Fabrication of Efficient Organic-Inorganic Perovskite Solar Cells in Ambient Air

Jian Wu, Jing-Jing Dong*, Si-Xuan Chen, Hui-Ying Hao, Jie Xing and Hao Liu

Abstract

Although many groups have been trying to prepare perovskite solar cells (PSCs) in ambient air, the power conversion efficiency (PCE) is still low. Besides, the effect of moisture on the formation of perovskite films is still controversial. In this paper, we studied the effect of moisture on the formation of perovskite films in detail, and found that moisture can speed up the crystallizing process of PbI$_2$ films to form poor-quality films with large grain size and surface roughness, while, for the conversion of PbI$_2$ to perovskite films, a small amount of moisture is not adverse, and even beneficial. On this basis, we report the successful fabrication of efficient mesoporous PSCs with PCE of 16.00% under ambient air conditions at 25% relative humidity by adding a small amount of n-butyl amine into the solution of PbI$_2$ to enhance the quality of PbI$_2$ films and thus to achieve high-quality perovskite films with smooth surface, large crystal grains, and high crystal quality.

Keywords: Ambient air, Moisture, N-butyl amine, Perovskite solar cells

PACS: 81.05.Lg, 61.72.Cc, 81.10.Dn, 84.60.Jt

Background

Organic-inorganic perovskite solar cells (PSCs) have become a pacemaker in the photovoltaic community with a rapid increase in the power conversion efficiency (PCE) from initial 3.8% in 2009 to a recently reported 22.7% [1–3], due to the high absorption coefficient, low exciton-binding energy, long charge carrier diffusion length, and high mobility of the organic-inorganic perovskite materials [4–12]. Unfortunately, the organic-inorganic perovskite materials are very sensitive to moisture due to the hygroscopic nature of the organic components [13], so the fabrication and long-term stability of PSCs in ambient air has been considered as one of the major challenges for future large-scale application. Interface engineering and encapsulation technology are widely used to improve the stability of PSCs in ambient air, which gains obvious effect [14, 15]. To avoid moisture in ambient air during the fabrication process of PSCs, most groups prepare PSCs inside a N$_2$-filled glove box. There are also several research groups, who found that when perovskite materials were prepared in glovebox under inert atmosphere, the resulting perovskite films remained poorly crystalline, but, once exposed to a special controlled humidity atmosphere, a rapid crystallization into highly oriented crystallites was observed [16–19]. However, for future mass production, it is the best choice to fabricate highly efficient PSCs with a facile and simple way in ambient air, neither glove box nor a special controlled humidity atmosphere.

Recently, strategies have been achieved to develop the air-processed PSCs, and they can be generally divided into two methods: (i) finding unique and simple manufacturing processes to achieve high-quality perovskite films in ambient air; (ii) exploring new perovskite materials with fundamentally good air stability. For the first method, preheating substrates has been employed as a simple and effective manufacturing process to fabricate PSCs in ambient air. One group reported a highest PCE of 7.9% by preheating substrates at 200 °C before the one-step spin-coating of perovskite films in ambient air [20]. For the second method, CsPbBr$_3$-based inorganic PSCs have been fabricated in ambient air which exhibits the highest PCE of 7.78% [21]. Besides, Tai et al. reported a type of efficient and stable perovskite solar cells prepared in ambient air by using lead (II) thiocyanate precursor instead of PbI$_2$. Upon optimization, the devices demonstrated average PCEs over 13%, together
with the maximum value of 15% [22]. However, the authors did not study the role moisture plays on the crystallizing process of PbI₂ films and conversion of PbI₂ to perovskite films in detail. Although many groups have been trying to prepare PSCs in ambient air, the PCE is still low, seldom reaches 16% as reported [13]. Besides, the effect of moisture on the formation of perovskite films is still controversial.

