Research Article

High-Performance and Hysteresis-Free Perovskite Solar Cells Based on Rare-Earth-Doped SnO₂ Mesoporous Scaffold

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Tin oxide (SnO₂), as electron transport material to substitute titanium oxide (TiO₂) in perovskite solar cells (PSCs), has aroused wide interests. However, the performance of the PSCs based on SnO₂ is still hard to compete with the TiO₂-based devices. Herein, a novel strategy is designed to enhance the photovoltaic performance and long-term stability of PSCs by integrating rare-earth ions Ln³⁺ (Sc³⁺, Y³⁺, La³⁺) with SnO₂ nanospheres as mesoporous scaffold. The doping of Ln promotes the formation of dense and large-sized perovskite crystals, which facilitate interfacial contact of electron transport layer/perovskite layer and improve charge transport dynamics. Ln dopant optimizes the energy level of perovskite layer, reduces the charge transport resistance, and mitigates the trap state density. As a result, the optimized mesoporous PSC achieves a champion power conversion efficiency (PCE) of 20.63% without hysteresis, while the undoped PSC obtains an efficiency of 19.01%. The investigation demonstrates that the rare-earth doping is low-cost and effective method to improve the photovoltaic performance of SnO₂-based PSCs.

1. Introduction

As a new generation of thin film photovoltaic technology, organometallic halide perovskite solar cells (PSCs) have been attracting considerable interest owing to their high efficiencies, minor environmental impact, and facile solution processability [1–4]. Since the birth of first prototype in 2009 [5], the power conversion efficiency (PCE) of PSCs has undergone rapid increment from 3.8% to 23.48% (certified) during the past several years [6]. This outstanding progress is attributed to the unremitting efforts of researchers on optimizing chemical composition of perovskite and deposition processes [7–10], as well as perovskite prominent optoelectronic properties, such as bandgap adjustability [11, 12] and long carrier lifetime [13–15]. Interestingly, the emergence of perovskite solar cells originated from dye-sensitized solar cells (DSSCs). In turn, the development of perovskite solar cells promoted the research of DSSCs, especially in polymer electrolytes and flexible devices [16–22].

Titanium dioxide (TiO₂) is a frequently used electron transport material for perovskite solar cells. However, TiO₂ shows a lower electron mobility of (0.1–1.0 cm² V⁻¹ s⁻¹), compared with conventional perovskite material (20–30 cm² V⁻¹ s⁻¹), which causes insufficient charge carrier separation at the TiO₂/perovskite interface [23–25]. In addition, the UV instability of TiO₂ upon UV exposure triggers a rapid decrease in performance of PSCs via the degradation of the organic components in the PSC (especially for mesoporous TiO₂-based PSCs) [26, 27]. Furthermore, high temperature processing (HTP) for TiO₂ electron transport layer (ETL) is also unfavorable for the fabrication of low-cost PSCs. To overcome these issues, various metal oxides (i.e., SnO₂, ZnO, WO₃, In₂O₃, and SrTiO₃) and fullerene are investigated as the substitute electron transport materials for TiO₂ [28–32]. Among them, SnO₂ has emerged as an especially promising candidate, owing to its low temperature processability, high optical transmittance in visible range, high electron mobility
(100–200 cm² V⁻¹ s⁻¹), less sensitive to UV radiation, and favorable energy level alignment to perovskite absorbers [33]. However, solution-processed planar SnO₂ films suffer from temperature-dependent nonideal electron mobility at low annealing temperature or crack defect morphology brought by high annealing temperature (i.e., 500°C), which both lead to inferior contact and electron transport at the ETL/perovskite interfaces and then manifested in J-V hysteresis [34–36]. Fortunately, a thin mesoporous ETL can be designed to ameliorate these issues by improving perovskite coverage condition to get large perovskite grains [37–39]. On this basis, mesoporous SnO₂ (m-SnO₂) ETL has been highlighted for the industrial production of stable and efficient SnO₂-based PSCs [40]. The PSCs embedded with full SnO₂ blocking layer (bl)/mesoporous (mp) layer have obtained inspiring advances [41]. Higher PCEs of 13.1% and 17% were obtained employing HTP m-SnO₂ and gallium-doped m-SnO₂ by Roose et al. [40, 42]. Afterwards, Liu et al. and Yang et al. reported the PSCs with LTP 2D SnO₂ nanosheet arrays and yttrium-doped SnO₂ nanosheets arrays; the PCEs increased to 16.17% and 17.29% [34, 43]. Recently, Xiong et al. reported a high-stabilized PCE of 19.12% on the planar Mg-SnO₂ PSC by using HTP m-SnO₂ scaffold [36]. More recently, low-temperature processed (LTP) planar SnO₂ PSCs have been achieved a PCE of 21.4% by using tin oxide precursors based on acetylacetone [44].

