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RESEARCH ARTICLE

Spray-coated SnO_2 electron transport layer with high uniformity for planar perovskite solar cells

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Abstract SnO_2 has been proven to be an effective electron transport layer (ETL) material for perovskite solar cells (PSCs) owing to its excellent electrical and optical properties. Here, we introduce a viable spray coating method for the preparation of SnO_2 films. Then, we employ a SnO_2 film prepared using the spray coating method as an ETL for PSCs. The PSC based on the spray-coated SnO_2 ETL achieves a power conversion efficiency of 17.78%, which is comparable to that of PSCs based on conventional spin-coated SnO_2 films. The large-area SnO_2 films prepared by spray coating exhibit good repeatability for device performance. This study shows that SnO_2 films prepared by spray coating can be applied as ETLs for stable and high-efficiency PSCs. Because the proposed method involves low material consumption, it enables the low-cost and large-scale production of PSCs.

Keywords spray coating, SnO_2 film, ETL, PSCs

1 Introduction

Organic–inorganic hybrid perovskite solar cells (PSCs) have received much attention in recent years owing to their low manufacturing cost and excellent photovoltaic performance [1]. The maximum power conversion efficiency (PCE) has been increased from 3.8% in 2009 to 24.2% in 2019, showing great potential for PSCs to replace traditional silicon solar cells [2–5]. Because the PCE is close to the theoretical efficiency limit, it is very important to develop fabrication techniques for high durability, low cost, and flexible devices, for which the low-temperature preparation of electron transport layers (ETLs) is a key technology [6,7]. Current high-efficiency PSCs typically use TiO_2 as the ETL. However, devices based on TiO_2 ETLs typically require TiO_2 to be annealed at temperatures above 450°C, which is detrimental to future commercial applications [8–11]. Other low-temperature processed materials, such as SnO_2 [12–15], WO_3 [16], ZnO [17,18], amorphous-TiO_x [19], and [6,6]-Phenyl-C61-butyric acid methyl ester [20,21], have been studied as ETLs to replace TiO_2. Despite its low-temperature processability, SnO_2 is regarded as the most promising alternative to TiO_2 owing to its deep conduction band, high electron mobility, high light transmittance, good ultraviolet resistance, and excellent chemical stability. SnO_2-based planar PSCs yield a high PCE close to 21%, which is comparable to that of TiO_2-based planar PSCs.

In order to obtain SnO_2-based ETLs, various methods have been studied, including spin coating and hydrothermal and chemical bath depositions [22–26]. However, these methods have limitations. For instance, only small- or large-area films with poor optical properties can be obtained, and it is difficult to obtain large-area SnO_2 films with excellent performance. Moreover, these methods usually require cumbersome production processes and produce a large amount of material waste, which is not conducive to low-cost and large-scale commercial production [27–30]. Some studies have reported the preparation of PSCs based on spray-coated TiO_2, but with low efficiencies comparable to those of solar cells based on films prepared by spin coating [11]. There are also some studies on the preparation of SnO_2 films by spraying $SnCl_2$ precursor, but the optical properties of these SnO_2 films are not good enough [31,32]. To solve this, we developed a spray coating method to prepare SnO_2 films using SnO_2 hydrocolloid instead of $SnCl_2$ precursor, which enables a more straightforward and efficient preparation of large-area SnO_2 films with excellent optical performance. In particular, the morphologies of SnO_2 films can be

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conveniently controlled by changing the spraying conditions, such as the substrate temperature, spraying time, solution flow rate, and nozzle-to-substrate distance. This method can also be used to improve the material utilization and, thus, reduce the manufacturing cost of PSCs [33–37].

In this work, we report a universal low-cost spray coating process for the preparation of SnO_2 films in an air environment and use it to prepare an ETL for PSCs. Specifically, dense and smooth SnO_2 films are produced by optimizing the spray conditions and film thickness to obtain the best PSCs. A dozen of devices fabricated from the same batch of spray-coated SnO_2 films showed similar high performance with an average efficiency of over 16%, demonstrating the reliability of the large-area SnO_2 films prepared by spray coating. The PSC based on a spray-coated SnO_2 film achieved a maximum conversion efficiency of 17.78%, which is almost the same as that of PSCs based on SnO_2 prepared by spin coating. Furthermore, the device based on the spray-coated SnO_2 ETL showed better device stability than the PSC based on SnO_2 prepared by spin coating.

