Room-Temperature Sputtered SnO₂ as Robust Electron Transport Layer for Air-Stable and Efficient Perovskite Solar Cells on Rigid and Flexible Substrates

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Extraordinary photovoltaic performance and intriguing optoelectronic properties of perovskite solar cells (PSCs) have aroused enormous interest from both academic research and photovoltaic (PV) industry. In order to bring PSC technology from laboratory to market, material stability, device flexibility, and scalability are important issues to address for vast production. Nevertheless, PSCs are still primarily prepared by solution methods which limit film scalability, while high-temperature processing of metal oxide electron transport layer (ETL) makes PSCs costly and incompatible with flexible substrates. Here, we demonstrate rarely-reported room-temperature radio frequency (RF) sputtered SnO₂ as a promising ETL with suitable band structure, high transmittance, and excellent stability to replace its solution-processed counterpart. Power conversion efficiencies (PCEs) of 12.82% and 5.88% have been achieved on rigid glass substrate and flexible PEN substrate respectively. The former device retained 93% of its initial PCE after 192-hour exposure in dry air while the latter device maintained over 90% of its initial PCE after 100 consecutive bending cycles. The result is a solid stepping stone toward future PSC all-vapor-deposition fabrication which is being widely used in the PV industry now.

Perovskite solar cells (PSCs) as a promising and emerging photovoltaic (PV) technology have quickly caught enormous attention in both academic research and PV industry over the past few years. As one of the most intensively researched types of solar cells, PSCs have been rapidly developed with unprecedented success, leading to a significant improvement on power conversion efficiency (PCE) from 3.8% to certified 22.7% within a decade. Besides high device performance, low fabrication cost as well as tunable composition and bandgap give this group of semiconductors gigantic potential and intriguing optoelectronic properties for next-generation solar cell. Crystal growth optimization, interfacial engineering, compositional optimization, and device architecture design have been further explored to enhance PCE and stability of devices and eventually make them competitive with conventional silicon and other leading thin film solar cell technologies.

Typically, a PSC consists of an electron transport layer (ETL), a perovskite film and a hole transport layer (HTL), in addition to top and bottom electrical contacts. Particularly, inorganic metal-oxide films, such as TiO₂ and ZnO, have been widely reported as effective ETLs for high-performance PSCs. Nevertheless, they both have major drawbacks. TiO₂ as the most commonly used ETL has low electron mobility and requires sintering at high temperature up to 500 °C. High temperature processing not only increases the cost of device fabrication, but also restricts the compatibility with flexible substrates. In addition, TiO₂ provokes perovskite degradation under exposure of UV illumination which is problematic during the prolonged device operation. On the other hand, the hygroscopic nature of ZnO easily causes perovskite decomposition in moisture environment. Moreover, ZnO has poor thermal stability so it can easily react with perovskite during annealing and thermal treatment at elevated temperature, which eventually stimulates undesired perovskite degradation or even decomposition. Like

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perovskite, TiO₂, and ZnO are mostly prepared by solution methods, which sacrifice film uniformity and limit large-scale device production. On the other hand, SnO₂ is regarded as an effective ETL to achieve low-cost PSCs with improved stability²¹,²². SnO₂ has a wider bandgap and its electron mobility is two orders of magnitude higher than that of TiO₂, making it a more suitable candidate for use in high performance devices²³. Compare to TiO₂ and ZnO, SnO₂ is less hygroscopic in nature, has better thermal and UV stability, and possesses lower photocatalytic activity²⁴. These properties prevent perovskite degradation and benefit PSC long-term stability. Despite that high-performance PSCs based on SnO₂ have been achieved, almost all reported SnO₂ films were prepared by spin-coating²⁵–³⁰, atomic layer deposition (ALD)³¹,³², plasma-enhanced ALD³³, sol-gel process³⁴, chemical bath deposition³⁵, hydrothermal process³⁶, and electrodeposition³⁷. In fact, many of these methods involve high-temperature processing and annealing ranging from 100 °C up to 550 °C, which again increases fabrication complexity and cost and makes it incompatible with flexible substrates. In order to make PSC technology cost-effective in the future, a fabrication technique allowing vast production is absolutely necessary.

