Development status of inverted perovskite solar cells

Sihan Lu[1, †], Jihui Xie[2, †], Xielin Yang[3, †], Guanlin Zeng[4, *, †]

[1]School of engineering and informatics, University of Sussex, Brighton, UK

[2]Warwick Mathematics Institute, The University of Warwick, Coventry, UK

[3]Queen Mary University of London Engineering School' NPU, Northwestern Polytechnical University, Xi'An, China

[4]Department of Materials Science and Engineering, University of Florida, Gainesville, USA

*Corresponding author: guanlinzeng@ufl.edu

†These authors contributed equall

Abstract: While the population has exploded, the world's energy demand has also risen exponentially. Energy pollution is also very severe. Therefore, it is urgent to increase the utilization of renewable new energy. Solar power has the greatest potential in the new energy sources. One kind of solar cell is the inverted perovskite solar cell (I-PSC). It has the advantages of simple device structure, high absorption coefficient, small hysteresis effect, and good defect tolerance. In this paper, the effects of electron transfer, hole transportation and manufacturing technology on the appearance of inverted perovskite-type solar cells are discussed, also the foreground of their commercialization is presented. It is believed these processes are a small step for ameliorating the photoelectric conversion efficiency and stability of these devices.

Keywords: Inverted perovskite solar cell, Electron transport layer, Hole transporting layer, Perovskite layer.

1. Introduction

Nowadays, with the population explosion and individual pursuit of high-quality life, world's energy demand is growing significantly. Accompanying with that, problems like greenhouse effect, water pollution become more and more severe. It is therefore urgent to go for reliable, cost effective and everlasting renewable energy. Among all new energy, solar energy has the largest potential. There is one type of third generation of solar cells called Perovskite solar cell (PSC). Its working principal is that the perovskite layer absorbs photons to form electron-hole pairs, electrons and holes are then absorbed to the corresponding electrodes respectively, and finally collected by the FBU. In these years, PSCs have been coming into people's sight more frequently because of their exceptional photoelectric properties such as long carrier transport lengths, large absorption coefficients, and steady defect tolerance, and solution processability [1]. Normally, there are two kinds of structures of perovskite solar cells, namely regular and inverted. Regular means that an n-type material covering the front electrode and a p-type material coating the back contact layer. Inverted has similar structure with regular type with an exchange of position of n-type and p-type material. The accredited power conversion efficiency (PCE) of regular and inverted perovskite solar cells (PSCs) are both more than 20%, which is competitive to other commercially available solar technologies like cadmium telluride (CdTe), polycrystalline silicon (p-Si), and so on. However, the issue of PSCs about stability and durability which have still not satisfied the requirement of commercialization to sustain the current photovoltaic technology have not been solved for decades. Therefore, it is reasonable that The perovskite phase transition process and the stability of PSCs under environmental, thermal challenges, lighting and have become the main areas of research on this topic. Under the premise of continuous improvement in PSC, it is likely to give human more ways of obtaining energy.

2. Brief introduction of Perovskite solar cell

2.1 Perovskite materials

Perovskite first specifically refers to CaTiO3 mineral, German mineralogist Gustav Rose is the first people who discovered it. After a long time of development, Chemical formula of perovskite structure material is become ABX_3, and now refers to a kind of crystalline materials, A,B and X are cations of different radii (A,B) and anions coordinated with B (X), respectively. Perovskite structure is shown in Figure 1.

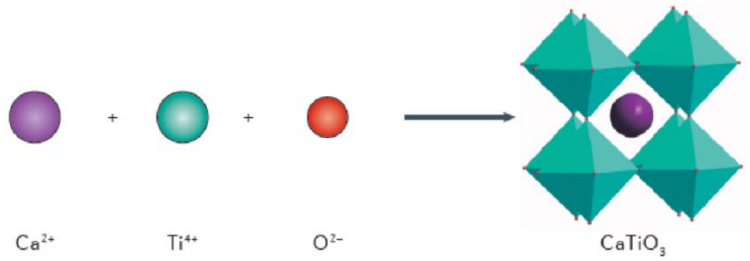


Figure 1. The detail crystal structure of the perovskite material.