2 Experimental

2.1 Materials

All chemicals were applied to the experiments without further purification, and all solvents were of super dehydrated grade. SnO_2, 15 wt-% in H_2O colloidal dispersion was purchased from Alfa Aesar. All perovskite materials (including $HC(NH_2)_2I$ (≥99.5%), CH_3NH_3Br (≥99.5%), PbI_2 (≥99.99%), $PbBr_2$ (≥99.99%), and CsI (≥99.99%)), 2,2',7,7'-tetrakis-(*N,N*-di-p-methoxyphenylamino)-9,9'-spirobifluorene (Spiro-OMeTAD, ≥99%) and lithium-bis(tri-fluoromethanesulfonyl)imide (≥99%) were purchased from Xi'an Polymer Light Technology Corp. 4-*tert*-Butyl pyridine (96%) and chlorobenzene (99.8%) were purchased from Sigma Aldrich. *N,N*-Dimethylformamide (99.7%) and dimethyl sulfoxide (99.8%) were purchased from Beijing Infinity Scientific.

2.2 Preparation of perovskite solar cells

The per-patterned indium tin oxide (ITO) glass substrates were cleaned with detergent, deionized water, acetone and isopropanol in an ultrasonic bath for 15 min, respectively. Before spin coating or spray coating, the substrates were treated with ultraviolet ozone cleaner for 15 min. SnO_2 in H_2O colloidal dispersion was diluted to different concentrations with ultrapure water and stirred for 30 min. A schematic view of the spray coating device is shown in Fig. S1(a) (cf. Electronic Supplementary Material, ESM). The spray nozzle was placed 20 cm above the surface of the substrate and the diluted SnO_2 colloidal dispersion was sprayed at a flow rate of 0.2 $mL \cdot min^{-1}$ for different duration. SnO_2 hydrocolloid (1 wt-%) was sprayed on ITO substrates for different duration to get various film thicknesses and then annealed at 150°C for 30 min. SnO_2 hydrocolloid (3 wt-%) was spin-coated on ITO substrates at 3000 $r \cdot min^{-1}$ for 30 s and then annealed at 150°C for 30 min. Then, the precursor solution of $Cs_{0.05}FA_{0.85}MA_{0.15}PbI_{2.9}Br_{0.15}$ was spin-coated at 5000 $r \cdot min^{-1}$ for 35 s in a nitrogen glove box, and 300 μL chlorobenzene was dropped 10 s after the beginning of spin-coating. And the substrates were annealed at 100°C for 60 min. After that, 80 mg Spiro-OMeTAD was dissolved in 1 mL chlorobenzene with additive of 4-*tert*-butylpyridine (10.5 μL) and 0.2 $mol \cdot L^{-1}$ solution of lithium-bis(tri-fluoromethanesulfonyl)imide in acetonitrile (15.5 μL). The Spiro-OMeTAD solution was spin-coated on perovskite film at 4000 $r \cdot min^{-1}$ for 30 s and place for more than 6 h in dry air. Finally, 60 nm-thick silver layer was vacuum-evaporated as the counter electrode to give a complete device.

2.3 Characterization

The morphologies of SnO_2 films and perovskite films were observed using scanning electron microscopy (SEM, Hitachi SU8000). The surface morphologies of SnO_2 films were analyzed through atomic force microscopy (AFM) in tapping mode under ambient conditions using a Bruker instrument. The thickness of SnO_2 films were analyzed using Dektak XT. The X-ray diffraction (XRD) patterns were recorded on Brucker D8 X-ray diffractometer with CuKα radiation (λ = 1.5418 Å) at 25°C. The data were collected with a 0.02° step size (2θ) for 0.2 s. The current density-voltage (*J-V*) characteristics of solar cells were measured by a computer-controlled source meter (Keithley 2400) under simulated one sun illumination (AM 1.5G, 100 $mW \cdot cm^{-2}$), as calibrated by a reference monocrystalline silicon solar cell (91150 V Oriel Instruments). The active area of the cell was fixed to be 0.04 cm^2 with a non-reflective metal mask. The external quantum efficiency (EQE) spectra were measured in air under short-circuit conditions using Crowntech QTest Station 1000AD equipped with a 100 W Xe arc lamp, a filter wheel, and a monochromator.