Considering the high reliability, maturity, and capability for large-scale production of sputtering technique in both industries and laboratories, SnO₂ prepared by magnetron sputtering for PSC application is however rarely reported³⁸. And previously studied sputtered SnO₂ film was calibrated based on deposition time instead of thickness, which is a more accurate and reliable approach in principle since deposition time depends on a number of deposition parameters and equipment infrastructure. Moreover, previous study lacked investigation on device stability as well as thorough thin film characterization on their SnO₂ and the corresponding glovebox-processed spin-coated perovskite absorber, particularly morphology and crystallinity analysis by scanning electron microscopy (SEM), X-ray diffraction (XRD), and photoluminescence (PL). Therefore, it was hard to convince the effectiveness and compatibility of sputtered SnO₂ with perovskite solar cells. On the other hand, perovskite films are typically prepared by solution methods inside a glovebox filled with inert gas. Similarly, those solution methods limit film scalability while the use of glovebox increases production cost and complexity. Researchers have therefore put a great amount of effort to fabricate perovskite films and devices in ambient condition without sacrificing film quality, device performance, as well as stability³⁹,⁴⁰.

Here, we demonstrate room-temperature RF sputtered SnO₂ film as an effective and robust ETL and meanwhile take one step forward to implement it together with vapor-deposited perovskite absorber for air-stable and efficient PSCs on both rigid and flexible substrates. By this application, we are now only one step away from sputtered SnO₂ based all-vacuum-deposited perovskite solar cells which will eventually enable industrialization. To the best of our knowledge, there is no report of using sputtered SnO₂ for flexible PSCs application. Both SnO₂ thickness and deposition conditions including working pressure and gas environment were systematically investigated. Device stability and hysteresis were also carefully studied.

**Results and Discussion**

In this work, we demonstrated n-i-p planar structure of PSCs with optimized room-temperature-processed SnO₂ as ETL prepared by RF magnetron sputtering and vacuum-deposited perovskite film. Figure 1a shows the schematic of device structure of our PSCs: ITO-PEN/SnO₂/MAPbI₃/Spiro-OMeTAD/Au. Figure 1b,c display SEM images of complete device based on rigid FTO glass substrate and flexible ITO-PEN substrate respectively. The morphology and surface roughness of bare FTO (Supplementary Fig. S1), 40 nm SnO₂-coated FTO (Fig. 2a,b), and solution-processed SnO₂ (Fig. 2c,d) were studied by SEM and atomic force microscopy (AFM). Supplementary AFM reveals the root-mean-square (RMS) roughness and mean roughness of bare FTO glass were 7.736 nm and 6.096 nm respectively. In contrast, 40 nm SnO₂-coated FTO had a RMS roughness and mean roughness of 5.488 nm and 4.358 nm respectively, while solution-processed SnO₂ had higher RMS roughness and mean roughness of 6.439 nm and 5.000 nm. It is reflected that sputtered SnO₂ film was uniformly deposited on FTO surface and SnO₂ grains were small enough to fill in the gaps between FTO grains, leading to a lower surface roughness than solution-processed SnO₂, which is beneficial for the growth of vapor-deposited perovskite. To illustrate how surface roughness matters, perovskite was vapor-deposited on a 10 nm SnO₂-coated FTO with RMS roughness and mean roughness of 7.199 nm and 5.708 nm respectively, measured by AFM (Supplementary Fig. S2).
was clear that perovskite grain sizes on the 10 nm SnO2-coated FTO were significantly reduced (Supplementary Fig. S3a). Moreover, cross-sectional SEM shown in Supplementary Fig. S3b reveals that the perovskite grains and shape became more irregular on 10 nm SnO2-coated FTO, while single-crystal-thick perovskite grains with larger grain sizes and regular shapes were crystallized on 40 nm SnO2-coated FTO (Supplementary Fig. S3c,d). In addition, small perovskite grains tended to crystallize in the perovskite-SnO2 interface on 10 nm SnO2-coated FTO, which could adversely affect the efficiency of carrier transport. Since materials were slowly deposited onto substrate down to a few angstroms per second, a rougher surface would hinder the ion migration and volumetric expansion as perovskite crystallization took place. In contrast, this problem becomes less significant when perovskite is prepared by solution methods because they allow ions within the precursors to easily spread all over the substrates without overcoming significant energy barriers. Therefore, this problem was not commonly discussed in depth before. In contrast, although perovskite grown on solution-processed SnO2 film (Supplementary Fig. S4) demonstrated comparable grain size with those grown on sputtered SnO2, the former perovskite films exhibit layered structure on most of the grains. This could be attributed to the higher roughness of solution-processed SnO2 film, leading to inconsistent rate and degree of perovskite crystallization and ultimately high surface roughness. These could increase the probability of carrier recombination between perovskite absorber and the HTL.