Two properties in perovskite materials, namely, conduction band minimum (CBM), and the second valence band maximum (VBM), are different from those of conventional semiconductors. Take the band structure of $CH_3NH_3PbI_3$ calculated by Yan as an example, its contribution to the density of states of organic molecules is far lower than the band edge position [2]. This unique structure makes the perovskite has the direct regulation of forbidden band width, low exciton binding energy, high absorption coefficient, balance of bipolar carrier transport and the carrier diffusion length.

2.2 The basic structure of an inverted perovskite solar cell

In conventional perovskite-type solar battery, it is possible to classify the basic structure as transparent conductive glass (ITO/FTO), electron transport layer (ETL), perovskite-type light absorbing layer, hole transport layer (HTL), and metallic electrodes. The main difference between the inverted structure and the traditional structure is the exchange of ETL and HTL positions. In general, the cells made up of ITO conducting glass, HTL, perovskite optical absorption layer, ETL, and metal electrode (Au, Ag) are referred to as inverted or trans-plane perovskite solar cells, which can be seen in Figure 2.

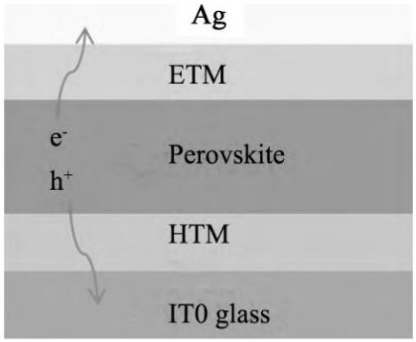


Figure 2. Inverted perovskite solar cell structure.

At present, the research on inverted perovskite solar cells mainly focuses on the material development of three functional layers, namely hole transport layer, solar cell absorption layer and electron transport layer, and the development of the production and processing technology of the cell.

3. Materials selection for inverted perovskite solar cell

3.1 Hole-transport layer (HTL) materials

The structure and performance of HTL greatly affect the quality of the crystal and decide the performance of the device.

Therefore, the construction of hole-transport layer with excellent photoelectric performance is the key to improve the efficiency of the battery, which has important practical significance.

To date, researchers have developed a variety of hole-transporting materials (HTM) for I-PSCs. The inclusion band mainly includes organic hole transporting materials such as poly (triarylamine) (PTAA) and the inorganic hole transporting materials (IHTMs) (CuO_x, NiO_x, etc.), conjugated polyelectrolytes (P3CT-K, MPS-TMA, etc.) and so on.

Among them, conjugated polyelectrolytes (CPEs) and inorganic hole-transporting materials (IHTMs) have been widely applied because of their superior properties and stability.

3.1.1 Conjugated polyelectrolytes (CPE)

HTLs based on Poly[3-(4-carboxybutyl) thiophene-2,5-diyl] (P3CT) is focused on due to its good properties and mature synthesis process. P3CT has excellent performance, while it also has the disadvantage of severe aggregation. This not only affects crystalline degree of perovskite, but also affects the film formation of the HTL. These will seriously influence the device performance.

Jiu et al introduced ethylenediamine molecules with multiple functional groups as counterion, and obtained a more appropriate energy level structure. At the same time, amine functional groups passivate perovskite defects and improved perovskite crystallization, and achieved a photoelectric conversion efficiency of 19.5% [3].

You et al. introduced Tris (Pentafluorophenyl) Borane (TPB) for increasing the steric hindrance of thiophene unit, thereby reducing the aggregation of P3CT-K and increasing the hole density, thus improving its hole-transportation capacity. Finally, the device efficiency based on $CH_3NH_3PbI_3$($MAPbI_3$) reaches 20.7% [4].

The battery performance can be improved making appropriate adjustments to the aggregation state of the conjugated polyelectrolyte.

