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The impact of annealing process on the grain morphology and performance of mesoporous n-i-p carbon-based perovskite solar cells

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ABSTRACT
Organic–inorganic perovskite solar cells (PSCs) have been emerging as one of the most promising photovoltaic technologies. Surface morphology is considered as a key-parameter in energy alignment and plays a dominant role in specifying the device performance. The large grains and low roughness enhance the transport of charge carriers from perovskite layers to the transport layers, and this reflects on the delivered power conversion efficiency (PCE). Therefore, in this study, we investigated the influence of the fabrication parameters on the grain size and the morphology of perovskite layers, thereby the PCE of PSCs. These parameters included the anti-solvent nature (chlorobenzene or toluene), annealing temperature, and annealing ramp rate (slow or flash annealing). The scanning electron microscope confirmed that flash annealing results in a better morphology than slow annealing whether by employing an anti-solvent dripping or not. Furthermore, the dripping of chlorobenzene as an anti-solvent produced better morphology and large grains compared with toluene. Therefore, combining chlorobenzene with flash annealing induced the formation of large grains, full cover, and a uniform perovskite layer, which reflects on the performance of the fabricated PSCs. Finally, employing the aforementioned optimum preparation parameters to fabricate carbon-based PSCs resulted in decent PCE, current density short circuit (Jsc), open circuit voltage (Voc), and fill factor (FF) of 7%, 11.3 mA/cm², 0.74 V, and 34%, respectively.

INTRODUCTION
Lead based-perovskite solar cells (PSCs) are settled as one of the most attractive topics in the photovoltaic research area owing to their simple device fabrication and high power conversion efficiency (PCE). Over the past few years, PSCs have attracted the researchers’ attention due to their perspective properties, such as a wide range of optical absorption, long diffusion length, high efficiency, low energy consumption, and easy solution-processed fabrication.

The pioneering work on PSCs was carried out by Kojima et al. in 2009, where methylammonium lead iodide (MAPbI3) was utilized as a light absorbing material in dye sensitized solar cells and PCE achieved was 3.8%. However, that cell suffered from rapid degradation due to the nature of the electrolyte. Remarkably, the actual breakthrough was achieved by Kim et al. in 2012 by fabricating solid state perovskite solar cells and PCE improved to 9%. Recently, the PCE of PSCs enhanced to 25% through further development of the perovskite layer and exploring the novel charge transporting material to decrease energy offset and thereafter decrease the loss of open circuit voltage (Voc). Overwhelmingly, the enlargement of the perovskite grains was carried out by the employed two-step deposition method, and the obtained PCE of as-fabricated PSCs achieved was 15%. Then, Jeon et al. enhanced PCE to 16.7% through the engineering of γ-butyrolactone and dimethylsulfoxide (DMSO) solvents with toluene as an anti-solvent in one step method, which resulted in large grains, low roughness, and a dense perovskite layer. Further development of the perovskite...
layer was achieved by incorporation of Cs\(^+\) cations into the perovskite layer and replacing MAI\(^+\) with FAI\(^+\), which resulted in a lower bandgap with higher optical absorption, so PCE enhanced to 18\%.\(^{6}\) Li et al. developed novel perovskite composition based on FA\(_{0.8}\)MA\(_{0.2}\)Pb\(_{0.65}\)I\(_{3}\), which pushed PCE of as-fabricated PSC to 20.6\%.\(^{26}\) Furthermore, the development of PCE was accomplished by exploring new hole transporting layers (HTLs), such as CoO\(_x\), NiO, and graphene oxide/polyaniline, with the well-matched highest occupied molecular orbitals (HOMO) owing to the valence band of the perovskite layer.\(^{27,28}\) Moreover, we investigate inorganic and organic electron transporting layers (ETLs) for developing the performance of PSCs.\(^{12,14}\)

Indeed, the obtained perovskite film with high crystallinity and controlled morphology can be considered as one of the critical factors for fabricating the high performance PSCs.\(^{23}\) The preparation of a high quality perovskite active layer depends on many parameters such as precursor compositions, annealing methods, appropriate selection of the solvents, anti-solvents nature, and deposition methods.\(^{21}\) Different methodologies have been reported so far, mostly to control the crystallization kinetics.\(^{19,20}\) The preparation parameters that controlled the crystallization process, surface morphology, and crystallinity of the perovskite films have a great influence on the cell’s performance.\(^{22}\) Controlling the crystal growth and thermal annealing process for the perovskite precursor film is a key to achieve high performance.\(^{23,24}\)