The full ultraviolet photoelectron spectroscopy (UPS) spectrum of sputtered SnO2 is shown in Supplementary Fig. S5a. The sputtered SnO2 film showed a secondary cutoff edge of 5.01 eV (Supplementary Fig. S5b), indicating a work function $W_S$ of 5.01 eV. Supplementary Fig. S5c shows the valence band maximum (VBM) of the sputtered SnO2 film is located at 3.07 eV below $E_F$. The bandgap of the sputtered SnO2 film acquired from the Tauc plot (Fig. 3a) was 3.72 eV, which is wider than that of ZnO and TiO2. A wider bandgap implies better hole blocking ability and can avoid absorption of high-energy photons which leads to small current loss. Based on the above values, it can be calculated using the semiconductor band structure ($E_C = W_S + VBM - E_G$) that the $E_C$ of the sputtered SnO2 film was 4.36 eV, which is deeper than that of TiO2 and ZnO, both are 4.2 eV. The deeper conduction band of SnO2 compared to TiO2 and ZnO could enhance electron transfer from perovskite to the ETL. On the other hand, calculation showed $E_V$ of the sputtered SnO2 film was 8.08 eV, which is much deeper than that of TiO2 and ZnO, 7.4 eV and 7.6 eV respectively. The deeper valence band of SnO2 can enhance hole blocking ability from perovskite to the ETL. Figure 3b shows the energy band diagram of each device component and the transportation of photo-generated electrons and holes.

Being an effective ETL for PSCs of n-i-p planar structure, transmittance, thickness, and film quality are crucial. XRD (Fig. 3c) revealed that both sputtered and solution-processed SnO2 films were polycrystalline but the former one exhibited better crystallinity. All XRD peaks for SnO2 were indexable to the tetragonal SnO2 structure, indicating the formation of pure SnO2 crystals. In addition, sputtered SnO2 film on FTO glass showed good
transparency with transmittance close to 90% in the visible region (Fig. 3d), while solution-processed SnO₂ had lower transmittance of about 80%. It is noteworthy the room-temperature sputtered SnO₂ here demonstrated even higher transmittance than other high-temperature-processed spin-coated SnO₂ films. To obtain high-quality SnO₂ films, impact of thickness, sputtering working pressure, and the flow rates of O₂ and Ar during sputtering were systematically studied.

Since the thickness of ETL can critically affect cell performance, SnO₂ film was first sputtered under the same sputtering power of 60 W on FTO glass substrates kept at room temperature with four different thicknesses, 20 nm, 40 nm, 60 nm, and 80 nm, which took 8 min, 15 min, 23 min, and 30 min for sputtering, respectively. It can be inferred that the deposition rate was approximately 0.43 Å s⁻¹. After sputtering, SnO₂-coated FTO substrates were transferred to the evaporator for perovskite fabrication via a two-step vapor deposition as described in the Method section. The as-deposited perovskite samples were annealed in ambient air condition with over 65% humidity. It has been reported that certain level moisture is helpful for perovskite crystallization but excessive moisture could be detrimental to perovskite. To overcome the humidity problem, perovskite samples were annealed for a short period of time at elevated temperature to accelerate the perovskite crystallization process and meanwhile minimize perovskite film degradation in ambient condition. As-deposited perovskite samples were annealed at 130 °C for 10 min instead of the conventional 100 °C for an hour. It turned out that this method is also workable for vapor-deposited perovskite films, not only for solution-processed perovskite films. The UV-vis absorption spectra shown in Fig. 4a of the vapor-deposited perovskite shows good absorption in the visible region. It also revealed that perovskite grown on sputtered SnO₂ exhibited higher absorption than that grown on solution-processed SnO₂, which was attributed to its lower transmittance than sputtered SnO₂. The absorption onset corresponded to an optical bandgap of 1.57 eV estimated from the Tauc plot (Supplementary Fig. S6). The estimation matches well with the perovskite PL peak at 788 nm and the steady PL showed a more significant quench when depositing the perovskite film on sputtered SnO₂ compared to solution-processed perovskite. It supports that sputtered SnO₂ possessed more efficient electron transport ability. XRD of perovskite (Fig. 4c) presented the expected perovskite pattern, with intense signals at 14.1°, 28.4°, and 31.9° corresponding to the (100), (200), and (310) directions, respectively. It showed an extra peak of PbI₂ at 12.7° for perovskite that underwent 30 min prolonged annealing in humid air condition. Supplementary Fig. S7 shows the SEM of perovskite annealed for 30 min. The perovskite decomposing into PbI₂ hindered its crystallization by grain boundary expansion and grain cracking. As a consequence, the intensity of each perovskite peak was clearly reduced as shown in Fig. 4c. It confirms the effectiveness of short-time annealing processing at elevated temperature in ambient condition.