3 Results and discussion

To prepare SnO_2 ETLs by spray coating for PSCs, we firstly determined some spray parameters, including the concentration of SnO_2 in H_2O colloidal dispersion, the flow rate of the gun, and the spraying time, which play an important role in the morphology of the prepared SnO_2 film. It has been found that the thickness and compactness of SnO_2 films are very important for high performance. Therefore, we chose a SnO_2 hydrocolloid with a lower concentration (1 wt-%) for spray coating than that for spin

coating (3 wt-%), which will make it easier to adjust the thickness and surface morphology of the SnO_2 films. Through preliminary tests, we found that the SnO_2 films become too thick and uneven, and their transmittance is deteriorated after being sprayed for more than one minute. The thickness of an SnO_2 film prepared by spraying for one minute was approximately 100–110 nm, which is too large for application in PSCs. When sprayed for 20 s, a smooth, dense, and high light-transmitting SnO_2 film with a thickness of ~30–35 nm, which is suitable for application in PSCs, was obtained. The thickness of SnO_2 films at different spraying times is shown in Fig. S2. Below, the surface morphology of a SnO_2 film spray coated at a flow rate of 0.2 $mL \cdot min^{-1}$ for 20 s will be compared with that of traditional spin-coated SnO_2 films.

Because SnO_2 droplets sprayed from a spray gun are not completely uniform, when they are sprayed onto ITO substrate, there is no guarantee that their density distribution on the surface will be uniform. This issue can be mitigated by spraying for a long time. However, unlike with spin coating, the volatilization process of SnO_2 droplets on the ITO substrate will affect the surface morphology of the resulting SnO_2 films [27,34]. To study the difference in surface morphology of SnO_2 films prepared by spray coating and spin coating, we first investigate their SEM images. Figures 1(a) and 1(b) show the top-view SEM images of SnO_2 films prepared by spray coating for 20 s and spin coating, respectively. It can be seen that both films are flat and dense, and there are no holes on their surface.

Although the SEM images prove that the SnO_2 film prepared by spray coating is dense, its surface roughness cannot be evaluated from these images. Accordingly, we collected AFM images of the SnO_2 films prepared by the two methods. Figures 2(a,b) and 2(c,d) show the AFM images of the SnO_2 films prepared by spray coating for 20 s and spin coating, respectively. Figures 2(a) and 2(c) show that, as expected, the SnO_2 film prepared by spray coating is rougher than that prepared by spin coating. The root-mean-square roughness (RMS) value of the SnO_2 film prepared by spray coating is 2.24 nm, which is almost twice that of the spin-coated film (RMS = 1.11 nm). Nevertheless, the surface roughness is still very small relative to the perovskite film thickness of several hundred nanometers typically used in PSCs, and this degree of roughness does not affect the perovskite layer.

To determine the performance of the SnO_2 film prepared by spray coating, we fabricate devices with the structure of ITO/SnO_2/$Cs_{0.05}FA_{0.85}MA_{0.15}PbI_{2.9}Br_{0.15}$/Spiro-OMeTAD/Ag. However, the formation of perovskite may be affected by the different surface morphology of the SnO_2 films prepared by spray coating and spin coating. To understand this impact, we performed XRD and SEM analysis of the perovskite films prepared with the different SnO_2 films, as shown in Figs. 3 and S3, respectively. No difference between the two perovskite films was observed, so we believe that the slight difference in surface morphology of the SnO_2 films does not affect the formation of perovskite. Considering that different spray coating times will lead to SnO_2 films with different thicknesses, we tested different spray coating times from 10 to 50 s to determine the performance of the SnO_2 films. The corresponding photovoltaic parameters of the PSCs are summarized in Fig. 4 and Table 1. It can be seen that the performance of the PSC based on the SnO_2 film prepared by spraying for 10 s is poor. This is because the SnO_2 film cannot fully cover the ITO surface, which forms a shunting path. With the spraying time of 20 s, both short-circuit current density (J_{sc}) and fill factor (*FF*) are improved, reaching maximum values of 23.35 $mA \cdot cm^{-2}$ and 0.666, respectively. As a result, the device achieved a maximum PCE of 17.78%. Such improvement may be attributed to the changes in the SnO_2 film thickness. An appropriate thickness of the SnO_2 film facilitates electron extraction. With longer spraying times, as the spraying time increase, J_{sc} and *FF* decrease. This is because when the spraying time is too long, the SnO_2 film becomes too thick, resulting in an increase in the series resistance (*Rs*) of the SnO_2 film.