In this work, monodisperse mesoporous SnO₂ nanospheres with large surface area are synthesized under 300°C posttreatment and are used as mesoporous scaffold in PSCs to improve photovoltaic performance of devices by modifying perovskite coverage condition with large perovskite grains without damaging the surface morphology of SnO₂ blocking layer. Moreover, rare-earth cations located in the third subgroup (Sc³⁺, Y³⁺, La³⁺) are introduced into the SnO₂ mesoporous scaffold to reduce trap state density and transport resistance, enhance charge carrier concentration, and regulate energy level of SnO₂, resulting in enhancement of photovoltaic parameters of the device. By optimizing the amount of Ln³⁺ dopants, the 3%-SnOYE device exhibits a hysteresis-free and high-stabilized power conversion efficiency of 20.63%, superior to those reported previously for full SnO₂ mesoporous structure PSCs. Furthermore, the UV stability is also investigated to illustrate the excellent long-term stability of these full SnO₂-based PSCs.

2. Results and Discussion

2.1. Structure and Morphologies. For research, SnO₂ were synthesized with planar (p-SNO), mesoporous (m-SNO), and doped Ln in Ln³+/Sn⁴⁺ molar ratio (x%-SNOLn). Figure 1(a) shows the X-ray diffraction pattern (XRD) of m-SnO₂ and 3% Ln³⁺ (Sc³⁺, Y³⁺, La³⁺) doped m-SnO₂. All peaks are readily indexed to the tetragonal rutile phase of SnO₂ (JCPDS card No. 41-1445); no additional peaks are observed, indicating that Ln³⁺ (Sc³⁺, Y³⁺, La³⁺) dopants do not change the phase structure of SnO₂. The range (2θ = 24°–28°) is magnified in Figure 1(b). The peaks for doped samples are slightly broader and shift to lower angles compared with the peak for undoped sample. This is due to the partially substitutional or interstitial incorporation of Ln³⁺ and the radius difference between Sc³⁺ (0.087 nm), Y³⁺ (0.1019 nm), La³⁺ (0.116 nm), and Sn⁴⁺ (0.069 nm), suggesting there is no distortion in the bulk SnO₂ lattice due to the small amount of doping.

The X-ray photoelectron spectroscopy (XPS) scans for all samples, as shown in Figure S1a–S1c, highlight that no impurities are found in the spectra, suggesting that the Ln³⁺ ions are incorporated successfully into m-SnO₂. From the high-resolution XPS spectra of Sn 3d (Figure 1(c)), undoped m-SnO₂ shows two signal peaks at 486.7 and 495.2 eV, respectively, corresponding to Sn 3d 5/2 and Sn 3d 3/2 states of Sn³⁺. After doping, all Sn 3d peaks shift to lower binding energies, arising from the variations of the chemical environment for Sn³⁺. In detail, the different binding interactions between Ln-O and Sn-O lead to the charge transfer effect around Sn⁴⁺ species [45]. Besides, compared with the binding energy of Sc₂O₃ (401.9 eV), Y₂O₃ (156.6 eV), and Ln₂O₃ (835.2 eV) [46], the shift to lower binding energy with different degrees indicates that Ln³⁺ exists in a substitutional or interstitial bonding mode of Sn-O-Ln [47]. The narrow spectra of Sc 2p, Y 3d, and La 3d are manifested in Figure 1(d) and Figure S1d, S1e; all characteristic peaks can be assigned to +3 oxidation state of Ln [48, 49].

Figure 2(a) shows TEM image of 3% Y-doped m-SnO₂, which mainly consists of monodisperse nanospheres with the average diameter about 54.19 ± 4.44 nm (Figure 2(c)). The enlarged TEM image shown in Figure 2(b) reveals that the 3% Y-doped m-SnO₂ nanospheres have granular structure and coarse surface that consist of small SnO₂ nanoparticles with a size of 6–8 nm, which endows the 3% Y-doped m-SnO₂ nanospheres with high surface area. From Figure 2(b) and Figure S2, the lattice spacing for m-SnO₂ and 3% Ln³⁺-doped m-SnO₂ is calculated as 0.334 nm, corresponding to the rutile SnO₂ phase of (110) lattice planes, indicating that the Ln³⁺ dopants have no influence on the crystalline phase of m-SnO₂, which is accorded with the XRD patterns (Figure 1(b)).