The J-V characteristics of devices based on FTO glass substrates with different SnO₂ thicknesses measured under AM1.5G illumination are shown in Fig. 5a. The device performance firstly increased and then decreased as...
The sputtered SnO$_2$ thickness increased. It is seen that devices with 40 nm SnO$_2$ yielded the best performance, with a PCE of 11.14%, a VOC of 0.934 V, a JSC of 22.91 mA cm$^{-2}$, and a fill factor (FF) of 52.1%, so 40 nm was taken as the optimum thickness. If the SnO$_2$ layer was too thin, it could not fully cover the FTO surface for effective electron transport. On the other hand, a too thick SnO$_2$ layer would induce a larger series resistance.

The sputtering working pressure is another critical factor to determine the sputtered film quality. We fabricated PSCs based on 40 nm SnO$_2$ sputtered under the same power of 60 W but three different working pressures, 0.25 Pa, 0.5 Pa, and 1.0 Pa. The $J$-$V$ characteristics of respective devices are shown in Fig. 5b. The device performance, particularly the $V_{OC}$, decreased as working pressure increased. It is seen that devices with SnO$_2$ sputtered at 0.25 Pa yielded the best performance, with a PCE of 12.18%, a $V_{OC}$ of 0.948 V, a $J_{SC}$ of 22.34 mA cm$^{-2}$, and an FF of 57.5%, so 0.25 Pa was taken as the optimum working pressure. An optimum working pressure is important so that the mean free path of gas molecules (O$_2$ and Ar) is comparable to the distance between the target and substrates. A high working pressure will reduce the mean free path of molecules. In other words, there will be so much scattering that electrons will not have enough time to gather enough energy between collisions to ionize the atoms on the target. As a result, it causes a less uniform film deposition over the substrates. The reduced $V_{OC}$ is attributed to uneven deposition due to too high working pressure. Sputtering under working pressure below 0.25 Pa was attempted, however, the plasma became unsustainable and unstable around 0.2 Pa due to too low gas molecule concentration. In order to yield a self-sustaining plasma, each electron has to generate enough secondary emission. Therefore, 0.25 Pa was concluded to be the optimum working pressure for SnO$_2$ sputtering without compromising film quality and device performance.
The impact of flow rate of O₂ and Ar during SnO₂ sputtering on device performance was also studied. The flow rate of Ar was kept constant at 50 sccm while the flow rate of O₂ was varied from 1 sccm, 5 sccm, to 10 sccm (defined as FR1:50, FR5:50, and FR10:50 respectively). Figure 5c shows the J-V characteristics of champion PSCs using 40 nm SnO₂ sputtered under the same working pressure of 0.25 Pa but different flow rates of O₂ and Ar. The FR5:50 (O₂:Ar) PSC showed a PCE of 12.82% with a VOC of 0.965 V, JSC of 22.91 mA cm⁻², and FF of 58.0%. Its performance was slightly better than that of the device with a VOC of 0.938 V, JSC of 19.97 mA cm⁻², and FF of 46.2%. A possible reason is that too low oxygen flow rate (or partial pressure) does not favor stoichiometric SnO₂ sputtering. The fewer O₂ amount was not sufficient to compensate and combine with the tin ions sputtered out of the target to form high-quality SnO₂ film and hence worsened the hole blocking ability. The performance of devices using SnO₂ ETLs with different parameters are summarized in Table 1.

