Evaluating the Optoelectronic Quality of Hybrid Perovskites by Conductive Atomic Force Microscopy with Noise Spectroscopy

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Supporting Information

ABSTRACT: Organic−inorganic hybrid perovskite solar cells have emerged as promising candidates for next-generation solar cells. To attain high photovoltaic efficiency, reducing the defects in perovskites is crucial along with a uniform coating of the films. Also, evaluating the quality of synthesized perovskites via facile and adequate methods is important as well. Herein, CH$_3$NH$_3$PbI$_3$ perovskites were synthesized by applying second solvent dripping to nonstoichiometric precursors containing excess CH$_3$NH$_3$I. The resulting perovskite films exhibited a larger average grain size with a better crystallinity compared to that from stoichiometric precursors. As a result, the performance of planar perovskite solar cells was significantly improved, achieving an efficiency of 14.3%. Furthermore, perovskite films were effectively analyzed using a conductive AFM and noise spectroscopy, which have been uncommon in the field of perovskite solar cells. Comparing the topography and photocurrent maps, the variation of photocurrents in nanoscale was systematically investigated, and a linear relationship between the grain size and photocurrent was revealed. Also, noise analyses with a conductive probe enabled examination of the defect density of perovskites at specific grain interiors by excluding the grain-boundary effect, and reduced defects were clearly observed for the perovskites using CH$_3$NH$_3$I-rich precursors.

KEYWORDS: excess CH$_3$NH$_3$I, grain size, perovskite solar cells, conductive AFM, noise spectroscopy

INTRODUCTION

In pursuit of developing high-efficiency devices utterly utilizing renewable energy sources, various research studies have been carried out. 1−5 Especially, organic−inorganic hybrid perovskite solar cells exhibit enormous improvement of their performances in a few years after they were applied to solid-state devices, and ∼20% of a certified solar-to-energy conversion efficiency was attained. 6,7 This outstanding performance stems from the properties of the perovskites such as a high absorption coefficient, a superior carrier mobility, a low exciton binding energy, a bipolar transport, and a long carrier diffusion length. 8−11 Furthermore, the merits of cost-efficient and low-temperature solution processability enable perovskite solar cells to be a viable candidate for commercialization among the next-generation solar cells.

To achieve a high photovoltaic efficiency, the complete coverage of the perovskite layer is necessary to absorb a larger portion of incident lights and reduce unwanted shunting paths. A lot of synthetic routes have been reported to produce the full coverage of perovskite films, such as two-step deposition, vapor-assisted deposition, solvent annealing, and second-solvent engineering. 12−17 Among them, second-solvent engineering is a straightforward and low-cost method to deposit high-quality films. In this approach, the secondary solvents like chlorobenzene or toluene are dripped during the spin-coating process. As such solvents hardly dissolve the solutes of perovskite precursor solution, the uniform nucleation of

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perovskite crystallites can occur instantly upon dripping of the solvent, and thereby the full-coverage films are readily obtained.\textsuperscript{16} Along with the importance of coverage, reducing the defects which act as traps and scattering centers is another critical issue to enhance a photoconversion efficiency.\textsuperscript{18} Enlarging the grain size to lessen grain boundaries with the enhanced crystallinity of perovskites has also been considerably studied.\textsuperscript{19,20–23}

Figure 1. Comparison of the perovskite films based on the stoichiometric or nonstoichiometric precursors. (a) Schematic for the effect of toluene dripping with different precursors. (b) SEM images of the perovskite films and (c) grain size distribution extracted from SEM. (d) UV–vis absorption spectra. The inset shows a plot of $\alpha^2$ vs $h\nu$ near the band edge. (e) X-ray diffraction patterns and (f) photocurrent–voltage ($J$–$V$) curves of the perovskite solar cells. The red dashed line represents the highest efficiency, and the cross-sectional SEM image is shown for the perovskite solar cell from nonstoichiometric precursor.