In this work, we report the successful fabrication of efficient mesoporous PSCs with PCE of 16.00% under ambient air conditions at 25% relative humidity (RH) by adding a small amount of n-butyl amine (BTA) into the solution of PbI₂ to enhance the quality of PbI₂ films and thus to achieve high-quality perovskite films with smooth surface, large crystal grains, and high crystal quality. Besides, to study the effect of moisture on the formation of perovskite films, the performance of mesoporous PSCs prepared under different RHs without BTA additive has been investigated in detail. Combining SEM and XRD characterizations of PbI₂ and perovskite films with and without BTA additive, it is clear that moisture can speed up the crystallizing process of PbI₂ films to form poor-quality films with large grain size and surface roughness, while, for the conversion of PbI₂ to perovskite films, a small amount of moisture is not adverse, and even beneficial.

Methods

Fabrication of Perovskite Solar Cells

A mesoporous device structure was adopted for the device fabrication, as shown in Fig. 1a. Fluorine-doped transparent conducting SnO₂-coated glass substrates (FTO) with a sheet resistance of 7 Ωsq⁻¹ were cleaned with acetone, ethanol, isopropanol, deionized water, and isopropanol respectively. A compact TiO₂ (c-TiO₂) layer was deposited on the FTO substrates by spin coating at 3000 rpm for 30 s (repeat twice, followed by annealing at 150 °C for 15 min for each time), and then the c-TiO₂ layer was annealed at 500 °C for 30 min. Once cooling to the room temperature, a mesoporous TiO₂ (mp-TiO₂) layer was deposited by spin-coating at 5000 rpm for 45 s using a TiO₂ paste (18NRD) diluted in EtOH (1:7, weight ratio). After drying at 80 °C for 40 min, the mp-TiO₂ layer was sintered at 500 °C for 30 min. Once cooling to the room temperature, the film was dipped in the aqueous solution of TiCl₄ for 30 min at 70 °C, rinsed with deionized water, and finally annealed at 500 °C for 30 min. After that, perovskite films were prepared by the two-step spin-coating method as follows. Firstly, 1 M of PbI₂ in N,N-dimethylformamide (DMF) (adding a small amount of BTA into the solution) was spin coated onto the mp-TiO₂ layer at 3000 rpm for 30 s, and then annealed at 70 °C for 15 min. After the PbI₂ films cooled down to room temperature, the solution of methylammonium (MA) iodide was spin coated onto PbI₂ films at 4000 rpm for 45 s. Finally, the samples were annealed at 100 °C for 30 min to grow into MAPbI₃ films. Cooling down to room temperature, the 2,2',7,7'-Tetrakis[N,N-di(4-methoxyphenyl)amino]-9,9'-spiro-bifluorene (Spiro-OMeTAD) layer was spin-coated at 2000 rpm for 45 s, where 80 mg Spiro-OMeTAD in 1 mL chlorobenzene solution was employed with the addition of 28.8 μL 4-tert-butylypyridine (TBP) and 17.7 μL lithium bis(trifluoromethanesulfonyl)imide (Li-TFSI) solution (520 mg Li-TFSI in 1 mL acetonitrile). Finally, Ag back electrode was deposited by thermal evaporation. The active area of the device was 0.1 cm².

During the fabrication process, four solar cells were fabricated in each FTO substrate. Among which, if the maximum PCE deviation is less than 3% in at least three solar cells with higher PCE values, then their performance parameters will be recorded.

Characterization

Current density-voltage (J-V) characteristic curves of photovoltaic cells were measured by a source meter (Keithley, 2400) with a solar simulator (Zolixss150) under 100 mW cm⁻² AM 1.5G illumination; the light intensity was calibrated by means of a silicon reference

![Fig. 1](attachment:image.png)
Fig. 2 Box Charts of (a) $V_{OC}$, (b) $J_{SC}$, (c) FF, and (d) PCE for mesoporous PSCs prepared under different RHs at 30 °C without the adding of BTA during the two-step spin-coating of perovskite films.