To verify the effectiveness of the spray-coated SnO_2 ETL in PSCs, we compared the best device based on an SnO_2 ETL prepared by spray coating with that prepared by conventional spin coating, and the results are shown in Fig. 5 and Table 2. The two devices show very similar PCE values, J_{sc}, voltage (V_{oc}), *FF*, and *Rs*. The EQE response of the device based on the spray-coated SnO_2 ETL is slightly

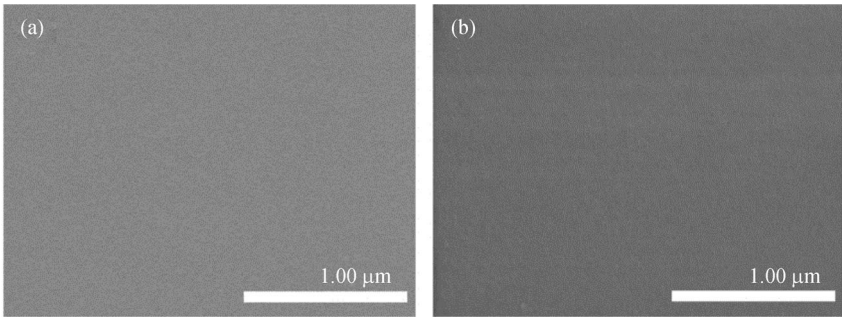

Fig. 1 SEM images of SnO_2 films prepared by (a) spray coating and (b) spin coating.

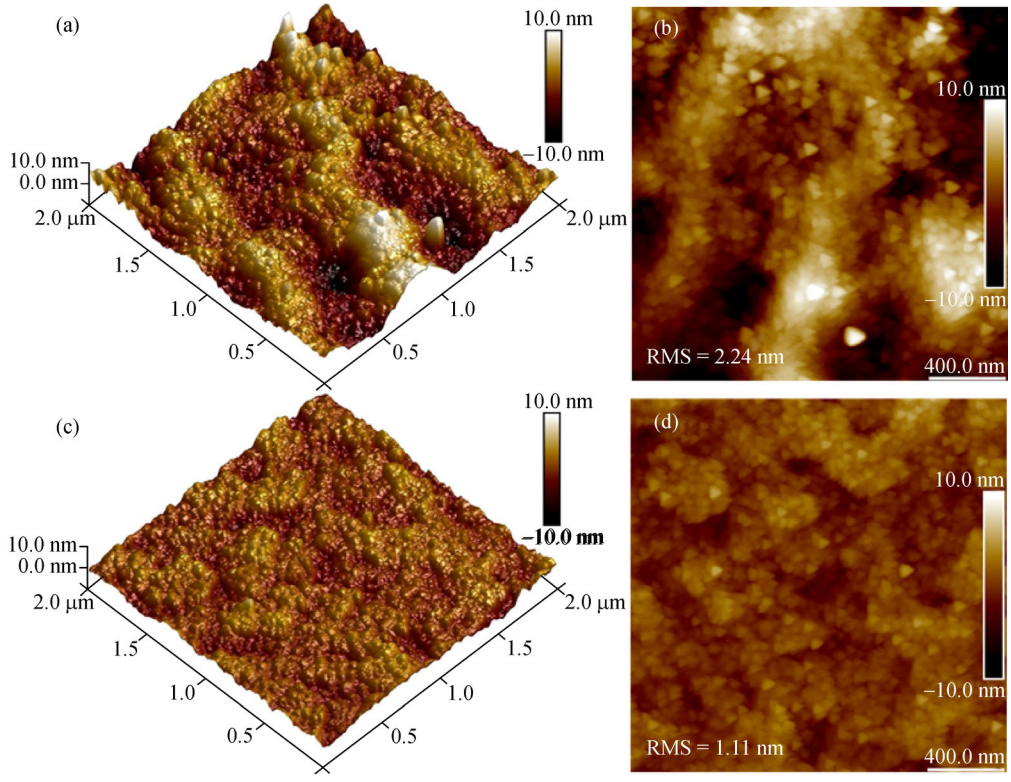

Fig. 2 AFM images of SnO_2 films prepared by (a,b) spray coating and (c,d) spin coating.

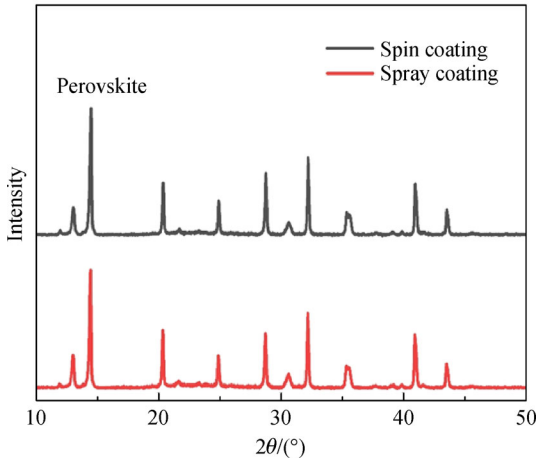

Fig. 3 XRD patterns of perovskite films deposited on SnO_2 films prepared by different methods.