3.1.2 Inorganic hole transporting materials

Among many inorganic hole transporting materials, nickel oxide has a suitable energy level structure, which is more compatible with perovskite energy level. Nickel oxide is expected to be a HTM in the commercialization of solar cells because it is stable to light and heat.

At present, the main problems of nickel oxide hole transporting materials are the energy level mismatch at the interface caused by surface defects and the lattice mismatch between nickel oxide and perovskite. Yu et al. inserted cesium bromide interface layer between nickel oxide and active layer, and the stability of I-PSCs was improved by UV irradiation. and achieved 19.7% PCE [5]. You et al. used a layer of P3CT-K(TPB) material on the surface of nickel oxide film by spin coating. The layer plays the role of connecting nickel oxide with perovskite, and then greatly reduces the hysteresis. Finally, the device efficiency of 20.68% is obtained. Figure 3 shows the solar device built by them [4].

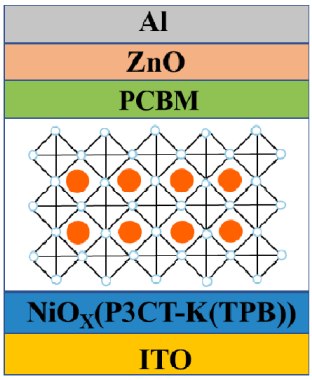


Figure 3. solar cell architecture built by You et al.

The interface layer of the Perovskite-Type layer with NiOx can efficiently decrease the interface defects due to the mismatching of the lattice. Optimization of energy level matching can make I-PSCs perform better.

3.2 Electron transport layer (ETL) materials

Electron transport materials is the material that allow electron carriers to flow into and transport in them, which can form a selective contact of electron with the perovskite layer. It can improve the extraction rate of photogenerated electrons and hinder the passage of holes [6]. The performance of the electronic transfer layer in an inverted perovskite-type solar cell is influenced by its transportation capability, power level matching, charge separation, and film-forming quality. So the selection of electron transport materials is particularly important. The material selection of electron transport layer has two main categories: the first one is fullerene materials and the second one is non-fullerene materials

3.2.1 Fullerene materials

For fullerene materials (including C_{60}, C_{70}, PCBM, etc.), its derivatives have good electron transport ability and avoid high-temperature sintering layer, so it is widely used in Perovskite solar cells. It has the characteristics of suitable energy level, high electron transport capacity and simple preparation process. Zheng Xueqing et al. replaced PCBM with C60. In the inverted PSCs based on ITO/NiO_x/$MAPbI_3$/C60/Ag structure, a layer of BCP of about 5 nm was first vaporized between the C_{60}/Ag interface, and then the BCP layer was removed. By changing the thickness of C60, the probability of carrier recombination was reduced. When increasing the thickness of C60 from 25 nm to 100 nm, the photoelectric conversion efficiency of the device increased first and then decreased, and the best effect was achieved at the thickness of C_{60} at 80 nm, and the PCE of the device was 18.12%. Zhu et al. inserted ZnO：Titanium (Di isopropyl oxygen) 2 (2, 4) glutaric hyaluronic acid salt (TIPD) composite membrane between PCBM layer and Ag electrode for the first time, the device structure of ITO/CuInS2/CH3NH3PbI3/ PCBM/ZnO: TIPD/Ag [7]. The modified ZnO: TIPD not only can restrain the recombining of electrical charges, but also has good water-resistant properties. Bai et al. improved the uniformity of ETL layer and reduced the electron-hole pair recombination in ETL layer by doping PCBM with (1.5%, 6%wt) PS, obtained 10.68% of PCE in FTO/NiO NCs/ $CH_3NH_3PBCL_{3-x}I_x$ /PCBM:1.5% PS/Al [8]. Zhu et al added PFNOX to PCBM, and in the apparatus with (ITO/PEDOT: PSS/CH3NH3PbCl3-xIx/PCBM: PFNOX/Ag), 14. 0% PCE was obtained [7]. In addition, a novel 2D carbon material, graphite diacetylene (GD), was added to (ITO/PEDOT: PSS/CH3NH3PbI3 - xClx/PCBM: GD/C60/Al). The PCE was increased from 13.6% to 14.8%.