Fig. 3 SEM images of PbI$_2$ films on FTO/c-TiO$_2$/mp-TiO$_2$ substrates without (a) and with (b) BTA additive; and corresponding MAPbI$_3$ films without (c) and with (d) BTA additive prepared under 25% RH.
solar cell. The active area of the devices was 0.1 cm². Typical J-V curves were obtained from scanning in reverse bias direction at the step width of 200 mV. The voltage was scanned from 1.2 to −0.2 V at a rate of 100 mV s⁻¹. The J-V measurement was carried out in ambient air. An emission Hitachi S-4800 was used to obtain scanning electron microscopy (SEM) images with the electron beam acceleration in the range of 15 to 60 KV. The characteristic X-ray diffraction (XRD) patterns were recorded between 10° and 70°, using the Cu-Kα radiation at 1.5405 Å. The light absorbance spectra were required by using Cary 5000 UV-Vis spectrophotometer in the wavelength range of 200 to 1200 nm with 1 nm increment. All the measurements of these films were carried out in ambient air without humidity control.

Results and Discussion

To study the effect of moisture on the formation of perovskite films, two-step spin-coating experiments under different RHs at 30 °C without the adding of BTA were designed, and the corresponding statistic results of detailed photovoltaic parameters are shown in Fig. 2. With the increase of RH from 0 to 15%, all of the photovoltaic parameters, including open-circuit voltage (VOC), short-circuit current density (JSC), fill factor (FF), and PCE, are improved obviously. As reported, a small amount of moisture could promote ion diffusion in the precursor film, facilitate the perovskite crystal growth, and thus induce a rapid crystallization into highly oriented crystallites [13, 23]. Therefore, better performance of PSCs under 15% RH was observed, compared with the PSCs fabricated in the glovebox (0% RH). Going on to increase the RH, the photovoltaic parameters, VOC, JSC, FF, and PCE, begin to drop sharply, as shown in Fig. 2. When the RH rises to 45%, the average value of VOC, JSC, FF, and PCE drops to 1.00 V, 9.84 mA/cm², 51.02%, and 5.02%, respectively. The drastic decline of PCE under 45% RH is mainly caused by the sharp decrease in JSC. It was reported that too much moisture could cause poor surface morphology and even decomposition of perovskite films, so the JSC of PSCs dropped sharply under 45% RH [18]. According to the results above, the optimal humidity conditions for two-step spin-coating of perovskite films in ambient air without the adding of BTA is 15% RH, and the corresponding highest PCE is 13.21% (average PCE is 12.48%), which is too low to meet future mass production. Besides, the results above are still insufficient to explain the role that moisture plays on the formation of perovskite films during two-step spin-coating.

To improve the performance of the PSCs prepared in ambient air and further investigate the role that moisture plays on the formation of perovskite films, a small amount of BTA was added into the solution of PbI₂. BTA, who has strong volatility, well infiltrative property, and strong Lewis base nature [13], will isolate the PbI₂ films from part of the moisture in ambient air, help the PbI₂ solution to spread out on the substrates easily and homogeneously, and greatly slow down the crystallization rate to form high-quality PbI₂ films.