Chen et al. found that the mixture of dimethylformamide/dimethylsulfoxide as a co-solvent has a great influence on enhancing the perovskite infiltration and crystal quality through the mesoporous layers due to its wettability and the proper coordination ability and promoted the cell PCE to 13.9\%.\(^{22,23}\) The annealing process is considered as one of the main parameters, which controls the perovskite film morphology via removing the residual solvent after spin coating as well as enhancing crystallization and grain growth. Eperon et al. optimized the surface morphology of the mixed halide perovskite by tuning the thermal annealing conditions. Annealing at high temperature resulted in the formation of coarse perovskite crystals and less perovskite surface coverage, while using a thicker film improved the surface coverage upon annealing.\(^{25}\) Ren et al. demonstrated that the higher photocurrent values are achieved only with the highest perovskite surface coverage.\(^{26}\) On the other hand, the flash annealing assists the rapid nucleation rate and improves the film crystallizing process and morphology.\(^{27}\)

The large grains have better photo-physical properties than small grains due to reduction of charge trapping and recombination, enhancement of the grain orientation and charge carrier collection efficiency, diminishing of the grain boundary, and enhancement of the intrinsic stability of the perovskite itself.\(^{28}\) It was reported that a modified anti-solvent-dripping method can effectively retard the crystal growth process of the perovskite material by forming a Lewis acid-base adduct and induced MAPb\(_3\)I\(_5\) film with high quality and full surface coverage.\(^{28}\) Due to the intrinsic instability of MAPb\(_3\) toward water vapor and oxygen, it is necessary to find new additives to enhance the stability issue or explore novel electrodes which protect MAPb\(_3\) against water vapor and oxygen. Therefore, a carbon electrode is employed as a back contact, which has the capability to protect the PSCs from water vapor. Moreover, the carbon electrode is distinguished by its low cost and facile deposition method compared with evaporated metallic back electrodes.\(^{29,30}\)

Herein, we investigate the effect of annealing rate combined with different anti-solvents on the MAPb\(_3\)I\(_5\) grain size, morphology of the perovskite layer, and thus on the PCE of as-fabricated PSCs. Different perovskite layers are deposited by employing different annealing rates (slow or flash annealing) with different anti-solvents (chlorobenzene or toluene). The morphology and grain size of the deposited perovskite layer are studied using scanning electron microscope (SEM). In addition, UV−visible spectroscopy and x-ray diffraction are utilized to examine the optical absorption and crystallinity of the perovskite layer, respectively. To evaluate the obtained optimum fabrication parameters, carbon-based PSCs are fabricated with different perovskite layers and characterized by measuring the current density short circuit (Jsc), Voc, fill factor (FF), and PCE under illumination.

**EXPERIMENTAL SECTION**

**Materials preparation**

Methylammonium iodide (CH\(_3\)NH\(_3\)I) was synthesized by reacting 27.8 ml of methylamine (40 wt. %) with 30 ml of HI (57 wt. %) dropwise with continuous stirring for 2 h at 0 °C until the formation of a white precipitate at the bottom of the flask. The precipitate was recovered and crystallized by evaporation technique using a rotary evaporator at 60 °C. The CH\(_3\)NH\(_3\)I powder was washed several times using diethyl ether until the powder became totally white colored. Finally, the powder was dried in a vacuum oven for 24 h at 60 °C. Then, the perovskite precursor solution (40 wt. %) was obtained by mixing Pb\(_2\) and CH\(_3\)NH\(_3\)I (MAI) in a co-solvent of anhydrous DMF/DMSO at 60 °C with a mole ratio of 1:1.\(^{31}\)