The pore width and the specific surface area of undoped m-SnO₂ and 3% Y³⁺-doped m-SnO₂, derived from nitrogen adsorption-desorption measurements, are shown in Figure 2(d) and Table S1. All samples exhibit a type H3 hysteresis loop according to the Brunauer-Deming-Deming-Teller (BDDT) classification, indicating the presence of mesopores (2–50 nm) [50, 51]. For 3% Y³⁺-doped m-SnO₂, the Barrett-Joyner-Halenda (BJH) desorption cumulative pore width is 13.8 nm, which is in agreement with the above BDDT classification. Compared with the pore width of undoped m-SnO₂ sample (9.80 nm), an increment of 40.8% is achieved by 3% Y³⁺ dopant [34]. According to the BET method, the specific surface areas of undoped m-SnO₂ and 3% Y³⁺-doped m-SnO₂ are 120.2 and 130.0 m² g⁻¹, respectively. Based on the BET results, the pore feature (especially for pore width) of the doped sample is improved due to the addition of rare-earth ions, which is profitable for the penetration of the perovskite into the mesoporous scaffold and then the formation of well-aligned perovskite morphology.
Figures S3a–S3c show the FE-SEM images of m-SnO$_2$ nanospheres with similar particle diameter for undoped and doped samples, indicating the doping hardly changes the morphology of particles; thus, the influence of morphology by doping on device performance can be excluded. However, the granular structure of m-SnO$_2$ nanospheres collapses when the Ln$^{3+}$ concentration is increased to 4% (Figure S3d, S3e) [34, 37]. Thus, a suitable Ln doping amount is crucial. In our experiment condition, the Ln optimal concentration is 3%.

Figure 3 shows the FE-SEM images of SnO$_2$ films (annealed at 300°C), perovskite films, and the devices. Figure S3 shows the corresponding FE-SEM images annealed at 180°C. In Figure 3(a) and Figure S3g, the morphologies of the p-SNO annealed at 300°C and 180°C are similar, indicating that the p-SNO films are thermal stable. From Figure 3(b), 3%-SNOY thin film consists of many monodisperse and well-aligned nanospheres, which increases contact area between m-SnO$_2$ scaffold/perovskite layer and results in the improvement of $J_{SC}$ and FF. From Figures 3(d)–3(f), 3%-SNOY perovskite film presents uniform, smooth-surface, and larger grains compared with that of the p-SNO perovskite film, while heavily Ln$^{3+}$-doped m-SnO$_2$ (4%-SNOY) (Figure 3(c)) leads to a rough and pin hole perovskite surface, which may have a detrimental effect on device performance. Compared with the cross-sectional SEM image of Figures 3(g) and 3(h), the SNOY-based perovskite film shows dense, large perovskite particles and thickness about 400 nm, proving that the perovskite is well crystallized in the 3%-SNOY scaffold.
2.2. Energy Band Structure. High optical transmission facilitates efficient utilization of sunlight and leads to an improved $J_{SC}$ and PCE for PSCs. Figure 4(a) shows the optical transmission of the films in the order: $3\% - \text{SNOY} > 3\% - \text{SNOSc} > 3\% - \text{SNOLa} > m - \text{SNO} > p - \text{SNO}$, which agrees with the photovoltaic performance of the devices. From Figure 4(b), the optical band edges ($E_g$) are calculated according to the formula: $(\alpha h\nu)^n = A(h\nu - E_g)$ ($n = 1/2$), and results are listed Table S2. Various samples have almost the same $E_g$ values (3.95 eV), indicating that the low amount of Ln doping does not affect $E_g$ of the film.

Based on the equation of (Fermi level) $E_F = E_{cutoff}$ (cutoff binding energy) $-21.2$ eV (emission energy from He irradiation) and Figure 4(c), $E_F$ of samples are calculated and the results are listed in Table S2. The gradual upward shift of the $E_F$ confirms the improvement in carrier concentration crosschecked by conductivity and Mott-Schottky measurements mentioned after [43, 52]. According to $E_{VB} = E_F - E_{on-set}$ (on-set binding energy) and $E_{CB} = E_{VB} + E_g$, the valence band positions ($E_{VB}$) and the conduction band ($E_{CB}$) are calculated and expressed in Figure 4(d) and Table S2. SnO$_2$ mesoporous scaffold plays a functional bridging role between SnO$_2$ bl and perovskite layer; the increase of $E_{CB}$ values of p-SNO, m-SNO to SNOL$n$ films is beneficial for the charge carrier extraction, which the results are good coincidence.
with the $J$-$V$ measurements. Meanwhile, the enhancement of $V_{OC}$ can be attributed to conduction band upward shift, influenced by the $E_{CB}$ and $E_{VB}$ of ETL and hole transport layer (HTL). According to the above discussions, the enhancement in photovoltaic parameters is ascribed to the optimization of morphology of perovskite film and charge transport dynamics.