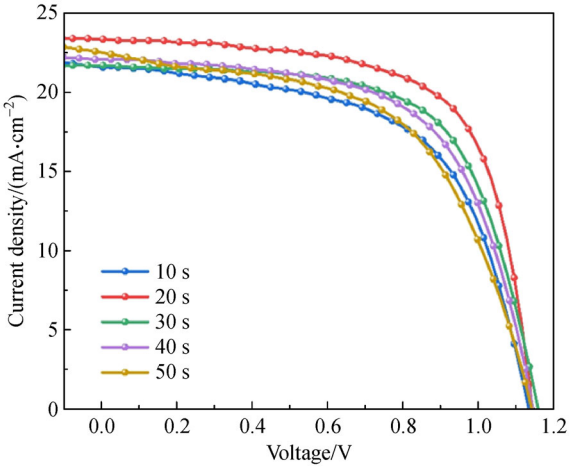

Fig. 4 *J-V* curves of PSCs based on SnO_2 prepared at different spraying times.

Table 1 Photovoltaic parameters of devices based on SnO_2 prepared at different spraying times

Spraying time/s	J_{sc}/(mA·cm^{-2})	V_{oc}/V	*FF*	*PCE*/%	*Rs*/Ω
10	21.61±0.35	1.134±0.009	0.592±0.025	15.42±0.50	240
20	23.35±0.50	1.144±0.010	0.666±0.030	17.78±0.42	156
30	21.69±0.45	1.159±0.011	0.642±0.028	16.14±0.39	196
40	22.03±0.48	1.145±0.011	0.616±0.035	15.73±0.56	233
50	22.51±0.45	1.143±0.010	0.559±0.040	14.37±0.58	266

higher than that of the device based on the spin-coated SnO_2 ETL. The integrated photocurrent of the SnO_2 ETL deposited by spin coating and spray coating, which were calculated from the EQE spectra, are 21.5 and 21.9 mA·cm^{-2}, respectively. This is consistent with the J_{sc} values of the *J-V* curves. These results show that the SnO_2 film prepared by spray coating can be used as an ETL for PSCs with performance similar to that of PSCs based on spin-coated SnO_2 films. In addition, we investigated the stability of the devices based on the spray- and spin-coated SnO_2 under simulated one-sun illumination in air without encapsulation (Fig. 6). The two devices show similar device stability. The PSC based on the spin-coated SnO_2 film, retained an efficiency of 85% of its initial value after storage for 600 h.

To confirm the performance of the large-area SnO_2 film prepared by spray coating, we spliced together twelve pieces of ITO substrates with dimensions of 1.5 cm × 2 cm and sprayed them with SnO_2. Then, we used these twelve substrates to prepare PSCs under the same conditions. Figure 7 shows the PCEs of the twelve cells based on the same batch of spray-coated SnO_2 films. As shown in the figure, all the devices have high efficiency. The corresponding photovoltaic parameters of the PSCs are summarized in Table S1. The devices in the middle zone have the best efficiency of approximately 17.6%, and the average efficiency of all the devices is 16.45%. This confirms that the large-area SnO_2 film prepared by spray coating is very reliable, and the whole film is dense and uniform. It is worth mentioning that the SnO_2 film preparation by spraying does not require a specific environment, and can be directly prepared in air.