3.2.2 Non-Fullerene materials

Non-fullerene materials have made rapid development in the field of perovskite solar cells in recent years due to their unique advantages such as diverse molecular structures, easy modification, and tunable frontier molecular orbitals, as well as their cheaper price compared with fullerene materials.

Chen et al. prepared A new D-A structure called TPA-3CN by using malononitrile (3CN) as acceptor group and triphenylamine (TPA) as donor group through molecular engineering methods [9]. Then, N-type dopant H_2 was used to optimize TPA-3CN as ETL in inverted PSCs. The doping of H_2 accelerated the electron transfer rate and improved the electrical conductivity of TPA-3CN. Shaikh substituted PCBM for DS1 and DS2 derivatives of Vinyl dithiofluoride (DTF) -naphthalene diimide (NDI) as ETL in reversed PSCs, thereby decreasing the band gap and supplying more sulphur atoms to bind perovskite via S-I and S-PB [10]. The interaction between perovskite layer and ETL layer is enhanced to promote electron migration.

3.3 Photoactive Perovskite layer

The inverted PSC has brought attention to scientists and researchers during the past decades due to its multiple advantages: low cost of production, easy-fabrication and suppressed hysteresis effect, etc [11]. Recently, inverted PSCs has been reported to reach a power conversion efficiency (PCEs) of over 24%, which show great potential in high PCE characteristics. However, due to lack of sufficient research, people are still looking for optimizing interface materials to increase the overall photovoltaic performance to be as good as regular PSCs. Compared with traditional PSC, inverted PSC switch the order of fabricating HTL and ETL, free electrons flow to electrode, free holes flow to rear electrode, forming a p-i-n structure. Because of the coefficient of electron diffusivity is higher than coefficient of hole diffusivity in perovskite layer, the diffusion length of electron is longer than the diffusion length of holes in inverted PSC.

As the core part of PSC, the perovskite layer between ETL and HTL is served with the functions of light absorption, charge generation and collection. Perovskites are materials with the same chemical formula as ABX_3, same crystal structure as $CaTiO_3$. The ABX_3 structure can be shown as Figure 4.

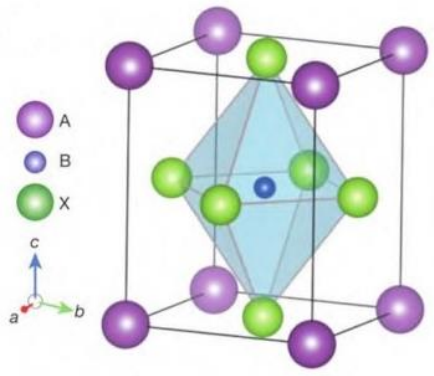


Figure 4. Atom arrangement of Perovskite.

In the perovskite materials, A stands for inorganic or organic cation (e.g., $CH_3NH_3^+$, $HC(NH_2)_2^+$, Cs^+), B stands for metal cation (e.g., Cu^{2+}, Sn^{2+}, Ge^{2+}, Pb^{2+}), X stands for halide anion (e.g., I^-, Cl^-, Br^-). The chemical composition can be engineered by changing element or organic group of A, B and X, on the purpose of achieving better performance on one or more characteristics such as stability, PCE, cost-effectiveness, etc. The mostly frequently utilized material in inverted PSC photoactive perovskite layer is $CH_3NH_3PbI_3$, which is known as $MAPbI_3$. There is development on selecting new perovskite layer materials based on the research of $MAPbI_3$.