Table 1. Device performance of devices based on different sputtering parameters of SnO₂.

| SnO₂ Sputtering Condition | VOC (V) | JSC (mA cm⁻²) | FF (%) | PCE (%) |
|---------------------------|---------|---------------|--------|---------|
| 20 nm                     | 0.903   | 21.90         | 53.0   | 10.48   |
| 40 nm                     | 0.934   | 22.91         | 52.1   | 11.14   |
| 60 nm                     | 0.893   | 20.90         | 53.9   | 10.06   |
| 80 nm                     | 0.855   | 20.26         | 54.9   | 9.51    |
| 40 nm 0.25 Pa             | 0.948   | 22.34         | 57.5   | 12.18   |
| 40 nm 0.50 Pa             | 0.865   | 21.93         | 55.0   | 10.44   |
| 40 nm 1.0 Pa              | 0.708   | 21.61         | 47.1   | 7.20    |
| 40 nm 0.25 Pa FR1:50      | 0.938   | 19.97         | 46.2   | 8.66    |
| 40 nm 0.25 Pa FR5:50      | 0.965   | 22.91         | 58.0   | 12.82   |
| 40 nm 0.25 Pa FR10:50     | 0.935   | 22.73         | 57.6   | 12.24   |

To investigate the stability, both champion devices were left in room-temperature dry air with 30% humidity in dark for 192 hours. The J-V characteristics of both devices could only retain 77% of its initial PCE while the solution-processed SnO₂ based champion device could only retain 93% of its initial PCE when measured after 24 hours under reverse voltage scanning. Therefore, the device exhibits a small hysteresis. In comparison, Fig. 5e shows the J-V characteristics of the champion PSC based on solution-processed SnO₂. It showed a lower PCE of 10.78% with a VOC of 0.901 V, JSC of 21.75 mA cm⁻², and FF of 54.9% when measured under reverse voltage scanning and a lower PCE of 9.58% with a VOC of 0.891 V, JSC of 21.54 mA cm⁻², and FF of 49.9% when measured under forward voltage scanning. It exhibited a more significant hysteresis. The external quantum efficiency (EQE) of both champion devices are shown in Fig. 5f.

Flexibility is a desirable feature of thin film solar cells for a variety of applications, such as portable power sources, building-integrated photovoltaics, clothing and textiles, power-generating fabrics, and electronics with light-weight curved surface. One of the main advantages in the use of sputtered SnO₂ is that no sintering or annealing step is required thus very flexible plastic substrates can be used. The other major fabrication steps (vapour deposition of perovskite, spin-coating of Spiro-OMeTAD, and thermal evaporation of Au) are also carried out in room temperature condition, which means this fabrication process as a whole is compatible with flexible substrates. To date, majority of the reported flexible PSCs employ spin-coated TiO₂, ZnO, or PCBM as ETL47–51, while very few of them used solution-processed SnO₂ as ETL. To illustrate the compatibility of sputtered SnO₂ with flexible substrates for perovskite photovoltaics, in our work rigid FTO glass substrate was therefore replaced by flexible substrate, namely indium-doped-tin-oxide-coated polyethylene naphthalate (ITO-PEN) (Fig. 6a). Supplementary Fig. S10a shows the XRD spectrum of vapour-deposited perovskite grown on flexible ITO-PEN. It presented an
expected perovskite spectrum with sharp signal intensities and without PbI$_2$ residue, showing that vapor deposition and post-annealing treatment of perovskite on flexible substrates did not induce any perovskite degradation. 20 devices were fabricated using the same preparation procedures and their PCE distribution is summarized in Supplementary Fig. S10b. Figure 6b shows the J-V characteristics of the champion perovskite solar cell measured under reverse and forward voltage scanning with AM1.5G illumination. Normalized PCE (measured on a flat surface) after bending the substrate with decreasing radii of curvature $R$. All measurements were performed on a single device from the highest radius of curvature to the lowest. The linear fit is provided as a guide to the eye. Normalized PCE of a flexible PSC as a function of bending cycles at a radius of 2 cm.