2.3. Photoelectrochemical Properties. The current-voltage ($I$-$V$) curves of the FTO/ETL/Au devices were measured in dark and are shown in Figure S4a. The conductivities of samples are calculated as $\sigma = d/AR$, where $d$ is the film thickness, $A$ is the film area, and $R$ is the film resistance. The enhanced conductivity indicates the passivation of charge trap states by Ln$^{3+}$ doping and facilitates the charge extraction for improving $J_{SC}$ and FF values.

Figure S4b shows Mott-Schottky (M-S) analysis of samples; all films show positive slope for $n$-type. The flat band potential $V_{fb}$, calculated from the intersection of the linear region with the X-axis, is 0.49 V (m-SNO), 0.35 V (3%-SNOSc), 0.29 V (3%-SNOY), and 0.41 V (3%-SNOLa) vs. Ag/AgCl (equivalent to 0.69, 0.55, 0.49, and 0.61 V vs. NHE). Fermi level ($E_F$) is calculated according to the empirical formula $E_F = -(V_{fb} + 4.5) \text{eV}$ by assuming the energy level of normal hydrogen electrode as $-4.5 \text{eV}$ [53]. Thus, the $E_F$ values of the films are $-5.19 \text{eV}$ (m-SNO), $-5.05 \text{eV}$ (3%-SNOSc), $-4.99 \text{eV}$ (3%-SNOY), and $-5.11 \text{eV}$ (3%-SNOLa), which are consistent with the UPS results. The M-S curves can be used to analyze the number of free electrons ($N_e$), which is inversely proportional to the straight line slope of the M-S plot using the equation: $\text{slope} = 2/\varepsilon \epsilon_0 A^2 q N_e$, where $\varepsilon$ is the relative dielectric constant for SnO$_2$, $\epsilon_0$ is the vacuum permittivity, $A$ is the sample area, and $q$ is the elementary charge [43, 54, 55]. The slope of the 3%-SNOY film ($2.10 \times 10^{16}$) is much...
smaller than that of m-SNO film ($10.22 \times 10^{16}$), suggesting a considerable increment of $N_c$. Simultaneously, it also confirms that Ln$^{3+}$ ions are incorporated interstitially into SnO$_2$ as p-type dopants, which make the increment of $N_c$ [43].

To further elucidate the effect of Ln$^{3+}$ doping on hysteretic behavior of the device, we carried out steady-state photoluminescence (PL) quenching experiment and time-resolved photoluminescence (TRPL) intensity decay measurement. As presented in Figure S4c, the samples with mesoporous scaffold show a faster electron quenching efficiency than the p-SNO film. According to the result, 3%-SNOY shows the fastest quenching rate, indicating an efficient electron transport and charge extraction at the interface of perovskite/SnO$_2$, which can prevent the accumulation of redundant capacitive charge that leads to hysteresis. Figure S4d and Table S3 show the TRPL decays of samples; the curves were fitted with a two-component exponential decay function $I = A_1 e^{-(t-t_0)/\tau_1} + A_2 e^{-(t-t_0)/\tau_2}$, where $\tau_1$ refers to the faster component of trap-mediated nonradiative recombination and $\tau_2$ is the slower component correlated to radiative recombination. The average PL decay times ($\tau_{ave}$) can be calculated with the formula $\tau_{ave} = (A_1 \tau_1^2 + A_2 \tau_2^2)/(A_1 \tau_1 + A_2 \tau_2)$, in which $A_1$ and $A_2$ represent the decay amplitudes. The fitted result for the 3%-SNOY film delivered a much faster PL decay rate (58.89 ns) than that of the p-SNO film (171.35 ns), validating the trap-assisted recombination is partly eliminated, which is beneficial for improving PCE output.

