Supporting Information

Enhancing the stability of perovskite solar cells and modules by two-dimensional $(PM)_2PbI_2Cl_2$

Yin Gao[a], Yanyan Gao[b,c], Maoyuan Wu[b,c], Shaohang Wu[b,c,*] Qian Chen[a], Yang Li[a,*], Yaohua Mai [b,c]

a *School of Electronics and Information Engineering, Wuyi University, Jiangmen 529 020,Guangdong,China*
b *Institute of New Energy Technology, College of Physics & Optoelectronic Engineering, Jinan University, Guangzhou 510632,Guangdong,China*
c. *Guangdong Mellow Energy Co., Ltd, Yuanming Road, Zhuhai 519075,Guangdong, China*

[*]Corresponding authors.
E-mail address: wushaohang@jnu.edu.cn (S. Wu), insidesun51@163.com(Y. Li);

1.Experimental

Materials: Lead(II) iodide((PbI_2， Purity>99.99%) was purchased from Xi'an Yil ante ;Formamidinium Iodide(FAI, Purity >99.99%) was purchased from Greatcell Sol ar Materials ; Methylamine hydrochloride (MACl, Purity >99.99%) and (Al_2O_3,Partic le size<50nm) were purchased from Sigma-Aldirch; Poly[bis(4-phenyl)(2,4,6-trimthyl phenyl)amine](PTAA, Purity >99.5%)、2-Phenylethanamine hydroiodide (PEAI, Pur ity >99%) and Fullerene-C60(C60, Purity >99%) were purchased from Xi'an Baolait C ompany; N,N-Dimethylformamide(DMF, Purity >99.8%)、Dimethyl sulfoxide(DMS O, Purity >99.8%)、Isopropyl alcohol(IPA, Purity >99.5%) and Chlorobenzene(CB, P urity >99%) were purchased from Maclean;N-Cyclohexyl-2-pyrrolidone (CHP, Purity >9 9%) and pentamidine hydrochloride (PMCl, Purity >99%) were purchased from Alad din. All Chemicals were used as received without further purification.

Solution preparation: The 3D perovskite solution was prepared by mixing PbI2 a nd FAI in a 1:1 ratio in the mixed solvent of DMF、DMSO and CHP (8:1:1,v:v:v), and

10%M MACl as the additive. The 2D perovskite solution was prepared by dissolving PMCl and PbI_2 in a 1:2 ratio in a mixed solvent of DMF and DMSO (4:1). The final 2 D/3D precursor solution was obtained by mixing the 2D solution and 3D solution in a volume ratio of 1:4.

Device Fabrication: The ITO-coated substrates (2.5×2.5cm^2) were ultrasonicated twice in water and detergent for 12 min each. The substrates underwent UV-ozone treatment for 10min. PTAA (1.5 mg/mL in chlorobenzene) was spin-coated onto the ITO at 4000 rpm for 30s. The layer was thenannealed at 100℃ for 10min. The PTAA substrate was spin-coated with 180μL of Al2O3 (in a volume ratio of 1:80 with IPA) and annealed at 100℃ for 10min to form the hole transport layer (HTL). Next, 150μL of the perovskite precursor was spin-coated at 4000 rpm with an acceleration rate of 800 rpm/s for 40s, and 300μL of EA was added as an anti-solvent at 30 s. The sample was then annealed at 105℃ for 30min. Afterwards, spin coat 100μL of PEAI （0.5mg/ml in IPA）passivation solution at 4000 rpm for 30 seconds, followed by annealing at 105℃ for 10min.Next, 30nm of C60 was evapo-rated, followed by the deposition of 20nm of SnO2 using atomic layer deposition (Super ALD Corp. E300). Finally, 150nm of Ag electrode was evaporated sequentially to complete the device. Perform other tests after heat treatment at 100℃ for 10 minutes.

Characterization: The current-voltage (J-V) curves of PSCs were characterized using a solar simulator with a spectrum of 1.5G. The light intensity was calibrated to 1000 W/m^2 using a standard silicon solar cell, and the illumination area was controlled using a black mask with an aperture area of 0.09 cm^2. The crystal structure of the perovskite film was characterized using a Bruker D8 Advance instrument. The time-resolved photoluminescence (TRPL) lifetime of the perovskite film was measured using a fluorescence spectrometer (FLS980) from Edinburgh Instruments. The external quantum efficiency (EQE) of the PSCs was measured using a spectral response system (Enlitech QE-R). The capacitance-voltage (C-V) curves of the PSCs were measured using an electrochemical workstation(ZAHNER GIMPS, Germany).

