Electronic Supporting Information

Low temperature processed solar cell with record-high-Voc of 1.61 V and FF of 0.77 based on solvent annealed $CH_3NH_3PbBr_3$/ICBA active layer

Chun-Guey Wu[a,b,*], Chien-Hung Chiang[b], Sheng Hsiung Chang[b]

[a]*Department of Chemistry and* [b]*Research Center for New Generation Photovoltaics, National Central University, Jhong-Li, 32001, Taiwan, ROC.*

E-mail address of Professor C. G. Wu: t610002@cc.ncu.edu.tw

Table S1: Curve fitting parameters of normalized time-resolved photoluminescence.

Sample	A_{NR}	τ_{NR} **(ns)**	A_R	τ_P **(ns)**
$CH_3NH_3PbBr_3$	0.39	2.05	0.61	4.66
$CH_3NH_3PbBr_3$/ICBA without solvent annealing	0.32	2.73	0.68	8.83
$CH_3NH_3PbBr_3$/ICBA with solvent annealing	0.83	0.75	0.17	1.32

A_{NR} is the normalized amplitude of non-radiative exciton annihilation.

A_R is the normalized amplitude of radiative excitons.

τ_{NR} is the lifetime for the non-radiative exciton annihilation.

τ_R is the radiative exciton lifetime.

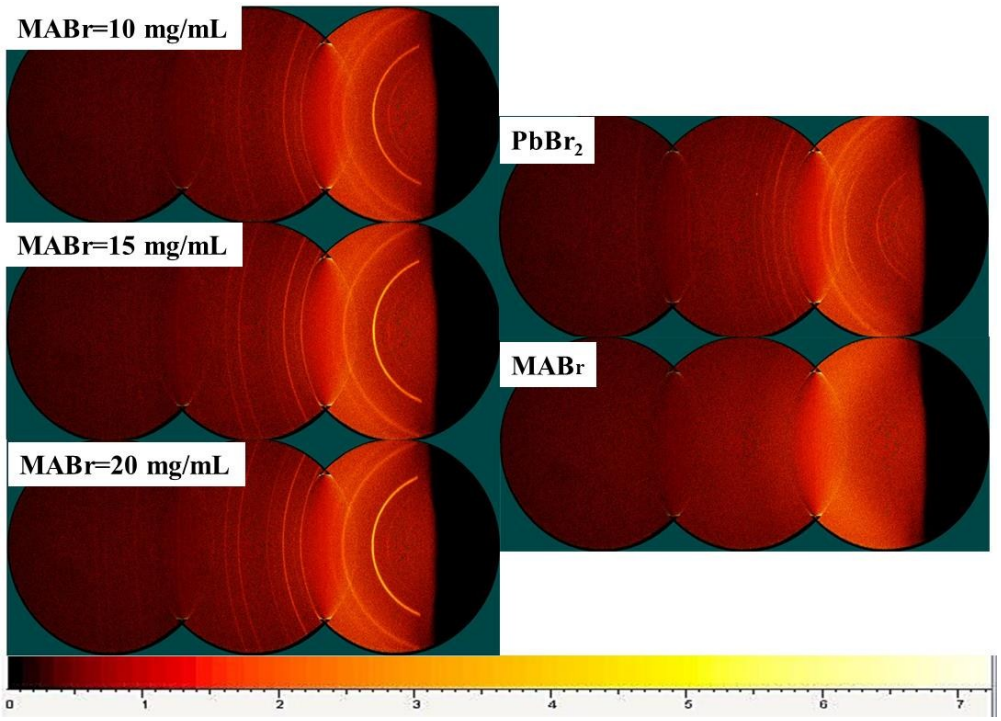
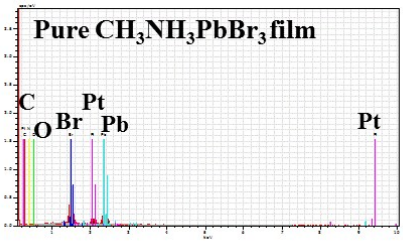
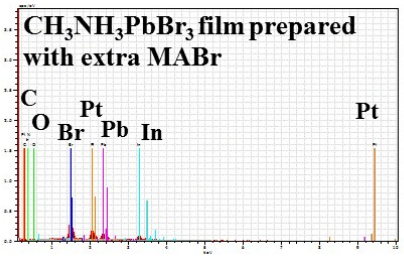


Figure S1: The origin 2D-XRD pattern of $CH_3NH_3PbBr_3$ films prepared with a two-step method and the starting materials.