Apart from the synthesis of well-structured morphology for photovoltaic applications, analyses to effectively figure out the quality of perovskites are crucial. Specifically, observing the nanostructures and electronic properties simultaneously is quite profitable because it can suggest guidelines to improve the photovoltaic performances by directly matching the morphology and property.\textsuperscript{20} Topography and photocurrent maps are obtained at the same time through conductive atomic force microscopy (cAFM), and the optoelectronic properties can be investigated on the microscale or even nanoscale.\textsuperscript{21,23} For instance, by locating the conductive-probe tip at different positions, both photocurrent characteristics in specific area, like grain interiors or grain boundaries, and inhomogeneities of photocurrent in each grain can be examined. On the other hand, measurement and analysis of electrical noises can also be extensively utilized to study the reliability and defects of electronic devices like solar cells, field-effect transistors, and light-emitting diodes.\textsuperscript{21–23} For example, noise spectroscopy can be used to evaluate the magnitude of the 1/f noise which can directly affect the quality of an electronic device.\textsuperscript{24} Combined with a high-spatial-resolution electronic measurement method by cAFM, noise spectroscopy can be an effective tool to characterize localized noise sources (or defects) in electronic channels.\textsuperscript{25} However, despite its useful outcomes with a simple method, noise spectroscopy has not been widely used in the field of perovskite solar cells yet.

Herein, perovskites were deposited by toluene dripping on nonstoichiometric precursors. The synthesized perovskites appeared to have a larger average grain size and a higher crystallinity compared with those from stoichiometric solutions. Moreover, planar perovskite solar cells from nonstoichiometric precursors exhibited improved photovoltaic properties. To scrutinize the performance enhancement, main factors affecting the photocurrent were analyzed in detail via topography and photocurrent mappings through cAFM. Also, the reduction of intragrain defects for the perovskites from nonstoichiometric precursors was confirmed by noise spectroscopy.

\section*{EXPERIMENTAL PROCEDURES}

1. Device Fabrication. Fluorine-doped tin oxide (FTO, TEC 8: Pilkington) glasses were cleaned in an ultrasonic bath by ethanol and deionized water, followed by O\textsubscript{2}-plasma treatments for 3 min. To deposit a TiO\textsubscript{2} blocking layer of 50 nm thickness, 150 and 300 mM titanium diisopropoxide bis(acetylacetonate) in 1-butanol (75.0 wt % in isopropanol) were sequentially spin-coated at 2500 rpm for 20 s and annealed at 500 °C for 30 min. The substrates were further treated with 40 mM titanium-chloride aqueous solutions at 70 °C for 30 min, followed by annealing at 500 °C for 30 min. For perovskites, precursor solutions were prepared with different PbI\textsubscript{2}/CH\textsubscript{3}NH\textsubscript{3}I (PbI\textsubscript{2}/MAI) molar ratios of 1:1 and 2:3 in n,n-dimethylformamide (DMF), and the nominal concentration of PbI\textsubscript{2} was fixed to 1.2 M. The solutions were spin-coated at 5000 rpm for 20 s, and 200 μL of toluene was dripped at 5 s during the spin coating. Then the films were annealed at 120 °C for 50 min. To deposit hole-transport layers, precursor solutions were prepared by mixing spiro-OMeTAD in chlorobenzene with tert-butylpyridine and lithium bis(trifluoromethylsulfonyl)imide salt in acetonitrile. The solutions were spin-coated at 4000 rpm for 40 s, and the samples were kept overnight in air for oxidation. Finally, 150 nm of Au electrodes were deposited by thermal evaporation.

2. Characterization. The morphology of the perovskite films was observed using a field-emission scanning electron microscope (FE-SEM, Merlin-Compact: Carl Zeiss), and the crystal structure was
analyzed by X-ray diffraction (XRD, D8 Advance: Bruker). The absorbance was recorded by a UV–vis spectrophotometer (Lambda 20: PerkinElmer). The photoluminescence (PL) spectra were obtained using a spectrofluorometer (Phontech Technology Inc.) at an excitation wavelength of 520 nm. The photocurrent–voltage (J–V) curves of the perovskite solar cells were obtained using a solar cell measurement system (K3000: McScience) under a solar simulator (xenon lamp), with a reverse scan rate of 300 mV/s and an active area of 0.09 cm². The incident photon-to-current conversion efficiency (IPCE) spectra were measured using an IPCE measurement system (K3100: McScience). The topography and photocurrent mapping data were obtained utilizing aAFM (XE-70: Park System). A solid metal probe based on Pt (25Pt300B: Park System, spring constant of ∼18 N/m with a diameter of ∼10 nm) was used as a conductive AFM probe. To obtain reliable mapping data, the pixel sizes of AFM images were set to be larger than the diameter of the probe tip. With use of an AFM contact mode, the probe was directly contacted on the surface of a perovskite film to form a heterojunction solar cell structure of Pt/probe/perovskite/TiO₂/FTO, as described in Figure 2a. In the contact mode operation, the contact force between the AFM probe and the film surface was maintained as ∼2 nN by a contact force feedback loop in the XE-70 AFM system. With use of a power-adjustable light source (LS-F100HS: Seokwang Optical), a white light of ∼80 mW/cm² was illuminated on the perovskite film to generate the photocurrents. Then the photocurrents through the Pt probe were amplified by a low-noise preamplifier (SR570: Stanford Research Systems); and the amplified signals could be recorded along with the position of the AFM probe by the data acquisition system. By scanning the perovskite film surface with the Pt probe measuring the photocurrent, we could obtain the photocurrent map showing the distribution of local photocurrents on the perovskite film. For the scanning, the typical scan speed of the AFM was ∼1 μm/s. In addition, when the AFM probe was at a specific location on the perovskite film, the power spectral densities of the photocurrent through the probe could be measured via a fast Fourier transform (FFT) network analyzer (SR770: Stanford Research Systems) for noise analyses.