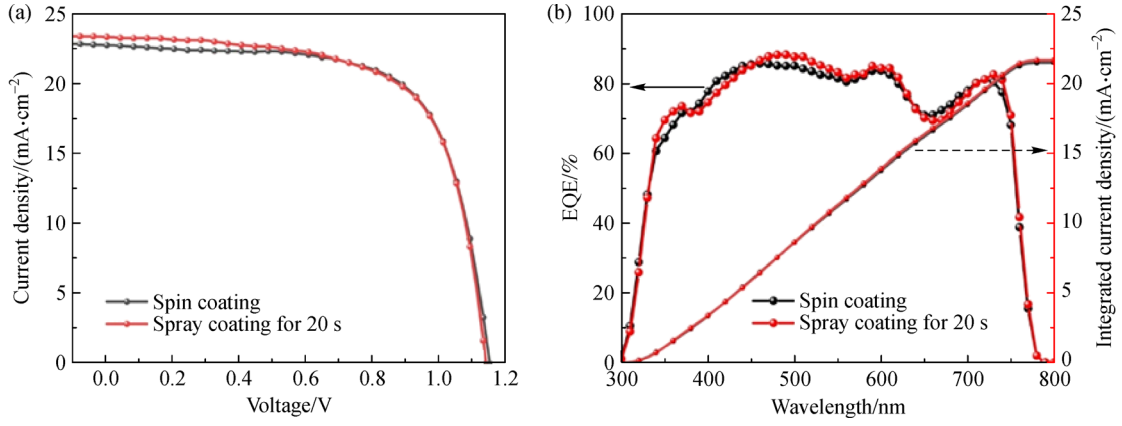

Fig. 5 (a) *J-V* curves and (b) EQE of PSCs based on SnO_2 prepared by spin coating and spray coating.

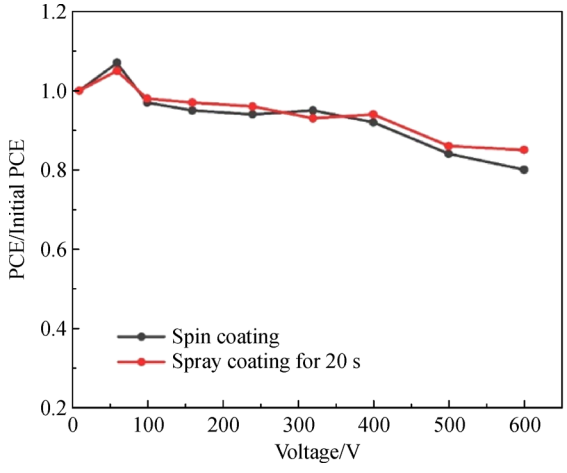

Fig. 6 Stability test of devices without any encapsulation.

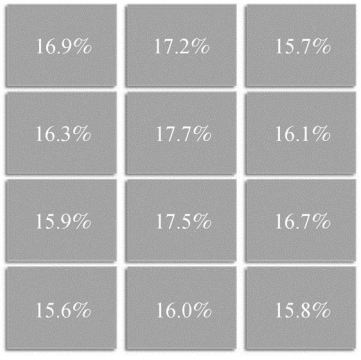

Fig. 7 PCEs of twelve PSCs based on the same batch of spray-coated SnO_2 films under the same conditions.

Table 2 Photovoltaic parameters of PSCs based on SnO_2 prepared by spin coating and spray coating for 20 s

Item	J_{sc}/(mA·cm^{-2})	V_{oc}/*V*	*FF*	*PCE*/%	*Rs*/Ω
Spin coating	22.80±0.48	1.156±0.010	0.679±0.030	17.90±0.39	160
Spray coating	23.35±0.50	1.144±0.010	0.666±0.030	17.78±0.42	156

Furthermore, almost all the way SnO_2 is prepared into the SnO_2 films with very little waste. These results indicate that the spray-coated large-area SnO_2 film has the characteristics of low cost and high output. This is clearly one of the most promising technologies for the commercial preparation of ETLs for PSCs.

4 Conclusions

In conclusion, we successfully developed a simple and reproducible spray method to prepare uniform and dense SnO_2 ETLs for PSCs. Parameters such as the precursor concentration, flow rate of the gun, and spray time for the formation of the SnO_2 films were evaluated. The optimal device based on a spray-coated SnO_2 ETL achieved an efficiency of 17.78%, showing the great potential of spray-coated SnO_2 film as alternative ETLs for highly efficient and stable PSCs. Besides, compared with the conventional spin coating method, the SnO_2 spray coating method has lower material consumption, larger producible area, and easier process. This is a promising way to reduce the manufacturing cost of PSCs and provides an inexpensive and efficient method for preparing large-area flexible PSCs.