The origin 2D-XRD data for $CH_3NH_3PbBr_3$ films prepared with various concentration of MABr/IPA as well as the starting materials (MABr and $PbBr_2$) were displayed in Figure S1. The photos proved that the quality of $CH_3NH_3PbBr_3$ film is very sensitive to the concentration of MABr/IPA used in the second step of the two-step method. Crystalline film with pure phase can be obtained by fine tune the concentration and quantity of each component as well as the spin program.



Element	Series	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]
Carbon	K-series	5.22	6.78	39.00
Oxygen	K-series	0.79	1.03	4.45
Bromine	L-series	31.80	41.31	35.71
Lead	M-series	27.28	35.43	11.81
Platinum	M-series	11.29	14.67	5.19
Nitrogen	K-series	0.60	0.78	3.83
	Total:	76.98	100.00	100.00



Element	Series	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]
Carbon	K-series	4.37	6.09	33.03
Oxygen	K-series	2.09	2.91	11.87
Bromine	L-series	20.78	28.95	23.60
Indium	L-series	13.72	19.11	10.84
Lead	M-series	14.68	20.45	6.43
Nitrogen	K-series	1.12	1.56	7.26
Platinum	M-series	15.01	20.91	6.98
	Total:	71.76	100.00	100.00

Figure S2: EDS data for pure $CH_3NH_3PbBr_3$ film and film prepared with high MABr/IPA concentration in the second step.

The stoichiometry of Br:Pb in $CH_3NH_3PbBr_3$ films obtained from the EDS data (displayed in Figure S2) is 3:1 for the best photovoltaic performance films synthesized with both one-step and two-step methods. The result suggests that by well-controlling the concentration and volume of MABr/IPA solution and the spin rate in the preparation step, highly pure $CH_3NH_3PbBr_3$ film can be made also with a two-step method. No other halide was detected suggesting the perovskite contains only bromide. On the other hand when the MABr/IPA concentration is too high, extra MABr may exist or decomposed to some bromides, therefore the Br/Pb ratio is higher than 3.

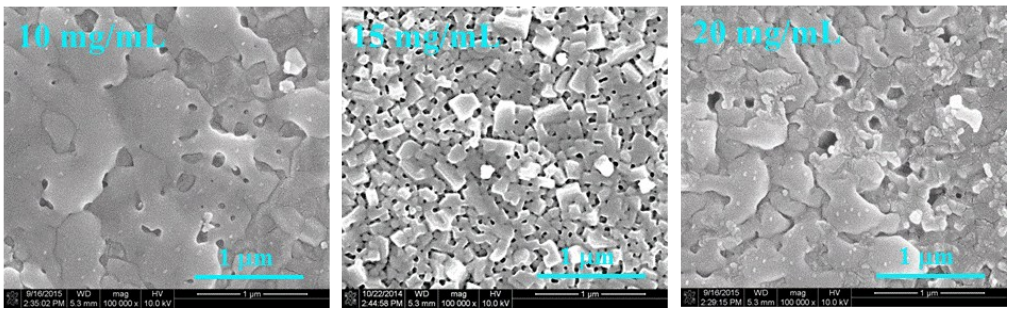


Figure S3: $MAPbBr_3$ films prepared with various concentrations of MABr/IPA solutions.

SEM images displayed in Figure S3 clearly revealed that $CH_3NH_3PbBr_3$ films prepared with lower or higher MABr/IPA solution all have poor quality.

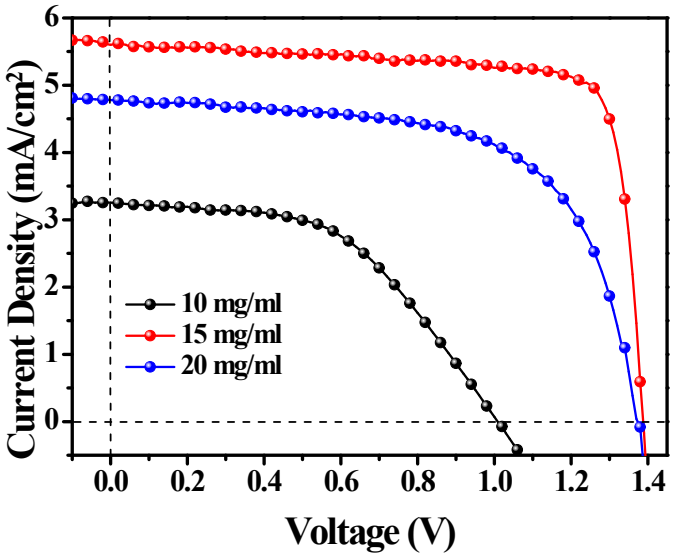


Figure S4: I-V curves of the cells based on $CH_3NH_3PbBr_3$ films prepared from various concentrations of MABr/IPA solutions in the second step using tow-step method.