## RESULTS AND DISCUSSION

Perovskite films comprised of large grains and dense structures can be achieved via a precursor-composition control combined with solvent engineering. Toluene dripping during spin coating is known to immediately induce uniform nucleation over the whole surface of substrates because of the low solubility of precursor components in toluene, enabling dense and pinhole-free film morphology. We have further investigated the effect of precursor composition (i.e., PbI₂/MAI ratio) employing the toluene dripping, and MAI-rich (nonstoichiometric) precursor resulted in the increase of grain size while maintaining the dense morphology (Figure 1a).

Figure 1b exhibits the perovskite films obtained by using either stoichiometric or nonstoichiometric precursors with toluene dripping. In both of the perovskite films, perfect coverages were observed with relatively larger grain sizes for perovskites from the nonstoichiometric precursors. To examine the effect of stoichiometry thoroughly, the distributions of grain sizes were extracted from the SEM images. As a result, the average grain size (∼1.5 μm) of the perovskite film obtained from the MAI-rich solution increased by a factor of 3, compared to the film obtained from the stoichiometric solution (∼530 nm), as shown in Figure 1c. The effect of grain enlargement was also ascertained from the red shift of the optical band gap, estimated from the α² versus hν plots of the films (Figure 1d). Moreover, less PbI₂ with a higher crystallinity was confirmed for the perovskites from nonstoichiometric precursors in the X-ray diffraction data (Figure 1e). Blue-shifted PL peak for the perovskite film using a nonstoichiometric precursor was also observed (Figure S1). With radiative recombination correlated to the PL data, peak shift to shorter wavelength suggests reduced trap states (band tails) in the high-quality perovskite film.

In the case of nonstoichiometric precursors which have excess MAI, it was reported that the perovskite grains toward (001) direction are observed at the intermediate stage of annealing which are not found for the perovskites from stoichiometric precursors. With further annealing, grains having (001) orientation disappeared, and the perovskite films were more oriented toward the (110) direction. From the diffraction results, the crystal growth mechanism can be suggested as follows: at the initial stage of annealing, in the case of nonstoichiometric precursor solution, both (110)- and (001)-oriented grains are nucleated simultaneously owing to the presence of excess MAI which may retard the crystallization kinetics, enabling the formation of less stable (001)-oriented grains. On the other hand, (110)-oriented grains are dominantly nucleated for the stoichiometric precursor case. Additional annealing leads to the grain growth of films, and grains toward the (110) direction grow at the expense of the (001)-oriented grains in the perovskites from nonstoichiometric precursors for further coalescence than those from stoichiometric precursors, presumably due to the orientation-dependent interfacial energies of the perovskite material.

Large-grain perovskite films with a dense morphology can be produced by using nonstoichiometric precursors. Based on these high-quality films, planar perovskite solar cells were fabricated using TiO₂ and spiro-OMeTAD as selective contacts. An enhanced photovoltaic performance of the solar cell based on the perovskite film produced using the nonstoichiometric precursor was clearly confirmed with the efficiency of 14.3% (Figure 1f and Table 1), which was mainly due to the suppressed recombination by better crystallinity and reduced PbI₂ impurities. It is interesting that the thicknesses of the perovskite films were constant to ∼370 nm regardless of the MAI amount (Figure 1f and Figure S2). The J–V curves with different scan rates exhibited almost similar shapes, and some photocurrent hysteresis (which is a general problem for the perovskite solar cells, especially in a planar structure using TiO₂ and spiro-OMeTAD as selective contacts) was observed (Figure S3).