A compact layer of the TiO\(_2\) precursor was prepared by mixing 0.6 ml of Ti(IV) isopropoxide and 0.4 ml of acetyl acetone in 7 ml of anhydrous ethanol under stirring for 30 min. TiO\(_2\) nanoparticles were prepared by the typical hydrothermal growth method, and 6 g of acetic acid (2 mol) was added at once to 29.3 g (0.2 mol) of titanium isopropoxide under stirring at room temperature. The precursor was stirred for 15 min and then poured into 145 ml of water as quickly as possible under vigorous stirring at 700 rpm for 1 h to form a white precipitate; after that, 2 ml of concentrated nitric acid was added to the mixture and heated gradually from room temperature to 80 °C for 40 min. Then, the mixture was peptized for 75 min and water was then added to the liquid mixture to have the final volume of 370 ml. In order to complete the TiO\(_2\) hydrothermal growth, the liquid mixture was poured in a 570 ml autoclave and heated at 250 °C for 12 h followed by adding 2.4 ml of 65% nitric acid. The solution was treated with an ultrasonic bath by immersing the flask for 2 s 30 times repeatedly. A rotary-evaporator technique was used to concentrate the TiO\(_2\) dispersed solution until it reaches 13 wt. % of its original weight. Finally, the concentrated solution was centrifuged three times by ethanol and dried in a vacuum oven at a temperature not exceeding 60 °C to obtain the final TiO\(_2\) white powder. For preparing the titanium paste, 45 g of low molecular weight ethyl cellulose EC (5–15, #46070) and 35 g of high molecular weight EC (30–50, #46080) were mixed and dissolved in ethanol to yield 10 wt. % mixture, and then 16 g of TiO\(_2\) nanoparticle powder and 64.9 g of α-terpineol (anhydrous, #86480, Fluka) were added to the EC mixture. The mixture was diluted with 80 ml of ethanol to obtain
a final volume of 280 ml under continuous stirring, and it was kept on the stirrer for 30 min at the room temperature, sonicated several times to ensure the homogeneity of the mixture, and finally diluted with ethanol at a ratio of 1:7 w/w to be used for the fabrication of perovskite solar cells. To be used as a counter electrode, carbon paste was prepared by mixing 10 g of graphite powder, 2 g of carbon black powder, and 1 g of ZrO$_2$ and 20 g of alpha-terpineol were mixed under continuous stirring for 30 min. This solution mixture was transferred to the mortar under stirring. After that, ethyl cellulose powder (5 wt. % ethyl cellulose #46080 and 5 wt. % ethyl cellulose #8648) was added in ethanol (10 wt. %) dropwise on the mixture with stirring for 1 h. The final carbon paste was transversely sonicated 30 times for 2 s for each to ensure the homogeneity of the mixture.

**PREPARATION PARAMETERS OF PEROVSKITE LAYERS**

**Anti-solvent treatment**

Two types of anti-solvents were applied to the perovskite layer during its deposition. The perovskite precursor solution was coated on a clean substrate by a consecutive one-step spin coating process at 2000 rpm for 60 s under controlled atmosphere of nitrogen with low humidity (1–5 ppm). To investigate the effect of the anti-solvent treatment, 350 ml of toluene or chlorobenzene was dropped just after the start of the ramping process by "46–50" s during the spin coating process, and the dripping time of the anti-solvent has a critical impact on the perovskite surface morphology and the crystallization process, as mentioned by Xia et al. In case of using toluene as the anti-solvent, a transparent layer of perovskite was formed consequently and the color can be prior evidence of the intermediate phase (DMSO–PbI$_2$–CH$_3$NH$_3$I) existence as reported by Xia et al. The thicknesses of the deposited layers are ranging from 450 to 650 nm.

**Annealing rate**

Slow annealing: The perovskite precursor was annealed on a hot plate at a slow ramping rate, and the temperature started to be raised from room temperature to reach 100 °C at the (4°C/min) ramp until the perovskite precursor was completely converted into perovskite film with a dark gray color with regard to Konstantakou et al. report.

Flash annealing: After the spin coated process, the samples were placed on a hot plate directly at 100 °C for 20 min, and this method is called "flash" annealing. The sudden or shock annealing at higher temperature is expected to enhance the perovskite crystallization.