I-V curves for the inverted cells based on $CH_3NH_3PbBr_3$ films fabricated using various concentrations of MABr/IPA solutions were illustrated in Figure S3. The quality of $CH_3NH_3PbBr_3$ film (therefore the efficiency of the corresponding device) is very sensitive to the film preparation condition. Pure $CH_3NH_3PbBr_3$ film was obtained only in very narrow MABr/IPA concentration range. XRD and EDS data reveal that film prepared with high MABr concentration will contain unreacted MABr residue whereas $PbBr_2$ was detected when low MABr concentration was used in the second step, all result in lower efficiency of the corresponding cells. The best photovoltaic performance $CH_3NH_3PbBr_3$ film was obtained when the concentration and volume of MABr/IPA solution is around 15 mg/mL and 30 μl, respectively when $PbBr_2$ film was prepared according to the procedure reported in the experiment section.

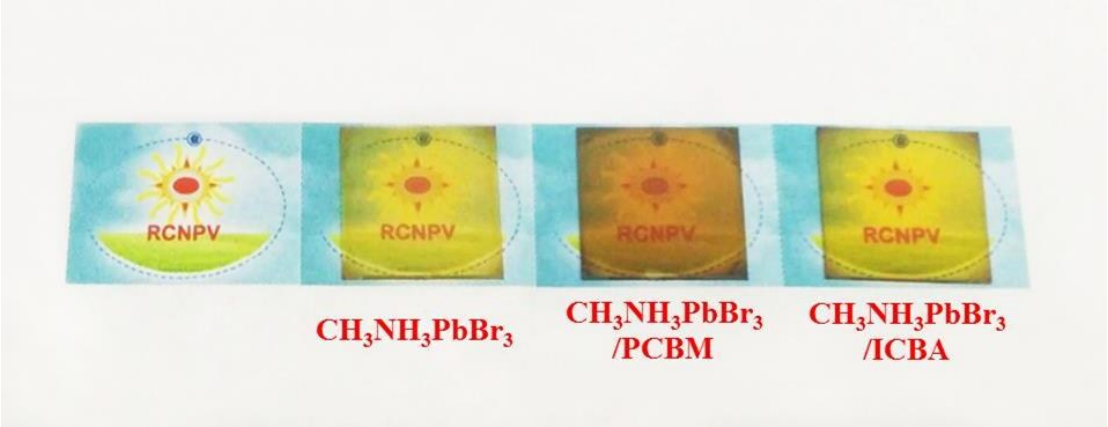


Figure S5: The pictures of blank background, ITO/PEDOT:PSS/$CH_3NH_3PbBr_3$, ITO/PEDOT:PSS/$CH_3NH_3PbBr_3$/PCBM, and ITO/PEDOT:PSS/ $CH_3NH_3PbBr_3$/ICBA.

The photos shown in Figure S4 reveal that $CH_3NH_3PbBr_3$ film is semi-transparent. $CH_3NH_3PbBr_3$ film does not change the transparency when a layer of ICBA was

deposited on tit. This is also one of advantages of using ICBA as an acceptor. If transparent cathode can be developed, a semi-transparent solar cell with high open-circuit voltage can be fabricated. It has a great potential to be applied in the tandem solar cell and the display related electronic devices.