As known, the morphology, such as grain sizes, surface roughness, and pinholes, of perovskite films plays an important role in the performance final PSCs. For the typical two-step spin-coating process of perovskite films, controlling the morphology of PbI₂ films is a key strategy for controlling the morphology of perovskite films [13, 19, 24]. However, it is disappointing to prepare high-quality PbI₂ films in ambient air with 25% RH, as illustrated by the SEM image shown in Fig. 3a, which exhibits inhomogeneous and porous structure with large grain size and surface roughness. The poor quality of the PbI₂ films under 25% RH can be mainly due to the moisture-induced rapid crystallization of PbI₂ films. After the addition of a small amount of BTA into the PbI₂ solution, a full coverage,
continuous, and homogeneous PbI\textsubscript{2} film with small grain size and low surface roughness is obtained, as presented in Fig. 3b. The high-quality PbI\textsubscript{2} films can be attributed to the strong volatility, well infiltrative property, and strong Lewis base nature of BTA, who will isolate the PbI\textsubscript{2} films from part of the moisture in the ambient air, help the PbI\textsubscript{2} solution to spread out on the substrates homogeneously, and greatly slow down the crystallization rate to form high-quality PbI\textsubscript{2} films in ambient air with 25% RH. As stated earlier, for the typical two-step spin-coating process of perovskite films, controlling the morphology of PbI\textsubscript{2} films is a key strategy for controlling the morphology of perovskite films [13, 19, 24]. By virtue of the high-quality PbI\textsubscript{2} films shown in Fig. 3b, high-quality MAPbI\textsubscript{3} films composed of densely packed big crystal grains without any pinholes are prepared as shown in Fig. 3d, while inhomogeneous MAPbI\textsubscript{3} films with small grain size and amounts of pinholes are obtained using the poor-quality PbI\textsubscript{2} films as shown in Fig. 3c. In addition, the high-quality MAPbI\textsubscript{3} films shown in Fig. 3d is converted from PbI\textsubscript{2} in ambient air with 25% RH, indicating a small amount of moisture (25% RH) is not adverse, and even beneficial for the conversion of PbI\textsubscript{2} to perovskite films.

The crystal quality of as-grown PbI\textsubscript{2} and MAPbI\textsubscript{3} films, prepared in ambient air with and without BTA additive, was characterized by the XRD measurement. Figure 4a, b shows the XRD patterns of PbI\textsubscript{2} and MAPbI\textsubscript{3} films respectively, and it can be seen that the PbI\textsubscript{2} and MAPbI\textsubscript{3} films with and without BTA additive exhibit almost the same crystalline phase. As shown in Fig. 4a, the XRD patterns of PbI\textsubscript{2} films with and without BTA additive show the intense diffraction peak at 12.69°, corresponding to the characteristic peak of PbI\textsubscript{2}. However, the peak at 12.69° reduces significantly in the PbI\textsubscript{2} film with BTA additive, which can be explained as follows. On the one hand, as mentioned above, BTA has well infiltrative property and can help the PbI\textsubscript{2} solution to spread out on the substrates easily and homogeneously. On the other hand, grain size of the PbI\textsubscript{2} film with BTA additive is much smaller than the PbI\textsubscript{2} film without BTA additive, as evidenced by the SEM images in Fig. 3 and the increase in full width at half maximum (FWHM) with BTA additive shown inset of Fig. 4a. Figure 3b shows the XRD patterns of MAPbI\textsubscript{3} films prepared with and without BTA additive. As can be seen, the diffraction peaks were present at 2θ values of 14.06°, 20.00°, 23.45°, 28.42°, 31.86°, 40.59°, and 43.21° corresponding to the reflection planes of (110), (112), (202), (220), (310), (224), and (404) of the tetragonal perovskite structure [25], respectively. Additionally, the characteristic peak of PbI\textsubscript{2}, at 12.69°, is also observed in both the two MAPbI\textsubscript{3} films prepared with and without BTA additive. The films prepared under ambient conditions lead to the incomplete conversion of PbI\textsubscript{2} to MAPbI\textsubscript{3}, due to the termination of nucleation and growth of the perovskite caused by the formation of relatively continuous capping layer on the surface [26]. It is reported that a little bit of PbI\textsubscript{2} can improve the performance of PSCs by passivating the defects in perovskite films [19, 26]. Furthermore, the MAPbI\textsubscript{3} film prepared without BTA additive shows much higher intensity for the peak at 12.69°, compared with the film prepared with BTA additive. This suggests that there are too much PbI\textsubscript{2} residual in the MAPbI\textsubscript{3} film prepared without BTA additive attributed to the poor-quality PbI\textsubscript{2} film without

---

**Fig. 5 UV-Vis absorption spectrum of MAPbI\textsubscript{3} films on quartz substrates with and without BTA additive. Insets are cross-section SEM images of MAPbI\textsubscript{3} films prepared with (a) and without (b) BTA additive.**
BTA additive leading to the insufficient reaction between PbI₂ and MAI.