Firstly, change "B" in "ABX3". For being free of heavy metal, clean and environmental-friendly, Pb^{2+} can be replaced by other elements such as Sn^{2+} and Ge^{2+}. Ge-based perovskite have wider bandgap which indicates a higher open-circuit voltage for the device. Sn-based perovskite device has features like less toxicity, less chemical stability and better light harvesting capacity. The most classic structure of non-Pb perovskite material is $HC(NH_2)_2SnI_3$, which is known as $FASnI_3$. But introduce Sn element also makes device more vulnerable to oxidation, which leads to serious vacancy in the film and decrease the performance of solar cell rapidly. Secondly, change "X" in "ABX_3". A way of changing property of perovskite layer is by replacing I^- with smaller ions like Br^- or Cl^-, to widen the

bandgap, layer structures become $MAPbI_{3-x}Br_x$ and $MAPbI_{3-x}Cl_x$, which leads to improve the open-circuit voltage and carrier diffusion length and charge mobility. Third way to do is changing "A" in "ABX_3". Research has shown that by replacing or incorporating MA^+ with FA^+ can successfully increase the short-circuit current. If we substitute Cs^+ with MA^+, the inorganic PSC show significantly improvement in thermostability with good PCE characteristics.

Other ways like doping can also change the property of perovskite layer. Classic way of doing this is P-type doping. For example, He, etc use V_2O_x as additives of perovskite precursor solution to adjust film crystallinity in order to improve PCE [12]. Also, researchers also use KI, NaI, RbI doping to improve efficiency of solar cell. The perovskite layer material can also be classified by dimension. Usually perovskite layer used 3D poly-crystalline thin film material. Other than 3D, there are also 2D materials (e.g., nanosheet), 1D materials (e.g., nanowire) and zero-dimension materials (e.g., quantum dot, nanocrystal). Low-dimension materials has certain features like particular direction of crystal growth, longer carrier lifetime. 3D perovskite materials are easier to fabricate, tunable bandgap, longer carrier diffusion length and better light absorption ability.

Finally, we could never ignore the influence of fabrication methods, atmosphere control and morphological control on the performance of PSC during the fabrication of photoactive perovskite layer. Different methods, different annealing temperature, different chemical atmosphere applied during film formation can seriously impact the film quality, which further affect the photovoltaic property of inverted PSC.

4. Progress in fabricating inverted perovskite solar cell

4.1 TOAB multi-functional passivation strategy

A multifunctional passivation strategy was developed to prepare the post-processing of tetraoctylammonium bromide (TOAB)-based I-PSCs. Firstly, cationic surfactant TOAB was coated on the surface of perovskite film (PVSK) as a surface passivation layer, and then TOAB was promoted to diffuse into the grains of perovskite by thermal annealing process. Thus, the PVSK surface and grain boundary can be passivated, and the high efficiency and stability of I-PSCs can be obtained.

The passivation layer was prepared by applying TOAB solution (isopropanol (IPA) as the solvent) evenly on the perovskite surface until it was fully spread, and then spinning at an acceleration of 500 r/min2 and at 4000 revolutions per minute for 30 seconds. After the spin-coating, it was placed on a 70℃ table for 10 minutes annealing to accelerate the drying of TOAB and promote the diffusion of TOAB to perovskite grain boundaries. The process of preparing the product is illustrated in Figure 5.

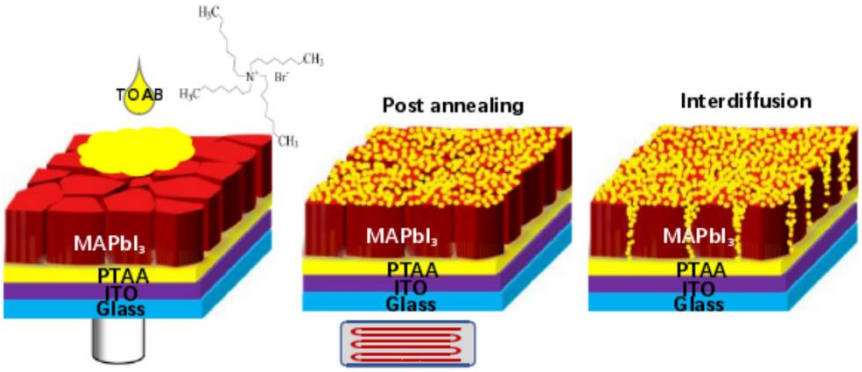


Figure 5. Schematic diagram of PVSK preparation using TOAB passivation strategy.