Figure S4e illustrates the Nyquist plots of PSCs devices; the intercept point on the real axis in the high-frequency range is the series resistance ($R_s$), the semicircle in the
high-frequency range is the charge-transfer resistance \( R_{ct} \) between at HTL/Au interface, and the value in low-frequency range is the recombination resistance \( R_{rec} \) at mesoporous/perovskite layer interface. The measured resistances are listed in Table S4, the \( R_{rec} \) trend is in good coincidence with the \( J-V \) measurements, and the improvement of FF can be attributed to the optimization of charge-transfer resistance of devices owing to Ln\(^{3+}\) doping.

2.4. Photovoltaic Performance. Figure 5(a) shows the structure diagram of fabricated PSCs. Figure 5(b) shows the characteristic photocurrent density-voltage curves \((J-V)\) curves of the optimized p-SNO, m-SNO, and 3%-SNO\(_{Ln}\) (Sc\(^{3+}\), Y\(^{3+}\), La\(^{3+}\)) devices; the relative photovoltaic data are given in Table S4. Impressively, compared to the p-SNO device, m-SNO cell shows an improved PCE of 19.01%, indicating a 10.46% enhancement in PCE (19.01% vs. 17.21%), which attributes to efficient electron transport brought by dense, large size, and vertical distribution of perovskite (Figure 3(h)) and improved interfacial connection between SnO\(_2\) scaffold and perovskite. We note that PCE reach a highest value of 20.63% for 3%-SNOY device, owing to the morphology optimization of perovskite layer, the adjustment of energy level alignment with perovskite layer, and the improvement of charge transport dynamics by Y\(^{3+}\) doping. The performance of PSCs is further improved owing to Ln ion doping, obeying an order of 3%-SNOY > 3%-SNO\(_{Sc}\) > 3%-SNO\(_{La}\) > m-SNO > p-SNO, yielding a champion PCE as high as 20.63% for 3%-SNOY tailored PSC. The photovoltaic performance of the 3%-SNOY device is higher than that of state-of-the-art PSCs based on mesoporous SnO\(_2\) scaffold (Table S5).

Figures S5a–S5c and Table S6 show \( J-V \) curves and photovoltaic parameters of the PSCs based on m-SNO layer doped with different Ln ion concentrations. To ensure the reliability and repeatability of data, average photovoltaic parameters of the each PSC device were obtained from 20 devices. As mentioned above, excessive dopants are detrimental to the device performance either by the hoist of conduction band leading to an inefficient electron injection, in which case \( V_{oc} \) keeps increasing, but \( J_{sc} \) decreases, or the dopants induce trap states, leading to a decrease of all device parameters [43]. In our case, both the trap state density increase induced by
heavily Ln$^{3+}$-doped m-SnO$_2$ (4%-Sc$^{3+}$, Y$^{3+}$, La$^{3+}$) and the dreadful recombination occurring at the interface of mesoporous scaffold/perovskite induced by the scaffold breakdown drag the parameters of PSC devices. The reproducibility statistics of 20 devices shown in Figures S5d–S5g and Table S7 further confirm the better photovoltaic data for the 3%-SNOLn devices than the p-SNO devices. Apparently, the 3%-SNOY device exhibits the highest average PCE value (20.26 ± 0.116%), and average $J_{SC}$, $V_{OC}$, and FF values of 3%-SNOY device are the highest among all devices. The reliability and repeatability tests distinctly demonstrate the champion performance of the 3%-SNOY devices.

Figure 5(c) shows the steady-state output of $J_{SC}$ and PCE for m-SNO and 3%-SNOY devices by tracking maximum power point (MPP) at a bias voltage 0.87 V and 0.94 V as shown in Figure 5(b). The p-SNO and 3%-SNOY devices yield stabilized PCE of 16.79% and 20.28%, respectively, which are comparable to the PCE obtained from the fresh device. The $J_{SC}$, $V_{OC}$, and FF values of the 3%-SNOY device show a decreased trend in comparison with the other two devices, which is proportional to trap state density ($n_{trap}$) according to $V_{TFL} = qn_{trap}L^2/2\varepsilon\varepsilon_0$, where $L$ is the thickness of the electron-only device, $\varepsilon$ is the relative dielectric constant for SnO$_2$, and $\varepsilon_0$ is the vacuum permittivity [58]. These results provide strong evidences that the trap defects are healed significantly owing to Ln$^{3+}$ ion doping, crosschecking the aforementioned conclusion.