Combining SEM and XRD results above, it is clear what role moisture plays in the two-step spin-coating of MAPbI₃ films in ambient air. For the PbI₂ films, moisture can speed up the crystallizing process to form poor-quality PbI₂ films with large grain size and surface roughness. However, for the conversion of PbI₂ to the MAPbI₃ films, a small amount of moisture (25% RH) is not adverse, and even beneficial.

UV-Vis absorption spectrum of MAPbI₃ films prepared with and without BTA additive is presented in Fig. 5. All the two samples show an absorbance at a threshold of about 780 nm in the overall visible region, indicating the formation of MAPbI₃ crystallites [27]. As can be seen, the MAPbI₃ films with BTA additive shows lower absorbance, which is attributed to its relatively smaller thickness compared with the films without BTA additive, as confirmed in the cross-section SEM images of MAPbI₃ films (insets of Fig. 5). Besides, the weak absorption shoulder at about 510 nm, which appears in all the two spectra, is a characteristic feature of PbI₂, implying the residual of PbI₂ as confirmed by the XRD measurement.

The MAPbI₃ films prepared with and without BTA additive was then used to construct PSCs with the structure of FTO/c-TiO₂/mp-TiO₂/MAPbI₃/Spiro-OMeTAD/Ag, and the corresponding J-V characteristics of the devices under AM 1.5G one sun (100 mW cm⁻²) illumination are shown in Fig. 6, the inset of which is the detailed photovoltaic performance.

![Fig. 6 J-V characteristics of the PSCs fabricated with and without BTA additive in ambient air with 25% RH under AM 1.5G one sun (100 mW cm⁻²) illumination, the inset is the detailed photovoltaic performance.](image)

BTA additive at 25% RH showed the highest PCE of 11.38%, with J_Sc of 19.97 mA/cm², V_OC of 0.98 V, and FF of 58.15%. When introducing BTA additive, the devices showed significant improvements in all of the four photovoltaic parameters. There into, the device using perovskite films prepared with BTA additive showed the highest PCE of 16.00%, which is improved by ~ 40% compared with the PSCs using perovskite films prepared without BTA additive, with J_Sc of 22.29 mA/cm², V_OC of 1.10 V, and FF of 65.25%, which was attributed to the high-quality perovskite films with smooth surface, large crystal grains, and high crystal quality.

**Conclusions**

In conclusion, we studied the effect of moisture on the formation of perovskite films in detail, and found that moisture can speed up the crystallizing process of PbI₂ films to form poor-quality films with large grain size and surface roughness, while, for the conversion of PbI₂ to MAPbI₃ films, a small amount of moisture (25% RH) is not adverse, and even beneficial. On this basis, by adding a small amount of BTA into the solution of PbI₂ to enhance the quality of PbI₂ films and thus to achieve high-quality perovskite films with smooth surface, large crystal grains, and high crystal quality, we fabricated mesoporous PSCs with PCE of 16.00% under ambient air conditions at 25% RH. The results may pave a new way for fabricating efficient and reproducible PSCs under ambient air condition.

**Abbreviations**

BTA: N-butyl amine; c-TiO₂: Compact TiO₂; DMF: N,N-dimethylformamide; FF: Fill factor; FTO: Fluorine-doped transparent conducting SnO₂-coated glass.
Acknowledgements

Thanks to China University of Geosciences Beijing for all the support through our research on perovskite solar cells.

Funding

This work was financially supported by “the National Natural Science Foundation of China” (Grant No. 11404283) and the "Fundamental Research Funds for the Central Universities" (Grant No. 2652017149 and 2652015189).