2. Figures and Tables

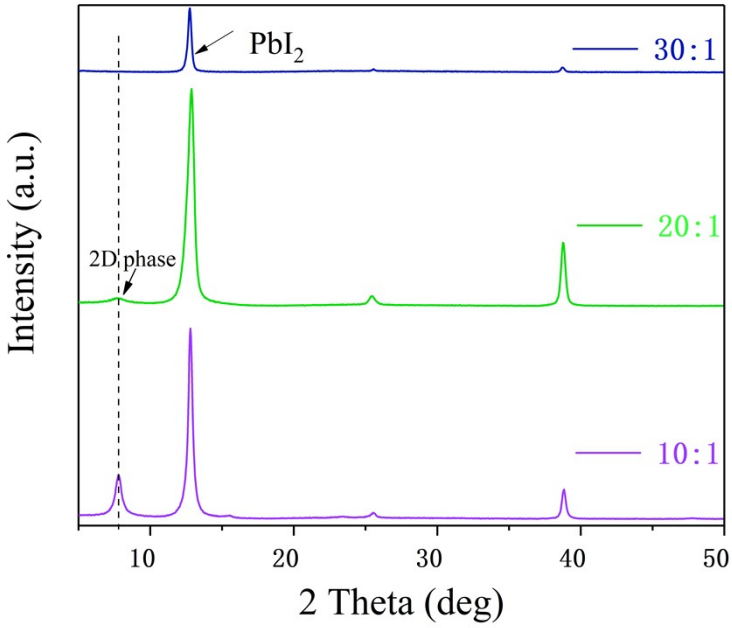

Fig. S1. XRD spectra of films prepared with different proportions of PbI_2 and PMCl.

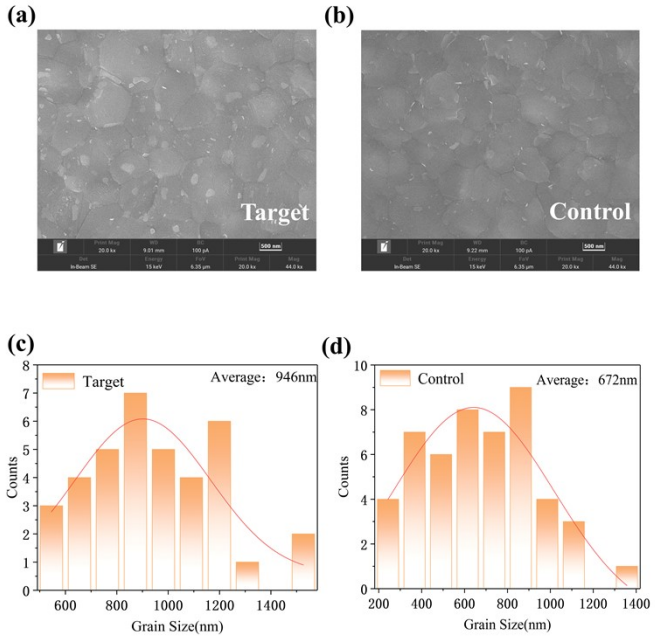

Fig. S2. a-d) SEM images and grain size distribution of perovskite films.

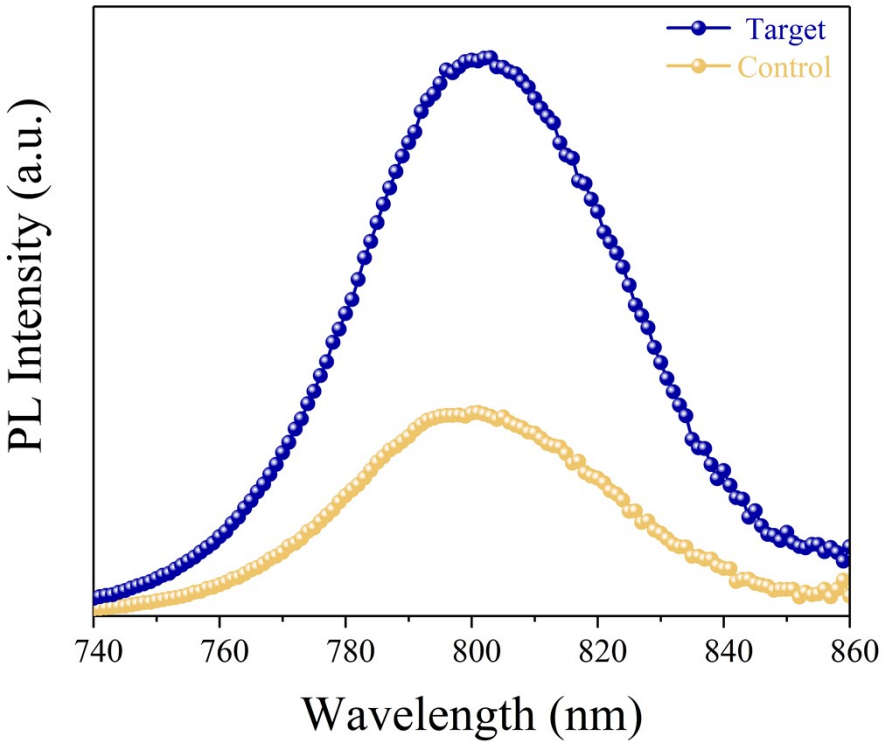

Fig. S3. Steady-state PL spectra of films incorporating bare $FAPbI_3$ (Control) and $FAPbI_3$ with 2D perovskite (Target).