**Device fabrication**

Fluorine-doped tin oxide (FTO) glass (surface sheet resistance ~13 Ω/sq, 1.1 mm thick) was obtained from Sigma-Aldrich; it was cut into pieces of 15 × 15 mm$^2$ and washed with sodium dodecyl sulfate, acetone, ethanol, and deionized water sequentially for 15 min by sonication. The last traces of organic residues were removed by oxygen plasma cleaning for 10 min. To avoid the short circuit during the contact of electrodes, an exposed part of the FTO anode layer on top of the substrate was removed by etching technique using diluted HCl and a part of the layer was covered by adhesive tape about 3 × 15 mm$^2$ for both opposite sides. The exposed part was immersed in a mixture consisting of zinc powder and HCl (2M) to obtain the required electrode pattern. The prepared TiO$_2$ blocking layer (bl) precursor solution was spin coated on a FTO substrate at 2000 rpm for 30 s, the substrate was immediately dried onto the hot plate at 100 °C, and then it was sintered at 450 °C for 30 min. A 450 nm mesoporous (ms)TiO$_2$ anatase layer was deposited over the TiO$_2$-bl layer by spin coating at 4000 rpm before annealing at 500 °C for 30 min to complete the.calcination and to ensure removing of any organic components. The FTO/TiO$_2$-bl/TiO$_2$-ms substrate was immersed in 40 mM aqueous TiCl$_4$ solution at 70 °C for 30 min and then washed by deionized water and left to dry at 100 °C before heated again at 500 °C for 30 min. The carbon counter electrode...
was coated using the doctor blade technique over the FTO/TiO$_2$-bL/TiO$_2$-ms, dried at 80 °C for 30 min, and annealed at 500 °C for 30 min. Finally, the perovskite precursor solution (MAPbI$_3$) was infiltrated and deposited onto the fabricated FTO/TiO$_2$-bL/TiO$_2$-ms/C mesoscopic structure at 2000 rpm using the spin coater in a glove box under nitrogen atmosphere and the whole cells were annealed at 100 °C for 30 min.

RESULTS AND DISCUSSION

To elucidate the influence of preparation parameters on the performance of the perovskite layer, different perovskite layers were prepared with different parameters, including heat treatment (slow rate and flash annealing) and anti-solvents of chlorobenzene and toluene. Interestingly, UV–vis absorption spectroscopy indicates the important impact of chlorobenzene on the light absorption of the perovskite layer, as shown in Fig. 1.

The perovskite layer treated with chlorobenzene as an anti-solvent shows a higher optical absorption compared with that treated without an anti-solvent or with toluene as an anti-solvent. The low absorption of the deposited perovskite layer without anti-solvent dripping was attributed to the remaining PbI$_2$, as shown in Fig. 2(a). Moreover, the low absorption of the deposited perovskite layer with toluene dripping as an anti-solvent was ascribed to the presence of numerous pin holes as depicted in Figs. 3(c) and 3(d). It is noteworthy that the morphology and the grain size of the perovskite layer are largely affected by changing the annealing temperature and utilizing different anti-solvents.

**FIG. 3.** SEM images of perovskite layers with different magnifications. (a) and (b) Perovskite layer deposited without an anti-solvent at slow rate annealing; (c) and (d) perovskite layer treated with toluene as an anti-solvent at slow rate annealing; and (e) and (f) perovskite layer deposited with chlorobenzene as an anti-solvent at slow rate annealing. * indicates the size distributing histogram of each layer.
X-ray diffraction technique was utilized to confirm the purity and the crystallinity of the prepared perovskite layer. Obviously, the anti-solvents enhance the purity of perovskite materials, which was confirmed by XRD. It is known that the pure perovskite layer has three significant diffraction peaks at $2\theta = 14.18^\circ$, $28.52^\circ$, and $31.96^\circ$ which were ascribed to (110), (220), and (310) crystal planes, respectively. XRD confirms the presence of unreacted PbI$_2$ in the prepared perovskite without the dripping of the anti-solvent at slow rate annealing, as shown in Fig. 2(a), where the weak diffraction peak originated at $2\theta = 12.7^\circ$ is attributed to PbI$_2$. Utilization of the anti-solvents during the fabrication process improves the purity of the perovskite layer, which was confirmed by total disappearing of the diffraction peak at $2\theta = 12.7^\circ$ and formation of the three obvious peaks at $2\theta = 14.18^\circ$, $28.52^\circ$, and $31.96^\circ$, as shown in Figs. 2(b) and 2(c).