Figure 6. Photograph and device performance of a perovskite solar cell prepared on a flexible PEN substrate. (a) Photograph of PSCs prepared on a flexible ITO-PEN substrate. (b) J-V characteristics of the champion perovskite solar cell measured under reverse and forward voltage scanning with AM1.5G illumination. (c) Normalized PCE (measured on a flat surface) after bending the substrate with decreasing radii of curvature $R$. All measurements were performed on a single device from the highest radius of curvature to the lowest. The linear fit is provided as a guide to the eye. (d) Normalized PCE of a flexible PSC as a function of bending cycles at a radius of 2 cm.

Mechanical flexibility of devices under bending stress is of great importance concerning flexible and/or wearable device applications. Bending tests showed how well the device performance retained after being bent repeatedly to decreasing radii of curvature. The identical flexible PSC was bent by mechanical force with 10 different radii of curvature in one bending cycle. After each round of bending, the device performance was measured repetitively. The impact of bending on device PCE is presented in Fig. 6c. Less than 12% drop in PCE was observed. This result indicated sputtered SnO$_2$ film is an effective and robust ETL for flexible PSC application. The impact of mechanical bending via multiple cycles of bending test was further evaluated. A total of 100 consecutive bending cycles at radius of 2 cm were performed. As shown in Fig. 6d, the device sustained over 90% of its initial PCE. After the bending test, $V_{OC}$, $J_{SC}$, and FF of the flexible device respectively dropped from 0.930 V to 0.929 V, from 8.76 mAcm$^{-2}$ to 8.72 mAcm$^{-2}$, and from 71.4% to 70.3%. Consequently, the PCE reduced from 5.82% to 5.69%. Although the flexible devices based on sputtered SnO$_2$ demonstrated lower PCE than devices based on TiO$_2$, ZnO, and PCBM, this is a pioneering work proving that sputtered SnO$_2$ is effective and robust on both rigid and flexible substrates for perovskite photovoltaics. Sputtering technique is desirable for upscaling device area with uniform film deposition while flexible devices are especially attractive for a variety of consumer-driven products.
Conclusion
We have pioneered the optimization and implementation of radio frequency magnetron sputtered SnO2 as electron transport layer for vapor-deposited-MAPbI3-based perovskite solar cells on both rigid and flexible substrates. It was demonstrated that neither mesoporous scaffold nor any high-temperature processing procedures were required to achieve efficient and air-stable devices without the use of a glove box. It is noteworthy that in the current device structure there was no backside passivation and all devices were not packaged, so the entire fabrication and characterization processes were subject to ambient condition of humidity greater than 65%. Despite the air processing in humid environment and perovskite annealing on flexible substrates, PSCs of 12.82% PCE on rigid glass substrates and 5.88% PCE on flexible substrates were achieved. We have also shown that the viability and repeatability of acquiring high-quality vapor-deposited perovskite films with large grain sizes and smooth morphology on sputtered SnO2 film via short-time annealing at elevated temperature processing in ambient condition, proving its compatibility with vapor-deposited perovskite films. More importantly, sputtered SnO2 based devices were demonstrated to have better device photovoltaic performance and stability than solution-processed SnO2 based devices. Such successful implementation of robust sputtered SnO2 films on flexible devices could serve as a promising route for future development and application of sputtered SnO2 film into large-scale cost-effective all-vacuum-deposited flexible perovskite photovoltaics.

Methods

Materials. FTO-coated glass substrates were purchased from Zhuhai Kaivo Optoelectronic Technology Co., Ltd. ITO-coated PEN substrates were purchased from Pecell Technologies, Inc. The SnO2 target of 2-inch diameter was purchased from Chinese Rare Metal Co. Ltd. CH3NH3I (MAI) was purchased from Dyosol. PbI2, bis(trifluoromethane)sulfonimide lithium salt (Li-TFSI), 4-tert-Butylpyridine (TBP), and chlorobenzene were purchased from Sigma-Aldrich. N2, N3,N3,N3,N6,N6,N6,N6-tetakis(4-methoxyphenyl)-9,9′-spirobi[9H-fluorene]-2,2′,7,7′-tetramine (Spiro-OMeTAD) was purchased from Lumtec. All materials were used as received.