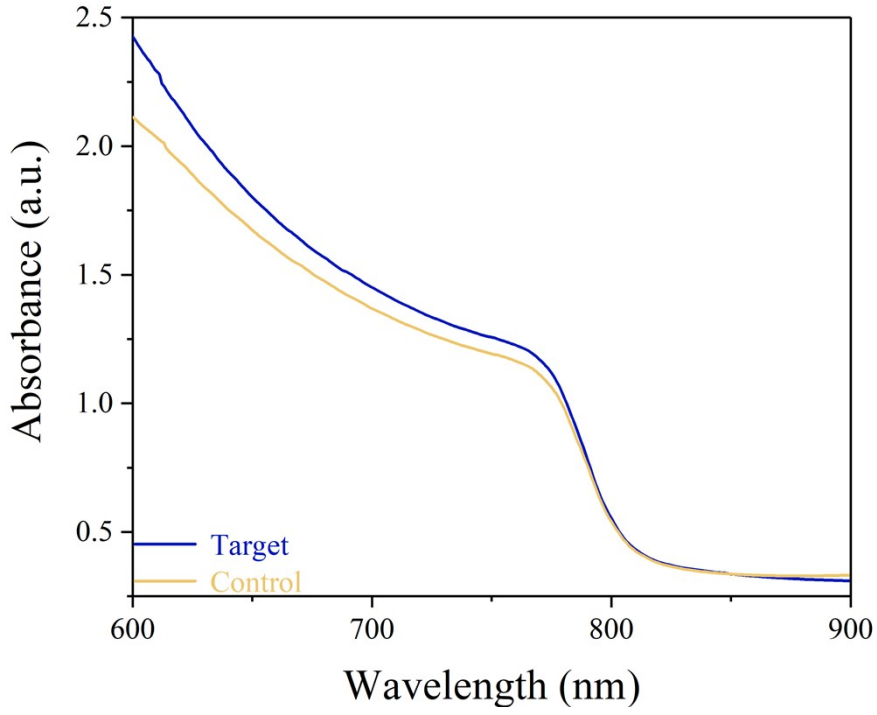

Fig. S4. The absorption spectra of PSCs incorporating bare FAPbI3 (Control) and FAPbI3 with 2D perovskite (Target).

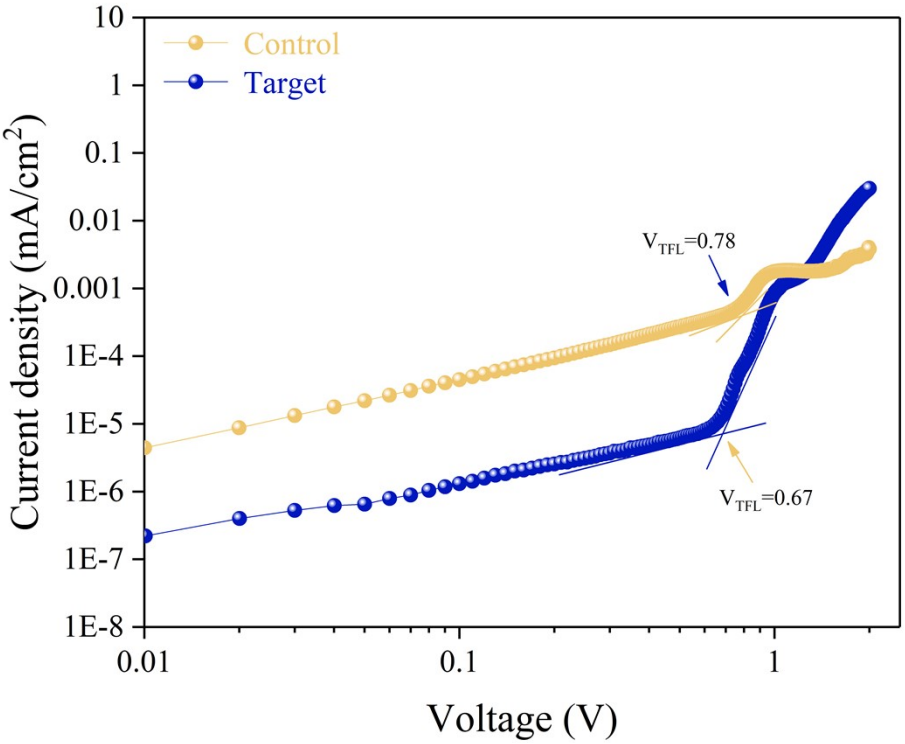

Fig. S5. J-V curves of PSCs incorporating bare FAPbI3 (Control) and FAPbI3 with 2D perovskite (Target) in the dark.