SEM images show that the deposition of the perovskite layer without an anti-solvent at slow rate annealing produces a rod-like structure. By magnifying the image, these rods consist of very small grains, as shown in Figs. 3(a) and 3(b). Finally, the as-deposited perovskite layer displays an inhomogeneous structure, which has a negative effect on the PCE of the as-fabricated solar cell. The perovskite layer exhibits a better morphology after addition of
FIG. 6. SEM images of perovskite layers after annealing at 130 °C, (a) large grains with lotus leaf shape, and (b) the magnified leaf core.

toluene as an anti-solvent compared with that obtained without an anti-solvent, since the rod-based materials completely disappeared. However, this layer has numerous and wide holes as depicted in Figs. 3(c) and 3(d). Chlorobenzene has a good miscibility in the DMF/DMSO co-solvent and a good capability to freeze the perovskite solution. By employing chlorobenzene as an anti-solvent, the perovskite layer is promoted to a smooth, uniform, and homogeneous pin-holes free layer with significant large grains, as shown in Figs. 3(e) and 3(f). Although the as-deposited perovskite layer with chlorobenzene is a pin-holes free layer, its grains are smaller than those of the deposited perovskite layer with toluene. Those grains are in a good interconnection between each other, resulting in pin holes free surface.

To understand the full effect of annealing on the morphology and grain size of the perovskite layer, flash annealing is combined with and without the anti-solvent to different deposited perovskite layers. The perovskite layer deposited with flash annealing without an anti-solvent is improved and exhibited better morphology compared with that deposited at slow rate without an anti-solvent. However, as shown in Fig. 4(a), there is a large crack in the inhomogeneous part, and in Fig. 4(b), the grain boundaries suffer from enormous pin holes.

On the other hand, to study the effect of the anti-solvent combined with flash annealing on the morphology of the perovskite layer, toluene was dripped as an anti-solvent and the perovskite layer was treated at 100 °C. The resultant perovskite layer has large grains up to 2.5 μm, while this layer has large holes, which concentrated at grain boundaries. Furthermore, many pin holes are formed inside the grains as illustrated in Figs. 5(a) and 5(b). More importantly, the dripping of chlorobenzene as an anti-solvent enhances the grains growth of the perovskite layer. The pin-holes free layer has a homogeneous and a uniform surface; in addition, the deposited layer has large grains. However, the grains are smaller than that of toluene, as shown in Figs. 5(c) and 5(d).

As illustrated in Figs. 6(a) and 6(b), annealing at higher temperature up to 130 °C deteriorates the morphology of the perovskite layer. Although the grains become larger, the grains have lotus leaf shape. Therefore, the as-deposited layer indicates disconnected grains. Zadeh et al. supposed that the growth of the lotus leaf like-shape crystal can be formed when the substrate surface has a larger

FIG. 7. (a) Meso-porous architecture of carbon-based PSC and (b) energy level diagram of each corresponding layer.
free energy than the sum of both the film–substrate interface energy and film surface energy.\textsuperscript{16,33} Annealing at higher temperature up to 140 °C even after treatment with chlorobenzene results in disconnected perovskite crystals with many holes in the perovskite layer. These defects could be due to the effect of high temperature, which resulted in insufficient crystal growth, quick solvent evaporation, and decomposition of PbI\textsubscript{2} as mentioned by Ye et al.\textsuperscript{26} It is observed that the treated perovskite layer during annealing at 140 °C with toluene results in the same aforementioned defects.

In order to fully study the effect of preparation parameters on the performance of PSCs, PSCs were fabricated with TiO\textsubscript{2} as an electron transporting layer, MAPbI\textsubscript{3} as an absorbing material, and carbon paste as a back electrode, as shown in Fig. 7(a). The energy level of each corresponding layer is shown in Fig. 7(b).

The XRD pattern of the TiO\textsubscript{2} nanoparticles obtained by hydrothermal growth technique is depicted in Fig. 8. The nanoparticles show a crystalline nature with diffraction peaks at 2θ = 25.34°, 2θ = 37.88°, 2θ = 48.06°, 2θ = 53.98°, and 2θ = 62.76°, which corresponded to the planes (101), (004), (200), (105), and (204), respectively. The preferred orientation is corresponding to the plane (101). All the diffraction peaks in the XRD pattern can be indexed as anatase phases of TiO\textsubscript{2}. Figure 9 demonstrates the SEM images of the TiO\textsubscript{2} electron transporting layer with different magnifications.