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References

1. Green M A, Ho-Baillie A, Snaith H J. The emergence of perovskite solar cells. Nature Photonics, 2014, 8(7): 506–514
2. Kojima A, Teshima K, Shirai Y, Miyasaka T. Organometal halide perovskites as visible-light sensitizers for photovoltaic cells. Journal of the American Chemical Society, 2009, 131(17): 6050–6051
3. Kim H S, Im S H, Park N G. Organolead halide perovskite: New horizons in solar cell research. Journal of Physical Chemistry C, 2014, 118(11): 5615–5625
4. Lee M M, Teuscher J, Miyasaka T, Murakami T N, Snaith H J. Efficient hybrid solar cells based on meso-superstructured organometal halide perovskites. Science, 2012, 338(6107): 643–647
5. Heo J H, Im S H, Noh J H, Mandal T N, Lim C S, Chang J A, Lee Y H, Kim H J, Sarkar A, Nazeeruddin M K, et al. Efficient inorganic–organic hybrid heterojunction solar cells containing perovskite compound and polymeric hole conductors. Nature Photonics, 2013, 7(6): 486–491
6. Huang J, Shao Y, Dong Q. Organometal trihalide perovskite single crystals: A next wave of materials for 25% efficiency photovoltaics and applications beyond? Journal of Physical Chemistry Letters, 2015, 6(16): 3218–3227
7. Snaith H J. Perovskites: The emergence of a new era for low-cost, high-efficiency solar cells. Journal of Physical Chemistry Letters, 2013, 4(21): 3623–3630
8. Burschka J, Pellet N, Moon S J, Humphry-Baker R, Gao P, Nazeeruddin M K, Gratzel M. Sequential deposition as a route to high-performance perovskite-sensitized solar cells. Nature, 2013, 499(7458): 316–319
9. Kazim S, Nazeeruddin M K, Gratzel M, Ahmad S. Perovskite as light harvester: A game changer in photovoltaics. Angewandte Chemie International Edition in English, 2014, 53(11): 2812–2824
10. Wei Z, Chen H, Yan K, Yang S. Inkjet printing and instant chemical transformation of a $CH_3NH_3PbI_3$/nanocarbon electrode and interface for planar perovskite solar cells. Angewandte Chemie International Edition in English, 2014, 53(48): 13239–13243
11. Zheng J, Zhang M, Lau C F J, Deng X, Kim J, Ma Q, Chen C, Green M A, Huang S, Ho-Baillie A. Spin-coating free fabrication for highly efficient perovskite solar cells. Solar Energy Materials and Solar Cells, 2017, 168: 165–171
12. Song J X, Zheng E Q, Bian J, Wang X F, Tian W, Sanehira Y, Miyasaka T. Low-temperature SnO_2-based electron selective contact for efficient and stable perovskite solar cells. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2015, 3(20): 10837–10844
13. Song J X, Zheng E Q, Wang X F, Tian W, Miyasaka T. Low-temperature-processed ZnO-SnO_2 nanocomposite for efficient planar perovskite solar cells. Solar Energy Materials and Solar Cells, 2016, 144: 623–630
14. Xiong L B, Qin M C, Chen C, Wen J, Yang G, Guo Y X, Ma J J, Zhang Q, Qin P L, Li S Z, et al. Fully high-temperature-processed SnO_2 as blocking layer and scaffold for efficient, stable, and hysteresis-free mesoporous perovskite solar cells. Advanced Functional Materials, 2018, 28(10): 1706276
15. Jung K H, Seo J Y, Lee S, Shin H, Park N G. Solution-processed SnO_2 thin film for a hysteresis-free planar perovskite solar cell with a power conversion efficiency of 19.2%. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2017, 5(47): 24790–24803
16. Mahmood K, Swain B S, Kirmani A R, Amassian A. Highly efficient perovskite solar cells based on a nanostructured WO_3-TiO_2 core-shell electron transporting material. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2015, 3(17): 9051–9057
17. Song J X, Liu L, Wang X F, Chen G, Tian W, Miyasaka T. Highly efficient and stable low-temperature processed ZnO solar cells with triple cation perovskite absorber. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2017, 5(26): 13439–13447
18. Song J X, Bian J, Zheng E Q, Wang X F, Tian W J, Miyasaka T. Efficient and environmentally stable perovskite solar cells based on ZnO electron collection layer. Chemistry Letters, 2015, 44(5): 610–612
19. Kim B J, Kim D H, Lee Y Y, Shin H W, Han G S, Hong J S, Mahmood K, Ahn T K, Joo Y C, Hong K S, et al. Highly efficient and bending durable perovskite solar cells: Toward a wearable power source. Energy & Environmental Science, 2015, 8(3): 916–921