2.5. Stability. The long-term stability of perovskite solar cells should consider both ultraviolet light and humidity sensitivities [39, 59]. Figure 6(a) shows the normalized PCE vs. time of the devices without encapsulation under simulated solar light illumination for 400 h in 30% RH ambient condition. The m-TiO$_2$ PSCs manifest a dramatic degradation to 64.8% of the highest PCE in the first 40 h arising from the photocatalytic properties of TiO$_2$ degrading perovskite and then followed by a plain to 53.2% of the highest PCE originating from that the defects in TiO$_2$ can be passivated by the adsorption of atmospheric oxygen [39]. While the 3%-SNOY devices decrease steadily at nearly 75.8% of the highest PCE under the same testing conditions, exhibiting remarkably improved UV stability. Table S9 shows the change of average PCE values of 3%-SNOY and m-TiO$_2$ devices with time, presenting similar results as Figure 6(a).

After exposure of the perovskite based on m-TiO$_2$ to AM1.5 illumination under 30% RH ambient condition for one week shown in Figure 6(b), a new sharp diffraction peak at 12.7° corresponding to the PbI$_2$ (001) lattice plane is observed in the XRD pattern, arising from the decomposition of the aged perovskite film caused by UV light and ambient humidity. The PbI$_2$ would block the charge transport, resulting in a decrease of PCE. Notably, the intensity of PbI$_2$ diffraction peak for the 3%-SNOY-based perovskite film aged in the same situations is very less, implying a much lower degree of decomposition, which is due to the passivation effect on defects and UV light stability by rare-earth ion doping.
3. Conclusions

In conclusion, rare-earth Ln-doped monodisperse SnO\(_2\) nanospheres with specific surface area of 130.0 m\(^2\) g\(^{-1}\) are successfully synthesized by a solution-phase route. The doped SnO\(_2\) nanospheres are used as scaffold to fabricate mesoporous perovskite solar cells. The observation of morphology, microstructure characterization, energy band analysis, photoelectric property investigation, and photovoltaic performance measurement indicate that the doping of rare-earth Ln ions promotes the formation of dense, even and large perovskite crystals, which facilitate better interfacial contacts of electron transport layer/perovskite layer. On the other hand, Ln dopants optimize the energy level of electron transport layer and reduce the resistance and charge trap states, resulting in an efficient electron transport and charge extraction. As a result, the Y\(^{3+}\) (3\%)-doped mesoporous SnO\(_2\)-based PSC achieved a champion efficiency of 20.63\% with hysteresis-free, while the planar and mesoporous SnO\(_2\)-based PSCs obtain efficiency of 17.21\% and 19.01\%, respectively. This investigation demonstrates a novel strategy for developing efficient and low-cost full SnO\(_2\)-based PSCs.

4. Materials and Methods

4.1. Materials. Formamidinium iodide (FAI, 99.5%), methylammonium iodide (MAI, 99.5%), and methylammonium bromide (MABr, 99.5%) were obtained from Xi’an Polymer Light Technology Corp, China. Lead iodide (PbI\(_2\), 99.99\%), lead bromide (PbBr\(_2\), 99\%), and cesium iodide (CsI, 99\%) were purchased from TCI. Bis(trifluoromethane) sulfonimide lithium salt (Li-TFSI, 99.95\%), anhydrous dimethyl sulfoxide (DMSO, 99.9\%), anhydrous N,N-dimethylformamide (DMF, 99.8\%), 4-tert-butylpyridine (98\%), anhydrous chlorobenzene (CB, 99.8\%), anhydrous acetonitrile (99.8\%), anhydrous 1-butanol (99.8\%), and SnCl\(_2\)2H\(_2\)O (99.995\%) were received from Sigma-Aldrich. K\(_2\)SnO\(_3\)·3H\(_2\)O (99.5\%), urea (99.995\%), YCl\(_3\)·6H\(_2\)O (99.99\%), LaCl\(_3\)·6H\(_2\)O (99.99\%), ScCl\(_3\)·6H\(_2\)O (99.9\%), and ethylene glycol (EG, 99\%) were obtained from Aladdin. All the chemicals were used as received without further purification. Deionized water (resistivity > 18 M\(\Omega\)cm) was obtained through a Millipore water purification system. Prepatterned fluorine-doped tin oxide-coated (FTO) substrates with a sheet resistance of 14 \(\Omega\) sq\(^{-1}\) were purchased from Pilkington.