The benefits of the TOAB post-processing approach are as follows. First, this strategy can clearly show the impact of surface passivation on the performance of device. When PVSK was treated by TOAB passivator, it did not participate in the crystallization or nucleation of PVSK, which indicated that TOAB existed only on the surface and the grain boundary.so the crystallinity and the grain size of

perovskite are not affected by passivation. Moreover, the formation of intermediate phase and the residue of TOAB can be regulated by adjusting the concentration of TOAB. Secondly, gradient distribution of passivator can be realized by this strategy. The molecules of TOAB on the top surface of PVSK are conducive to the formation of interface dipoles and increase the hydrophobicity of the film, which significantly affects the stability of the device [13]. Thirdly, the diffusion of TOAB into the $MAPbI_3$ film can not only adjust the refractive index of PVSK, but also the photoelectric field distribution in the device, which can promote light absorption in the long-wavelength region and improve energy conversion efficiency. Finally, the multifunctional passivation strategy of surface passivation and grain boundary modification can be realized by post-processing.

4.2 Femtosecond laser processing technology

Laser processing is based on the control of the interaction between laser and local material, by adjusting the laser wavelength to match the optical properties of materials, materials local heating, melting or even ablation processing industry [14]. The femtosecond laser and material interaction, can avoid heat accumulation and unnecessary secondary effects, and will lead to rapid ionization of materials, so it is very suitable for cutting technology.

The femtosecond laser system consists of femtosecond laser oscillator, pump source and regenerative amplifier, which can be shown as Figure 6. The femtosecond laser oscillator first generates a low energy laser pulse, and then the pulse pass into the regenerative amplifier and is amplified into a high energy pulse and output. The Q-switched laser pulse with a central wavelength of 532 nm was acting as pump source. The results show that the central wavelength is 800nm, the pulse width is 35fs, the repetition rate is 1 KHz, and the highest single pulse is 7mJ.

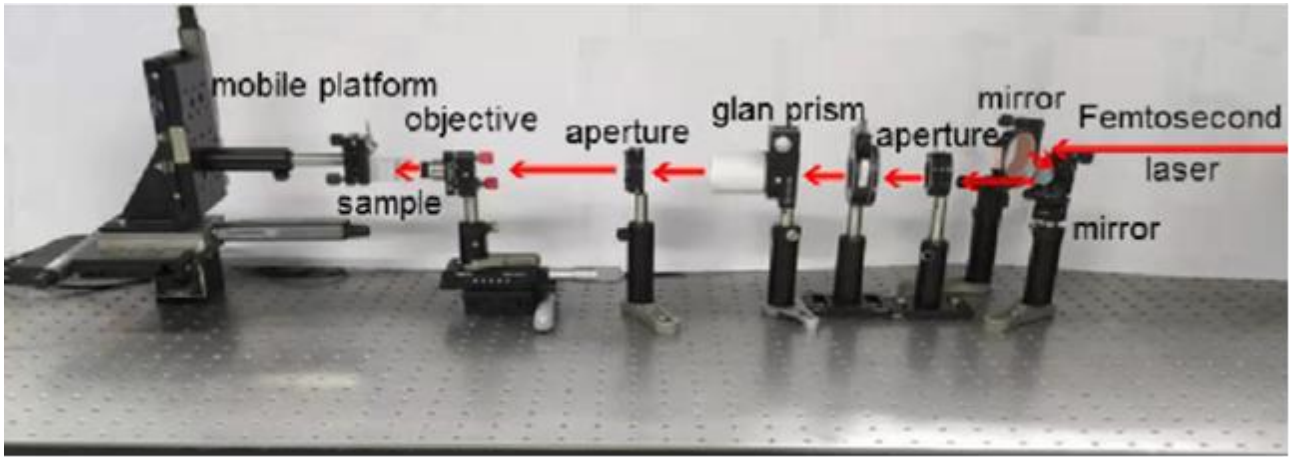


Figure 6. Single beam femtosecond laser processing device.