20. Heo J H, Han H J, Kim D, Ahn T K, Im S H. Hysteresis-less inverted $CH_3NH_3PbI_3$ planar perovskite hybrid solar cells with 18.1% power conversion efficiency. Energy & Environmental Science, 2015, 8(5): 1602–1608
21. You J B, Hong Z R, Yang Y, Chen Q, Cai M, Song T B, Chen C C, Lu S R, Liu Y S, Zhou H P, Yang Y. Low-temperature solution-processed perovskite solar cells with high efficiency and flexibility. ACS Nano, 2014, 8(2): 1674–1680
22. Guo Y, Yin X, Liu J, Chen W, Wen S, Que M, Xie H, Yang Y, Que W, Gao B. Vacuum thermal-evaporated SnO_2 as uniform electron transport layer and novel management of perovskite intermediates for efficient and stable planar perovskite solar cells. Organic Electronics, 2019, 65: 207–214
23. Mahmood K, Khalid A, Nawaz F, Mehran M T. Low-temperature electrospray-processed SnO_2 nanosheets as an electron transporting layer for stable and high-efficiency perovskite solar cells. Journal of Colloid and Interface Science, 2018, 532: 387–394
24. Mohamad Noh M F, Arzaee N A, Safaei J, Mohamed N A, Kim H P, Mohd Yusoff A R, Jang J, Mat Teridi M A. Eliminating oxygen vacancies in SnO_2 films via aerosol-assisted chemical vapour deposition for perovskite solar cells and photoelectrochemical cells. Journal of Alloys and Compounds, 2019, 773: 997–1008
25. Subbiah A S, Mathews N, Mhaisalkar S, Sarkar S K. Novel plasma-assisted low-temperature-processed SnO_2 thin films for efficient flexible perovskite photovoltaics. ACS Energy Letters, 2018, 3(7): 1482–1491
26. Huang L, Sun X, Li C, Xu J, Xu R, Du Y, Ni J, Cai H, Li J, Hu Z, Zhang J. UV-sintered low-temperature solution-processed SnO_2 as robust electron transport layer for efficient planar heterojunction perovskite solar cells. ACS Applied Materials & Interfaces, 2017, 9(26): 21909–21920
27. Ayadi M, Benhaoua O, Sebais M, Halimi O, Boudine B, Aida M S. Effect of cerium doping on the structural, optical and photocatalytic properties of SnO_2 thin films prepared by spray pyrolysis method. Materials Research Express, 2019, 6(7): 076407
28. Palanichamy S, Mohamed J R, Kumar P S S, Pandiarajan S, Amalraj L. Physical properties of nebulized spray pyrolysised SnO_2 thin films at different substrate temperature. Applied Physics. A, Materials Science & Processing, 2018, 124(9): 643
29. Benhaoua B, Abbas S, Rahal A, Benhaoua A, Aida M S. Effect of film thickness on the structural, optical and electrical properties of SnO_2: F thin films prepared by spray ultrasonic for solar cells applications. Superlattices and Microstructures, 2015, 83: 78–88
30. Jiang Y Y, Wu C C, Li L R, Wang K, Tao Z, Gao F, Cheng W F, Cheng J T, Zhao X Y, Priya S, et al. All electrospray printed perovskite solar cells. Nano Energy, 2018, 53: 440–448
31. Elangovan E, Ramamurthi K. Studies on micro-structural and electrical properties of spray-deposited fluorine-doped tin oxide thin films from low-cost precursor. Thin Solid Films, 2005, 476(2): 231–236
32. Thangaraju B. Structural and electrical studies on highly conducting spray deposited fluorine and antimony doped SnO_2 thin films from $SnCl_2$ precursor. Thin Solid Films, 2002, 402(1-2): 71–78
33. İskenderoğlu D, Guney H. Effect of mg dopant on SnO_2 thin films grown by spray pyrolysis technique. Modern Physics Letters B, 2019, 33(4): 1950030
34. Palanichamy S, Mohamed J R, Kumar P S S, Pandiarajan S, Amalraj L. Volume of precursor solution effect on the properties of SnO_2 thin films prepared by nebulized spray pyrolysis technique. Optical and Quantum Electronics, 2018, 50(9): 346
35. Palanichamy S, Mohamed J R, Kumar K D A, Anitha M, Pandiarajan S, Amalraj L. Effect of molar concentration on physical properties of spraydeposited SnO_2 thin films using nebulizer. Journal of Sol-Gel Science and Technology, 2019, 89(2): 392–402
36. Abdelkrim A, Rahmane S, Nabila K, Hafida A, Abdelouahab O. Polycrystalline SnO_2 thin films grown at different substrate temperature by pneumatic spray. Journal of Materials Science Materials in Electronics, 2017, 28(6): 4772–4779
37. Dhandayuthapani T, Sivakumar R, Ilangovan R, Gopalakrishnan C, Sanjeeviraja C, Jeyadheepan K. Eco-friendly nebulized spray deposition of bifunctional anatase TiO_2 thin films exhibiting multicolor switching and efficient NH_3 gas sensing at room temperature. Materials Research Express, 2019, 6(6): 065053