Finally, five cells were fabricated using different treatments for the active layer MAPbI\textsubscript{3} with the mesoporous structure of FTO/TiO\textsubscript{2}-bL/TiO\textsubscript{2}-ms/MAPbI\textsubscript{3}/carbon, and the carbon counter electrode was annealed at 500 °C before the deposition of the perovskite solution through the mesoporous layers of the carbon-ms and TiO\textsubscript{2}-ms layers. The perovskite active layer was adjusted on top of the TiO\textsubscript{2}-bL layer using the infiltration method by injecting MAPbI\textsubscript{3} through the carbon and TiO\textsubscript{2} mesoporous layers. Employing the infiltration deposition technique may avoid excess heating of the perovskite active layer and consequently reduce the probability of its degradation according to the work of Baker et al.\textsuperscript{29} The first cell was fabricated using slow annealing rate without anti-solvent treatments, and two more cells were fabricated using the slow annealing rate and combined with toluene or chlorobenzene as anti-solvents. Another two cells were fabricated with flash annealing at 100 °C for 20 min combined with toluene or chlorobenzene.
as anti-solvents. Briefly, the PSCs fabricated with flash annealing exhibit PCE better than that for slow rate annealing. Moreover, chlorobenzene produces higher performance as an anti-solvent than toluene. The lowest PCS is obtained from PSC fabricated with slow rate annealing without anti-solvent dripping. The disconnected perovskite rods with very small perovskite crystals enhances the charge recombination, declines the shunt resistance, and leads to poor optical absorption, which reflected on the photovoltaic performance, where the values of FF, Voc, and PCE are found to be 27%, 0.34 V, and 0.52%, respectively. The addition of toluene before slow annealing promotes the formation of perovskite film. However, this film suffers from large cracks and non-uniformity. Therefore, the enhancement is insignificant. The addition of chlorobenzene as an anti-solvent before slow annealing delivers a uniform and pin-hole free perovskite layer with small grains, which enhances the optical absorption and decreases the charge carriers’ recombination. Hence, the values of Jsc, Voc, FF, and PCE are jumped to 7.5 mA/cm$^2$, 0.71 V, 34%, and 4.4%, respectively. The perovskite grains are enlarged up to 2.5 μm by adopting flash annealing with toluene as an anti-solvent. Although the corresponding PSC has higher Jsc compared with that of PSCs with slow rate annealing, Voc is dropped to 0.51 V. The poor Voc is due to the numerous holes which concentrated in the grain boundaries. A uniform, homogeneous, compact, and pin-holes free perovskite layer is obtained by dripping chlorobenzene as an anti-solvent and then annealing the perovskite layer with fast rate (flash annealing). The superior properties of that perovskite film are reflected on its photovoltaic parameters, where Voc is improved to 0.74 V and PCE significantly is jumped to 7%. The most important limiting factor for achieving high efficiency of the paintable carbon-based PSCs lies in the poor contact at perovskite/carbon interface suppressed hole extraction, which seriously decreases the fill factor (FF). Chlorobenzene as an anti-solvent improves the interface contact and significantly boosts the Voc due to more efficient hole extraction, all of which finally resulted in a PCE of 11.3% with a Voc of 0.74 V and a FF of 0.34. Generally, the obtained Jsc of all fabricated PSCs are considered low compared with reported works because all PSCs are measured under illumination of (40 mW/cm$^2$). Figure 10 shows J–V curves of fabricated PSCs with different parameters, and the photovoltaic parameters are summarized in Table I.

**CONCLUSIONS**

Large MAPbI$_3$ perovskite grains up to 2.5 μm were obtained by addition of toluene as an anti-solvent combined with fast rate annealing (flash annealing). Anti-solvent treatment proved that it has a strong enhancement effect on MAPbI$_3$ absorption and optical properties, and hence, it played a critical role in the final film morphology. It was also enhancing the photo carrier collection and the performance of the cell. Annealing temperature should neither be lowered below 100 °C nor be raised more than 130 °C to avoid distortion in the crystal morphology of the perovskite layer. Carbon-based PSCs with PCE up to 7% were fabricated with optimum fabrication parameters.

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### DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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### Table I. Photovoltaic parameters of the fabricated cells with different conditions.

| Cell parameters | Annealing method | Anti-solvent treatment | Voc (V) | Jsc (mA/cm$^2$) | FF (%) | PCE (%) |
|-----------------|------------------|------------------------|--------|----------------|--------|---------|
| Slow rate       | N/A              | Toluene                | 0.34   | 2.50           | 27     | 0.57    |
| Slow rate       | Toluene          |                        | 0.46   | 5.80           | 34     | 2.30    |
| Slow rate       | Chlorobenzene    |                        | 0.71   | 7.50           | 34     | 4.40    |
| Fast rate (flash)| Toluene          |                        | 0.53   | 11.9           | 34     | 5.35    |
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