Availability of Data and Materials

The datasets supporting the conclusions of this article are included within the article.

Authors’ Contributions

JJD carried out the experiment and characterization, analyzed results, and participated in the draft of the manuscript. JJD designed the experiment, supervised the research, and revised the manuscript. SXC, HYH, JX, and HL offered the technique supports. All authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

Publisher’s Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Received: 17 August 2018 Accepted: 10 September 2018

Published online: 21 September 2018

References

1. Green M, Ho-Baillie A, Snath H (2014) The emergence of perovskite solar cells. Nat Photonics 8:506–514
2. Shi D, Adinolfi V, Comin R, Yuan M, Alarousu E, Buin A, Chen Y, Hoogland S, Rothenberger A, Katsiev K, Losowy Y, Zhang X, Dowben P, Mohammed O, Sargent E, Barz O (2015) Low trap-state density and long carrier diffusion in organoaluminum halide perovskite single crystals. Science 347:519–522
3. Kojima A, Teshima K, Shirai Y, Miyasaka T (2009) Organometal halide perovskite as visible-light sensitizers for photovoltaic cells. J Am Chem Soc 131:6025–6026
4. You J, Meng L, Song T, Gou T, Yang Y, Chang W, Hong Z, Chen Z, Hou Z, Chen Q, Liu Y, Marco N, Yang Y (2015) Improved air stability of perovskite solar cells via solution-processed metal oxide transport layers. Nat Nanotechnol 11:75–81
5. Tan H, Jain A, Voznyy O, Lan X, Arquer F, Fan J, Quintero-Bermudez R, Yuan M, Zhang B, Zhao Y, Fan F, Li P, Quan L, Zhao Z, Yang Z, Hoogland S, Sargent E (2017) Efficient and stable solution-processed perovskite solar cells via contact passivation. Science 355:722–726
6. Zhou H, Chen Q, Li G, Luo S, Song T, Duan H, Hong Z, You J, Liu Y, Yang Y (2014) Interfacial engineering of highly efficient perovskite solar cells. Science 345:542–546
7. Breen TM, Egger DA, Kronik L, Hodes G, Cahan D (2016) Hybrid organic—inorganic perovskites: low-cost semiconductors with intriguing charge-transport properties. Nat Rev 1:15007
8. Correa-baena JP, Anaya M, Lozano G, Tress W, Domanski K, Saliba M, Matsui T, Jacobsson T, Calvo M, Abate A, Grätzel M, Míguez H, Hagfeldt A (2016) Unbroken perovskite interplay of morphology, electro-optical properties, and ionic movement. Adv Mater 28:5031
9. Ke W, Xiao C, Wang C, Saparov B, Duan HS, Zhao D, Xiao Z, Schulz P, Harvey S, Liao W, Meng W, Yu Y, Cimaroli A, Jiang C, Zhu K, Al-Jassim M, Fang G, Mitzi D, Yan (2016) Employing Lead thiocyanate additive to reduce the hysteresis and boost the fill factor of planar perovskite solar cells. Adv Mater 28:5214–5221
10. Giuri A, Masi S, Colella S, Kovtun A, Dell’Elce S, Treossi E, Liscio A, Corcione CE, Rizzo A (2016) Cooperative effect of GO and glucose on PEDOT:PSS for high Voc and hysteresis-free solution-processed perovskite solar cells. Adv Funct Mater 26:6985–6994
11. Yuan Y, Wang Q, Shao Y, Lu H, Li T,Groverman G, Huang J (2016) Electric-field-driven reversible conversion between methylammonium lead triiodide perovskites and lead iodide at elevated temperatures. Adv Energy Mater 6:1501803–1501809