The micro surface of perovskite polycrystalline film after femtosecond laser processing is very smooth, which is conducive to the fabrication of high-performance devices. The residual PbI_2 will also be produced during processing, which has an impact on the order of the film. Further processing technology should be used to remove the excess PbI_2.

5. Future perspectives

The inverted perovskite solar cells have been in existence for many years. The performance of inverted PSCs has significantly improved at the same time that perovskite solar cells are gaining ground in the efficiency race. The PCE has been reached at over 26 percent. The alignment of interfacial energy level, improvement in charge extraction, surface shape and crystallinity optimization of the perovskite active layer, and perovskite composition engineering are all part of the systematic study of the device manufacturing process. At the same time, the underlying mechanism of device

stability is improved on the basis of understanding. All these efforts expedite the process of commercialization tremendously.

Inverted PSCs provide advantages for achieving low-cost photovoltaics in addition to great device performance. Inverted PSCs can be produced using low temperature solution methods including slot die coating and roll-to-roll processes instead of the high temperature sintering process. They function well with production on large surfaces and flexible substrates.

Device stability continues to be a major obstacle to the use of inverted PSC at this point. It is far from enough to store stability in the air for about 60 days. To increase stability, interface materials and superior perovskite candidates must be developed. To locate better candidate materials to increase device stability, inverted PSC can be used to further examine a number of good interfacial materials in organic thin-film devices (such as OPV and OLED). to improve the inverted PSCs' electron transport efficiency. In order for increasing the electron transport efficiency in inverted PSCs, to further enhance electron mobility and mechanical stability, inverted PSCs need an electron transport layer that is denser and more intricate. At present, when using common fullerenes and their derivatives to prepare inverted PSCs, there are still problems such as high preparation cost and rough morphology. Therefore, it is imperative to find better electron transport materials to prepare inverted PSCs. Besides that, if we want to achieve mass manufactory, the pollution generated during the fabrication process needs to be considered.

6. Conclusions

This article reviews the modified techniques of ETL in I-PSCs and introduces some non-fullerene small molecules or polymers as ETL, so as to further improve the performance of ETL. In addition, a brief overview of the hole transport layer is given, moreover, the photo-electric property of the device is enhanced by modifying the conjugated polymer and the inorganic material. Furthermore, the photoelectric conversion efficiency of perovskite film is improved through some optimized preparation methods. Inverted PSCs will have great prospects for development in the future, but there are also some problems. To realize the commercial application of inverted PSCs, there are the following prospects:

1. The carrier material was modified to make the inverted perovskite battery stable for a long time. In the modification methods of the transporting materials, few modified techniques are directly about improving the stability of the device. That can be studied and improved.

2. Improve the transmission efficiency to realize the application of inverted PSCs devices. In the current common inverted PSC, PCE is still relatively low, so it is still necessary to find better transporting materials to prepare inverted PSCs.

3. Other factors influence the large-scale industrial production of inverted PSCs. At present, there are still some problems in inverted PSCs such as low mechanical stability and environmental pollution, therefore further research is needed.

References

[1] Liu Sanwan, Guan Xinyu, Xiao Wenshan, Chen Rui, Zhou Jing, Ren Fumeng, Wang Jianan, Chen Weitao, Li Sibo, Qiu Longbin, Zhao Yan, Liu Zonghao, Chen Wei. Effective Passivation with Size-Matched Alkyldiammonium Iodide for High-Performance Inverted Perovskite Solar Cells[J]. Advanced Functional Materials,2022,32(38).

[2] Wan-Jian Yin, Tingting Shi, Yanfa Yan. Unusual defect physics in CH3NH3PbI3 perovskite solar cell absorber[J]. Applied Physics Letters,2014,104(6).