Device fabrication. The substrates were sequentially washed with acetone, isopropanol, and deionized water. The sheet resistance of FTO is 15Ω/□ and the thickness of glass and FTO are 1.6 mm and 420 nm respectively. The average transmittance of FTO glass in the visible region is 85%. The ITO-PEN has a sheet resistance of 15Ω/□, a thickness of 0.125 mm, and 78% transmittance in the visible region. SnO2 was deposited on FTO glass and ITO-PEN by radio frequency magnetron sputtering in room temperature. The clean substrates were transferred to a vacuum chamber and evacuated to a pressure of 4×10−4 Pa for SnO2 sputtering. The substrates were mounted on a rotating platform, 10 cm above the SnO2 target (China Rare Metal Co. Ltd.). The sputtering atmosphere was consisted of O2 and Ar. When 4×10−4 Pa was reached, O2 (99.99%) and Ar (99.99%) were pumped into the chamber. The gas flow rates of O2 and Ar were controlled by gas-flow meters and the gas flow ratio of O2 and Ar was set 1 sccm and 50 sccm, 5 sccm and 50 sccm, or 10 sccm and 50 sccm respectively. The working pressure for sputtering was maintained 0.25 Pa, 0.5 Pa, or 1.0 Pa. The SnO2 target was sputtered with a sputtering power of 60 W. The sputtered SnO2 thickness was set as 20 nm, 40 nm, 60 nm, or 80 nm at a deposition rate of 0.43 Å s⁻¹. Solution-processed SnO2 films were prepared by spin-coating 0.1 M precursor solution of SnCl2 · 2H2O in ethanol at 3000 rpm for 30 seconds on clean FTO substrates. The SnO2 thin films were finally heated in air at 180 °C for 1 hour. The MAPbI3 perovskite was fabricated by a 2-step vapor deposition. The vapor deposition rate was controlled using a quartz sensor and calibrated after measuring the thickness of PbI2 and MAI films. The sources were located at the bottom of the chamber with an angle of 90° with respect to the SnO2-coated substrates. The distance between source and substrate was 20 cm. The evaporation rate of both PbI2 and MAI was maintained in a range of 1.5–2.0 Å s⁻¹. 120 nm PbI2 and 280 nm MAI were evaporated to generate a resultant 400 nm MAPbI3 film. The as-deposited films were annealed at 130 °C for 10 minutes in ambient condition of 65% humidity. The perovskite films were then covered by Spiro-OMeTAD, which composed of 80 mg mL⁻¹ chlorobenzene, 17.5 µL Li-TFSI (520 mg mL⁻¹ acetonitrile), and 28.5 µL TBP, which was spin-coated at 3000 rpm for 30 s. The films were left in a desiccator overnight. To complete the devices, 100 nm gold was deposited by thermal evaporation at 1 Å s⁻¹ as an electrode. The device area on FTO glass and ITO-PEN were 0.0314 cm² and 0.1 cm², respectively.

Device measurements. The AM1.5G solar spectrum was simulated by an Abet Class AAB Sun 2000 simulator with an intensity of 100 mW cm⁻² calibrated with a KG5-filtered Si reference cell. The current-voltage (I–V) data were measured using a 2400 series source meter (Keithley, USA). I–V sweeps (forward and reverse) were performed between −1.2 and +1.2 V with a step size of 0.02 V and a delay time of 100 ms at each point.

Material characterization. Field-emission scanning electron microscopy (JEOL JSM-7100F) and X-ray diffraction measurement (Bruker D8 X-ray diffractometer, USA) utilizing Cu Kα radiation were used to study the thickness, morphology, roughness of the films, and phase characterization. The optical absorption and steady-state photoluminescence spectra were recorded on a Lambda 20 spectrophotometer (Perkin Elmer, USA) and InVia (Renishaw) micro raman/photoluminescence system, respectively. Ultraviolet photoelectron spectroscopy (Axis Ultra DLD) was used to determine the valence band maximum of SnO2 films. Scanning probe microscopy (NanoScope III) (Digital Instruments) was used to characterize the surface roughness of films.

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**Author Contributions**

M.K. and Z.F. designed the experiments. M.K., Q.Z., D.Z. and Z.F. carried out experiments. M.K., Q.Z., D.Z. and Z.F. contributed to the data analysis. M.K., Q.Z. and Z.F. wrote the paper.

**Additional Information**

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