to meet the usage conditions of flexible substrates. The methods of grain modulation and grain boundary modification of high-quality perovskite films are analyzed to improve the flexibility and efficiency of F-PSC functional layers. Although F-PSC has been fully developed in recent years, there is still a long way to go to achieve large-scale commercial production and application. At present, F-PSC is still difficult to be applied in daily life due to high cost and poor stability. Meanwhile, the large-scale integrated production technology of F-PSC and the module technology involving multiple sub-cells still need to be studied.

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