Spectral responses were compared through IPCE which appeared almost identical for both solar cells (Figure S4), with slightly higher integrated current for the nonstoichiometric precursor case. When the ratio of PbI₂/MAI further increased to 1:2, an incomplete perovskite coverage with many pinholes, causing shunting paths, resulted in poor cell performance (Figure S5). The device from the 100 °C-annealed perovskites (stoichiometric solutions) resulted in lower photovoltaic efficiency. In the case of nonstoichiometric precursors which have excess MAI, it was reported that the perovskite grains toward (001) direction are observed at the intermediate stage of annealing which are not found for the perovskites from stoichiometric precursors. With further annealing, grains having (001) orientation disappeared, and the perovskite films were more oriented toward the (110) direction. From the diffraction results, the crystal growth mechanism can be suggested as follows: at the initial stage of annealing, in the case of nonstoichiometric precursor solution, both (110)- and (001)-oriented grains are nucleated simultaneously owing to the presence of excess MAI which may retard the crystallization kinetics, enabling the formation of less stable (001)-oriented grains. On the other hand, (110)-oriented grains are dominantly nucleated for the stoichiometric precursor case. Additional annealing leads to the grain growth of films, and grains toward the (110) direction grow at the expense of the (001)-oriented grains in the perovskites from nonstoichiometric precursors for further coalescence than those from stoichiometric precursors, presumably due to the orientation-dependent interfacial energies of the perovskite material.

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### Table 1. Photovoltaic Parameters of the Perovskite Solar Cells Based on the Stoichiometric or Nonstoichiometric Precursors

<table>
<thead>
<tr>
<th>PbI₂:MAI</th>
<th>Jsc (mA/cm²)</th>
<th>Voc (V)</th>
<th>FF</th>
<th>η (%)</th>
</tr>
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<tbody>
<tr>
<td>1:1</td>
<td>20.7 ± 0.9 (20.0)</td>
<td>0.88 ± 0.05 (0.94)</td>
<td>0.66 ± 0.03 (0.70)</td>
<td>12.1 ± 0.9 (13.2)</td>
</tr>
<tr>
<td>2:3</td>
<td>21.2 ± 0.3 (21.1)</td>
<td>0.90 ± 0.01 (0.92)</td>
<td>0.72 ± 0.02 (0.74)</td>
<td>13.7 ± 0.4 (14.3)</td>
</tr>
</tbody>
</table>

**The data in the parentheses are from the highest efficient device by more than nine cells in each condition.**
efficiency (Figures S6 and S7) owing to the extended grain boundary regions and inferior crystallinity compared with 120 °C-annealed perovskites.

To investigate the microscopic origin of the performance enhancement, cAFM analyses were carried out. The perovskite samples were prepared with electron-selective contacts (TiO₂) as an underneath layer to maintain the morphology and quality of perovskite films used in cAFM measurement to be the same with those of solar cells, and topography and photocurrent maps were simultaneously obtained using the cAFM system. Figure 2a shows the schematic of the AFM measurement setup and the energy level diagram (Figure 2b). Photocurrent−voltage (I−V) curves obtained using a conductive AFM at a grain interior.

Figure 2. (a) Schematic illustration of conductive AFM setup and energy level diagram. (b) Photocurrent−voltage (I−V) curves obtained using a conductive AFM at a grain interior.

and the energy level diagram of the solar cell structure. Details of the photocurrent mapping method are described in the Characterization section. Photocurrent−voltage (I−V) curves were measured at grain interior regions, as shown in Figure 2b. Here, enhanced short-circuit current and open-circuit voltage were observed for the perovskite film produced using the nonstoichiometric precursors.