4.2. Preparation of SnO\(_2\) and Ln-Doped Solutions. SnO\(_2\) solution was prepared by dissolving SnCl\(_2\)·2H\(_2\)O in 1-butanol in the concentration of 0.1 M. Monodisperse SnO\(_2\) nanospheres were synthesized by a solution-phase route [50]. In a typical procedure, 8 mL of aqueous solution containing LnCl\(_3\) (Sc\(^{3+}\), Y\(^{3+}\), La\(^{3+}\)) and K\(_2\)SnO\(_3\) with different Ln\(^{3+}/\text{Sn}^{4+}\) molar ratios (0~4\%) mixed with 15 mL of EG was added into a 50 mL Teflon-lined autoclave and maintained at 170°C for 13 h. The air-cooled precipitation was washed thoroughly with deionized water for removal of K\(^+\) and organic residue followed by a centrifugation and then diluted with deionized water in the concentration of 0.1 g mL\(^{-1}\) prior to use.

4.3. Fabrication of Perovskite Solar Cells. Laser-patterned FTO glass with size of 1.5 \(	imes\) 1.5 cm\(^2\) was cleaned by detergent and sonication in isopropanol, acetone, deionized water, and ethanol and finally treated with UV ozone for 30 min. SnO\(_2\) block layer (bl) was deposited on FTO by a spin-coating step (3000 rpm, 30 s) and then annealed at 150°C for 1 h, named as p-SNO. SnO\(_2\) scaffold layer contained different Ln\(^{3+}/\text{Sn}^{4+}\) molar ratios (0~4\%) with thickness about 100–200 nm was covered by spin-coating the SnO\(_2\) solution at 2000 rpm for
30 s and then annealed at 300°C for 1 h to remove the organic residue, named, respectively, as m-SNO and x%-SNOLn (x = 1, 2, 3, 4). The cesium-containing triple cation perovskite was deposited by an anisothermal method according to the literatures [27, 60]. The perovskite precursor solution was spin-coated at 1000 rpm for 10 s and then at 6000 rpm for 20 s on the p-SNO and full SnO2 as bl/mp layers substrates. During the second step, 130 μL of chlorobenzene was poured on the spinning substrate 5 s prior to the end of the program to rinse out residual DMSO and DMF in the precursor films. Afterwards, the substrates were heated immediately at 100°C for 1 h and then were cooled down to room temperature naturally. Subsequently, the spiro-OMeTAD layers were subsequently deposited on top of the as-prepared perovskite layers by spin-coating 20 μL of chlorobenzene solution containing chlorobenzene (1 mL), spiro-OMeTAD (80 mg), 4-tert-butylpyridine (28.8 μL), and Li-TFSI (17.5 μL, 520 mg Li-TFSI in 1 mL acetonitrile) at 4000 rpm for 30 s. Finally, about 100 nm thick Au electrodes were thermally evaporated on the spiro-OMeTAD layers under high vacuum via a shadow mask. Thus, the PSCs with the active area of 0.1 cm2 (0.25 × 0.4 cm2) were prepared. For clarity, PSC devices based on planar structure SnO2 and mesoporous structure SnO2, with different Ln3+/Sn4+ molar ratios (0–4%) are denoted as p-SNO device, m-SNO device, and x%-SNOLn devices (x = 1, 2, 3, 4). The PSCs with full TiO2 as bl/mp layers named as m-TiO2 were also fabricated as previously reported for comparative study [27].

4.4. Characterization. The crystal structures of samples were determined by powder X-ray diffraction (XRD, Smart Lab, Rigaku) using graphite monochromatic copper radiation (λ = 1.5418 Å). The morphology characterizations were performed on the field emission scanning electron microscopy (FE-SEM, SU8000, Hitachi) and a JEOL JEM-2100 transmission electron microscopy (TEM). Surface electronic states and UV photoelectron spectroscopy (UPS) were carried out using a UPS/UPS system (Thermo Scientific, ESCALAB 250XI, USA). UPS was performed using He I radiation at 21.22 eV with bias (−5 V) on the samples to separate the sample and analyzer low kinetic energy cutoffs. For UPS, all binding energies were referenced to the C1s peak (284.8 eV) of the surface adventitious. The Brunauer-Emmett-Teller (BET) specific surface area was determined using N2 adsorption apparatus (ASAP 2020 HD88, micromeritics) at 77 K after a pretreatment at 453 K for 3 h. The flat band potential was performed by using a CHI760E (Chenhua Co. Ltd, Shanghai) electrochemical workstation with a standard three-electrode configuration, which employed a Pt plate as the counter electrode and Ag/AgCl (saturated Na2SO4) as the reference electrode. Ultraviolet-visible (UV-vis) absorption spectra of samples were recorded on a PerkinElmer Lambda 950UV/VIS/NIR spectrometer in the wavelength range of 300–800 nm. The steady-state photoluminescence (PL) spectra were acquired using a fluorescence spectrophotometer (Lumina, Thermo Fisher) equipped with a Xenon lamp at an excitation wavelength of 507 nm. The time-resolved photoluminescence (TRPL) spectrum was recorded on an Omni-λ monochromator excited with a 760 nm laser.