[3] Guodong Zhang, Yunxin Zhang, Siqi Chen, Hao Chen, Le Liu, Wenming Ding, Jinhui Wang, Anyu Zhang, Shuping Pang, Xin Guo, Lianqing Yu, Tonggang Jiu. Improved interfacial property by small molecule

ethanediamine for high performance inverted planar perovskite solar cells[J]. Journal of Energy Chemistry,2021,54(prepublish).

[4] You Gengshu, Liu Le, Wang Jin, Zhao Min, Zhao Chengjie, Cai Xu, Tang Jin, Lu Fushen, Jiu Tonggang. Tris(pentafluorophenyl)borane‐Modified P3CT‐K as an Efficient Hole‐Transport Layer for Inverted Planar MAPbI3 Perovskite Solar Cells[J]. Advanced Sustainable Systems,2021,5(8).

[5] Zhang Bingjuan, Su Jie, Guo Xing, Zhou Long, Lin Zhenhua, Feng Liping, Zhang Jincheng, Chang Jingjing, Hao Yue. NiO/Perovskite Heterojunction Contact Engineering for Highly Efficient and Stable Perovskite Solar Cells[J]. Advanced science (Weinheim, Baden-Wurttemberg, Germany),2020,7(11).

[6] Kumar Anjan,Singh Sangeeta. Advancement in Inorganic Hole Transport Materials for Inverted Perovskite Solar Cells[J]. Journal of Electronic Materials,2020,49(10).

[7] Zhu Zonglong, Xue Qifan, He Hexiang, Jiang Kui, Hu Zhicheng, Bai Yang, Zhang Teng, Xiao Shuang, Gundogdu Kenan, Gautam Bhoj Raj,Ade Harald, Huang Fei, Wong Kam Sing, Yip Hin-Lap, Yang Shihe, Yan He. A PCBM Electron Transport Layer Containing Small Amounts of Dual Polymer Additives that Enables Enhanced Perovskite Solar Cell Performance[J]. Advanced science (Weinheim, Baden-Wurttemberg, Germany),2016,3(9).

[8] Yang Bai, Hui Yu, Zonglong Zhu. High performance inverted structure perovskite solar cells based on a PCBM:polystyrene blend electron transport layerf[J]. Journal of Materials Chemistry, A. Materials for energy and sustainability,2015,3(17).

[9] Chen C, Li H P, Ding X, et al. Molecular Engineering of Triphenylamine-Based Non-fullerene Electron Transport Materials for Efficient Rigid and Flexible Perovskite Solar Cells[J]. Acs Applied Materials & Interfaces, 2018.

[10] Shaikh D B，Said A A，Bhosale R S, et al. Dithiafulvenyl-Naphthalenediimide-based Small Molecules as efficient Non-Fullerene Electron-Transport Layer for Inverted Perovskite Solar Cells [J], Asian Journal of Organic Chemistry，2018，7(11):2294-2301.

[11] Tanghao Liu, Ke Chen, Qin Hu, Rui Zhu, Qihuang Gong. Inverted Perovskite Solar Cells: Progresses and Perspectives[J]. Advanced Energy Materials,2016,6(17).

[12] Liu Zhiyong, He Tingwei, Liu Kaikai, Wang Jiaxiang, Zhou Yawei, Yang Jien, Liu Hairui, Jiang Yurong, Ma Heng, Yuan Mingjian. Efficient and stable perovskite solar cells based on high-quality CH3NH3PbI3−xClx films modified by V2Ox additives[J]. Journal of Materials Chemistry A,2017,5(46).

[13] Poli Isabella, Eslava Salvador, Cameron Petra. Tetrabutylammonium cations for moisture-resistant and semitransparent perovskite solar cells[J]. J. Mater. Chem. A,2017,5(42).

[14] Qi Yifang,Green Kevin A.,Ma Guorong,Jha Surabhi,Gollinger Kristine,Wang Chen,Gu Xiaodan,Patton Derek,Morgan Sarah E.,Dai Qilin. Passivation of iodine vacancies of perovskite films by reducing iodine to triiodide anions for high-performance photovoltaics[J]. Chemical Engineering Journal,2022,438.