In the topography images (Figure 3a), the differences in grain sizes were confirmed again. The overall photocurrent level was larger for the 2:3 ratio than for the 1:1 case, and more than a twofold increase in the average photocurrent was observed, as shown in Figure 3b. For the in-depth study of the optoelectronic performance, the variation in the AFM-photocurrent data is reasonably categorized by three factors: (i) difference between grains and grain boundaries, (ii) the degree of nonuniformity inside grains, and (iii) grain-to-grain variation. We have sequentially validated these factors to figure out the main underlying mechanisms of the performance enhancement. First, when the topography and photocurrent signals were compared by overlapping the line profiles (Figure 3c), there was not any evidence showing that the grain boundaries produce lower or higher photocurrents compared to the grain interior. Grain boundaries have been generally considered as a recombination center. Thus, it can be expected that photocurrents at the grain boundaries in cAFM images are lower than those at the grain interiors due to the higher density of defects. However, several research studies have also addressed that band bending around grain boundaries, due to the interstitials and vacancies resulting in divergence of polarity between grain boundary and grain interior, can favorably separate photo-generated carriers. The effects of grain boundaries on the photocurrents act differently depending on each grain structure, composition, device structure, and so forth. Also, current hysteresis at grain boundaries owing to the ion migration can affect the photocurrent in cAFM. Such diverse causes can vary the photocurrent behavior at grain boundaries, and we have not found any consistent relationship between grain boundary and photocurrent in the synthesized perovskites. To rationally investigate the photocurrent at grain boundaries, further studies are needed.

Second, all the photocurrent data in the scanned area are plotted against the height of the topography map, and any correlation is not observed (Figure 4b). Thus, the inhomogeneous distribution of the photocurrents cannot be attributed to the height effects (e.g., thickness inhomogeneities in grains). Finally, we statistically analyzed the photocurrent as a function of grain size (Figure 4a). The average value and standard deviation of photocurrents from all the grains were extracted by overlapping the topography and photocurrent maps. As a result, a linear relationship between photocurrent and grain size was confirmed in each perovskite film, indicating that the grain size works as the main factor for the photocurrent variation.

The analysis of electrical noises is a powerful tool to evaluate the quality of electronic materials by a nondestructive manner. The inset of Figure 5 shows the time-domain measurement results of random-fluctuating photocurrents obtained for the 2:3 and 1:1 samples, while the AFM probe was at an average-sized grain interior in each sample. Note that the power spectral density (PSD) analysis is a powerful tool to characterize a random fluctuation of a value. Thus, the noise can be quantified by the PSD spectra (S(f)) in the frequency domain:

\[
S(f) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} X(t) e^{-2\pi jft} dt
\]

where \(X(t)\) is a fluctuating quantity of photocurrent against a zero mean value. It was reported that the noise S(f) spectra in many electronic materials can be described by Hooge’s relation:

\[
S(f) = A \frac{I^2}{f}
\]

where \(A\) represents a noise amplitude, and the current-normalized PSD (S/I²) should be a useful parameter representing a level of electrical noise in an electronic material.

The current-normalized noise PSD spectra for each perovskite film clearly exhibited the 1/f behavior (Figure 5). Such 1/f noises in a perovskite film may originate mainly from the trapping and detrapping of charge carriers by multiple inhomogeneous defects with different trapping-time constants in the film. A single defect with a specific trapping-time constant generates a Lorentzian-shaped noise spectra. It was reported that defects in a perovskite film produce electronic states which can trap or release charge carriers in the film.
The random trapping and detrapping of the carriers with characteristic lifetime will generate the fluctuation of the total number of mobile carriers in the film, resulting in electrical noises. In this perspective, the measured noise PSD was the summation of noises generated by defects in a perovskite film. Therefore, the magnitude of 1/f noise will presumably have a positive correlation with the density of defects, as previously reported in various semiconductor materials. Thus, the reduced magnitude of the 1/f noise in the 2:3 sample reveals that the use of nonstoichiometric precursor not only enhances the grain growth but also diminishes the density of defects in grain interiors (i.e., improved crystallinity), as confirmed by SEM, optical absorption, diffraction, photocurrent in cAFM, and PL spectra (Figures 1, 3, and 4 and Figure S1), which in turn increases the photoconversion efficiency. The presence of PbI$_2$ can also be one of the reasons increasing the magnitude of noise PSD for the perovskites using stoichiometric precursor.

Figure 3. (a) Topography and (b) photocurrent maps at a short-circuit condition for the perovskite films based on the stoichiometric or nonstoichiometric precursors. (c) Heights and photocurrents are indicated along the white line. The pink dashed lines are for some representative positions of several selected grain boundaries.