12. Liu Y, Hong Z, Chen Q, Chen H, Chang WH, Yang Y, Song T, Yang Y (2015) Perovskite solar cells employing dopant-free organic hole transport materials with tunable energy levels. Adv Mater 28:440–446
13. Liu D, Li Y, Shi B, Yao X, Fan L, Zhao S, Liang J, Ding Y, Wei C, Zhang D, Zhao Y, Zhang X (2017) Tailoring morphology and thickness of perovskite layer for flexible perovskite solar cells on plastics: the role of CH3NH3I concentration. Sol Energy 147:222–227
14. Luo H, Lin X, Hou X, Pan L, Huang S, Chen X (2017) Efficient and air-stable planar perovskite solar cells formed on graphene-oxide-modified PEDOT:PSS hole transport layer. Nano-Micro Lett 9:39
15. Bi E, Chen H, Xie F, Wu Y, Chen W, Su Y, Islam A, Gratzel M, Yang X, Han L (2017) Diffusion engineering of ionic charge carriers for stable perovskite solar cells. Nat Commun 8:15330
16. Bass K, Mcanally R, Zhou S, Djurovich P, Thompson M, Melet B (2014) Influence of moisture on the preparation, crystal structure, and photophysical properties of organohalide perovskites. Chem Commun 50:15819–15822
17. Xu Y, Zhu L, Shi J, Xu X, Xiao J, Dong J, Wu H, Luo Y, Li D (2016) Meng Q: the effect of humidity upon the crystallization process of two-step spin-coated organic-inorganic perovskites. Chemphyschem 17:112–118
18. Yang J, Siempelkamp B, Liu D, Kelly T (1995) Investigation of CH3NH3PbI3 degradation rates and mechanisms in controlled humidity environments using in situ techniques. ACS Nano 9:1955
19. Kumar Y, Regalado-Pérez A, Ayala A, Mathews N, Mathew X (2016) Effect of heat treatment on the electrical properties of perovskite solar cells. Sol Energy Mater Sol Cells 157:10–17
20. Shin G, Cho W, Na S, Ryu S, Moon T (2016) Rapid crystallization in ambient air for planar heterojunction perovskite solar cells. Electron Mater Lett 13:1–5
21. Chen W, Zhang J, Xu G, Xue R, Li Y, Zhou Y, Hou J, Li Y (2018) A semitransparent inorganic-perovskite film for overcoming ultraviolet light instability of organic solar cells and achieving 14.03% efficiency. Adv Mater 30:1800855
22. Tai Q, You P, Sang H, Liu Z, Hu C, Chan H, Yan F (2016) Efficient and stable perovskite solar cells prepared in ambient air irrespective of the humidity. Nat Commun 7:11105
23. You J, Yang Y, Hong Z, Song T, Meng L, Liu J, Yang C, Zhou H, Chang W, Li G, Yang Y (2014) Moisture assisted perovskite films growth for high performance solar cells. Appl Phys Lett 105:945
24. Zheng J, Zhang M, Lau C, Deng X, Kim J, Ma Q, Chen C, Green M, Huang S, Ho-Baillie A (2017) Spin-coating free fabrication for highly efficient perovskite solar cells. Sol Energy Mater Sol Cells 168:165–171
25. Tripathi B, Bhart P, Kanth PC, Yadav P, Desai B, Pandey M, Kumar M (2015) Temperature induced structural, electrical and optical changes in solution processed perovskite material: application in photovoltaics. Sol Energy Mater Sol Cells 132:615–622
26. Kim Y, Jeon N, Noh J, Yang W, Seo J, Yun J, Ho-Baillie A, Huang S, Green M, Seidel J, Ahn T, Seok S (2016) Beneficial effects of PbI2 incorporated in organo-lead halide perovskite solar cells. Adv Energy Mater 6:1502104–1502111
27. Guo Y, Liu C, Tanaka H, Nakamura E (2015) Air-stable and solution-processable perovskite photodetectors for solar-blind UV and visible light. J Phys Chem Lett 6:535.