4.5. Measurement. The photocurrent density-voltage (J-V) curves of PSCs were recorded with a Keithley 2420 source-measure unit under 100 mW cm−2 (AM 1.5G) with presweep delay of 0.04 s, max reverse bias of 0.2 V, max forward bias of 2.0 V, and dwell time of 30 ms in ambient environment. The illumination source was a solar light simulator (Newport Oriel Sol 3A class, USA, calibrated by a Newport reference cell). Average photovoltaic parameters of the PSC devices were obtained from 20 devices to ensure the reliability and repeatability of data. Dark J−V curves were measured on a Keithley 2420 source meter in the dark. The stabilized power output was recorded close to the maximum power point, which was extracted from the J−V curves on an electrochemical workstation (CHI660E, Chenhua Co. Ltd, Shanghai) under simulated sunlight irradiation with intensity of 100 mW cm−2 at AM 1.5G. The incident photo-to-current conversion efficiency (IPCE) curves were measured as a function of wavelength from 300 nm to 800 nm using a QE-R quantum efficiency measurement system (Enli Technology Co. Ltd). The electrochemical impedance spectroscopy (EIS) measurements were conducted on a Zennium electrochemical workstation (IM6) under AM 1.5G with the frequencies from 100 mHz to 1 MHz, the bias of 0 V, and the amplitude of 20 mV. Long-term stability under persistent moisture (30% RH) was tested by XRD measurement for 7 days and record of time-dependent photovoltaic performances for 400 h under ambient condition with 30% RH. All the average values for long-term stability were obtained from 8 devices for each sample.

Conflicts of Interest
The authors declare no conflict of interest.

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Supplementary Materials
Figure S1: (a)–(c) survey XPS spectra of 3% Ln3+(Sc3+, Y3+, La3+)-doped m-SnO2, (d), (e) Narrow XPS spectra of Sc 2p and La 3d. Figure S2: (a) TEM and (b) HRTEM images of undoped m-SnO2. Figure S3: FE-SEM images of (a) m-SnO2, (b) 3% Sc3+, (c) 3% La3+, (d) 4% Sc3+, and (e) 4% La3+-doped m-SnO2. Top view FE-SEM images of (f) bare FTO glass and (g) p-SNO (annealed at 180°C). Figure S4: (a) I−V curves of various films under dark condition. (b) M−S plot of various films. The electrodes were submerged in a 0.5 M KCl solution with a Pt counter electrode and Ag/AgCl reference electrode. (c) PL spectra and (d) TRPL spectra of the perovskite films based on various SnO2 films. (e) Fitting curves from Nyquist plots for various SnO2 devices. The inset is the corresponding equivalent circuit. Figure S5: J−V curves of the PSCs based on m-SNO doped with (a) Sc3+, (b) Y 3+, (
and (c) La 3+ in different concentrations. (d)–(g) Average photovoltaic data of the devices with Ln-doped SnO2 scaffold. Average photovoltaic parameters of the each PSC device were obtained from 20 devices to ensure the reliability and repeatability of data. Figure S6: (a), (b) Dependence of JSC and VOC on light intensity of PSCs. (c) Dark J–V curves of PSCs. (d) J–V curves under dark conditions for the electron-only devices with the inserted structure. Table S1: pore properties of 3% Y-doped m-SnO2 and undoped m-SnO2. Table S2: band edge (Eg), Fermi level (EF), valence band (EVB), and conduction band (ECB) of samples. Table S3: fitted data from TRPL spectra in Figure S4d. Table S4: photovoltaic and impedance data of the PSCs. Table S5: PCE comparison of the PSCs based on full SnO2 mesoporous structure [S1–S8]. Table S6: photovoltaic data of the PSCs with different Ln3+ (Sc3+, Y3+, La3+) concentrations. Table S7: average photovoltaic data of the PSCs. The average values were obtained from 20 devices. Table S8: photovoltaic parameters of the PSCs scanning in different directions. Table S9: PCE values for 3%-SNOY and m-TiO2 devices. Average values were obtained from 8 devices. (Supplementary Materials)

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