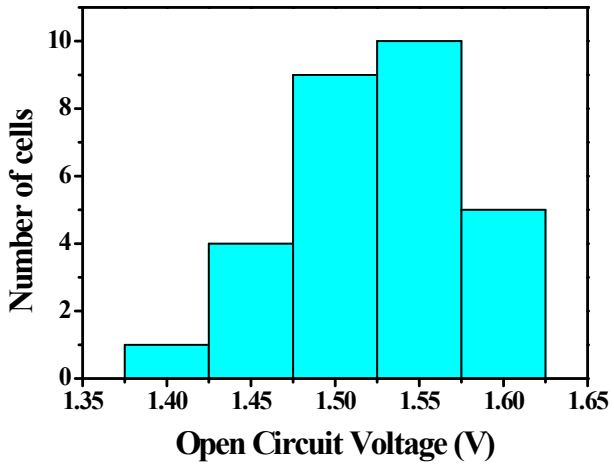


Figure S6: *Voc* statistics (based on 29 devices) of the inverted ITO/PEDOT:PSS/$CH_3NH_3PbBr_3$/ICBA/Ca/Al solar cells prepared at the similar conditions.

The V_{oc} statistics (based on 29 devices) showed in Figure S5 reveals that the high open-circuit voltage is a general phenomenon observed in the inverted ITO/PEDOT:PSS/$CH_3NH_3PbBr_3$/ICBA/Ca/Al devices. The average V_{oc} is *ca.* 1.55 V and cell with the V_{oc} higher than 1.6 V was obtained frequently.

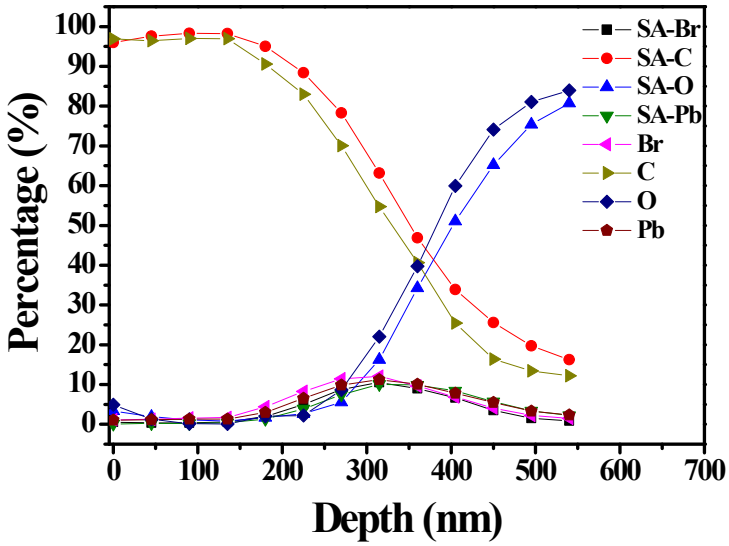


Figure S7: Depth profile XPS analysis of the contents of 4 elements of $MMAPbBr_3$/PCBM film with (SA) and without solvent annealing..

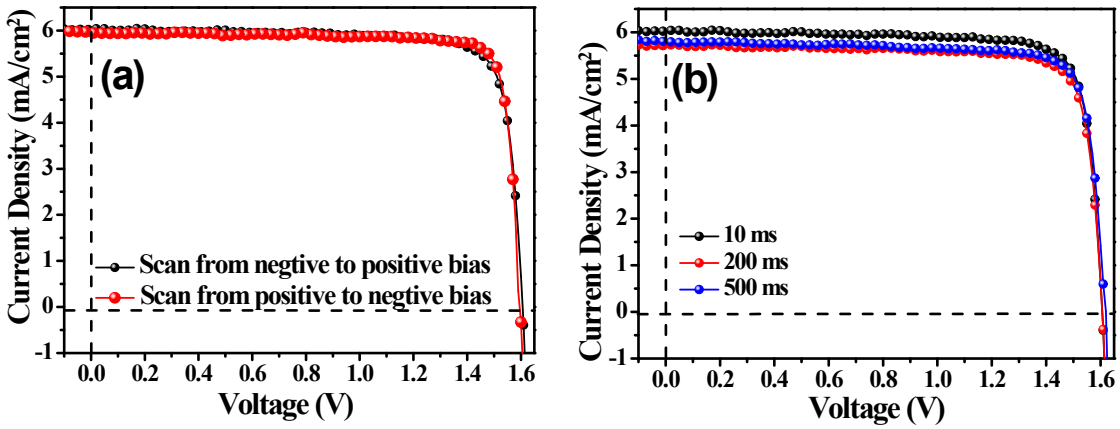


Figure S8: I-V curves of the champion cell scan at (a) two different directions and (b) various scan rates.

The I-V curves of the champion cell scan from various rates and direction displayed in Figure S7 revealed the current hysteresis is very limited.