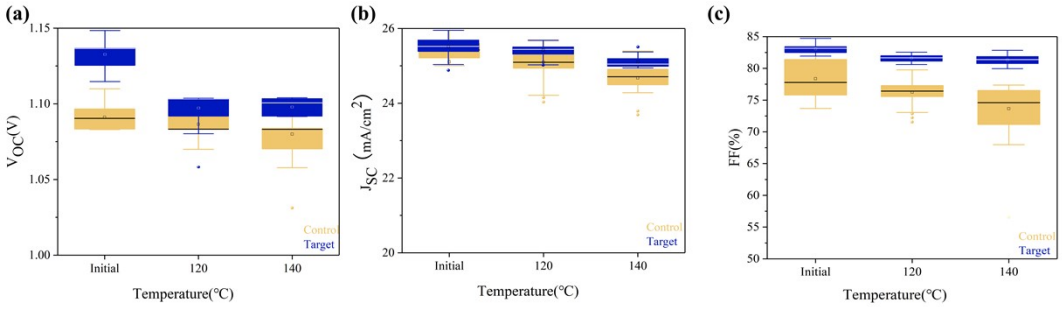

Fig. S6. statistics of V_{OC} (a), J_{SC} (b) and FF (c) of PSCs incorporating bare $FAPbI_3$ (Control) and $FAPbI_3$ with 2D perovskite (Target).

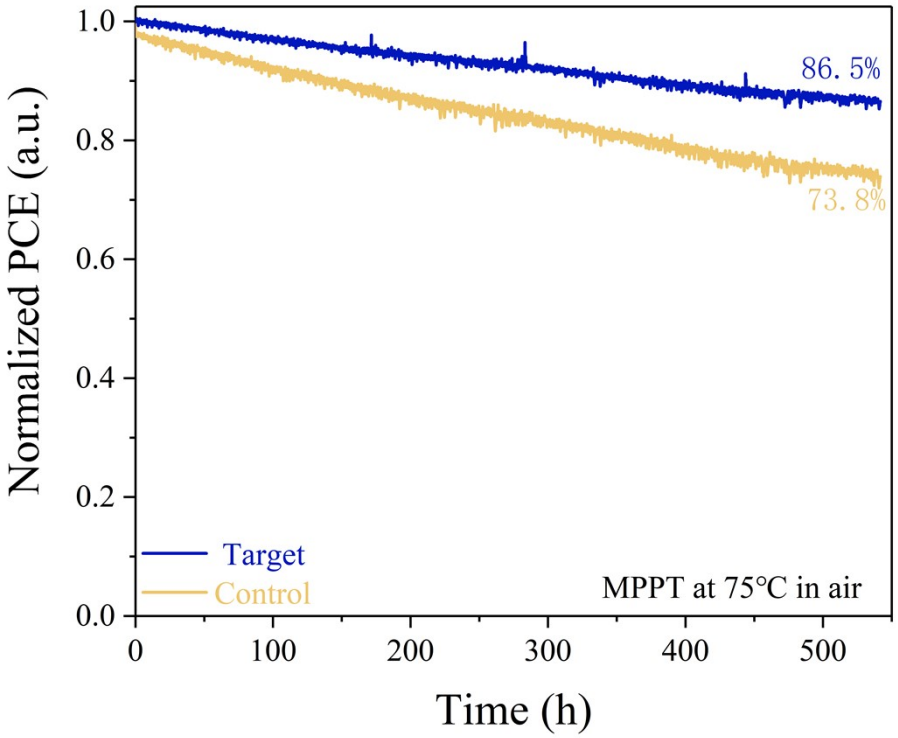

Fig. S7. Comparison of the stability of corresponding packaged moudle under continuous one-sun illumination at 75℃.

Table S1. Average efficiency of modules incorporating bare $FAPbI_3$ and $FAPbI_3$ with 2D perovskite (16 modules each).

	V_{OC} **(V)**	J_{SC} **(mA/cm²)**	**FF (%)**	**PCE (%)**	**σ(standard deviations)**
Target	7.956	3.562	0.782	22.457	0.183
Control	7.914	3.540	0.733	20.526	0.516