Figure 4. Photocurrent dependence on (a) the grain size and (b) height of the perovskite films at a short-circuit condition.

Figure 5. Current-normalized power spectral densities (S/I$^2$) quantifying the noise magnitude of the perovskite films based on the stoichiometric or nonstoichiometric precursors at grain interiors. Average values (blue dots) from different grains with standard deviations are plotted. The dashed fitting lines exhibit the 1/f noise behavior, with the inset for the photocurrents as a function of time.
Since PbI, is almost insulating, the grains containing PbI phase should exhibit negligible photocurrent in cAFM. To reduce the effect of PbI, we carefully chose the grains in photocurrent maps to have an average current value of average-sized grains for the noise spectroscopy. These statistical analyses indicate a strong relationship between the crystalline quality inside grain interiors (bulk effects) and photocurrent responses, rather than grain-boundary effects. Although various causes such as grains, interfaces, or device structures may affect the solar cell results as aforementioned, this novel research provides a clear message on the great importance of the crystallinity for the photoelectronic responses.

**CONCLUSIONS**

In this work, the quality of perovskite films, deposited using a second-solvent dripping method, was improved by controlling the composition of precursor solutions. The perovskite films using MAI-rich solutions had a higher crystallinity and ~3 times larger grain sizes compared to that from stoichiometric solutions. The resulting perovskite films were adopted to the solar cells, and the cells exhibited enhanced photovoltaic parameters with the efficiency of 14.3%. Topography and photocurrent maps were compared to analyze the origin of the efficiency improvement. Grain boundaries or inhomogeneities of film thicknesses did not affect the disparity in photocurrents, but the grain size was found to be one of the main factors varying the photocurrents with a linear dependence. Moreover, we carried out noise analyses using a conductive probe at a grain interior. As a result, the lower degree of a noise level was observed for perovskites from the nonstoichiometric precursors, indicating that less defective films were synthesized compared to those from stoichiometric precursors. From these consequences, we confirmed that the crystalline quality of grain interiors significantly influences the optoelectronic performance rather. Our approach with cAFM and noise spectroscopy can be a useful guideline for evaluating and quantifying a crystalline quality, eventually leading toward a high photovoltaic efficiency.

**ASSOCIATED CONTENT**

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**REFERENCES**


Supporting Information

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Fig. S1. Photoluminescence (PL) spectra of the perovskite films based on the stoichiometric or non-stoichiometric precursors of PbI₂:MAI (deposited on the glass substrates).
Fig. S2. Cross-sectional SEM images of the perovskite solar cells from the 1:1 or 1:2 molar ratio of PbI$_2$:MAI precursor solutions.
Fig. S3. Photocurrent-voltage curves of the perovskite solar cells based on the non-stoichiometric precursor: (a) various scan rates, and (b) reverse and forward directions at 1000 mV/s.
Fig. S4. Incident photon-to-current conversion efficiency (IPCE) of the perovskite solar cells from the 1:1 or 2:3 molar ratio of PbI$_2$:MAI precursor. The abnormal increase of IPCE below ~450 nm arises from the instrumental factors.
Fig. S5. Perovskite films deposited from the 1:2 ratio of PbI₂:MAI precursor. (a) SEM image of the perovskite film. (b) Photocurrent-voltage curve of the perovskite solar cell.
Fig. S6. Perovskite films deposited from the 1:1 ratio of PbI$_2$:MAI precursor and annealed at 100°C for 20 min. (a) SEM image of the perovskite film. (b) Grain size distribution extracted from SEM.

320 ± 130 nm
Fig. S7. (a) Photocurrent-voltage curve of the perovskite solar cell annealed at 100°C for 20 min for stoichiometric precursor solution. (b) X-ray diffraction of perovskite films with different annealing conditions. Annealing at a higher temperature for an improved grain size with enhanced crystallinity is correlated to the improved photovoltaic efficiency in spite of the presence of PbI$_2$ phase.

<table>
<thead>
<tr>
<th>$J_{sc}$ (mA/cm$^2$)</th>
<th>$V_{oc}$ (V)</th>
<th>$FF$</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.6 ± 0.6</td>
<td>0.88 ± 0.03</td>
<td>0.61 ± 0.09</td>
<td>9.4 ± 1.7</td>
</tr>
</tbody>
</table>

PbI$_2$:MAI = 1:1
100°C for 20 min
120°C for 50 min