

Supporting Information

***In-situ* polymerization assisted strain release to enable efficient and mechanically robust flexible perovskite solar cells and modules**

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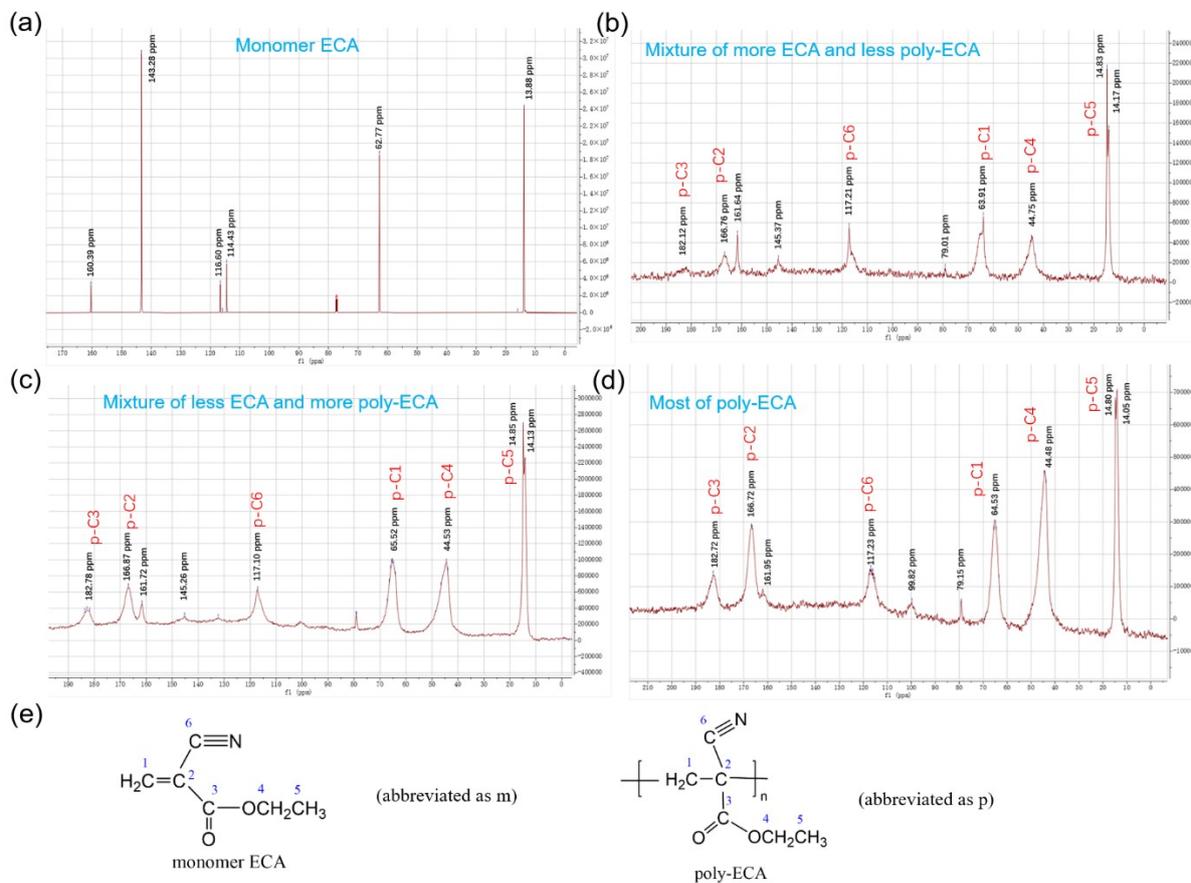


Figure S1. ^{13}C NMR spectra of (a) Monomer ECA in CDCl_3 ; (b) Mixture of more ECA and less poly-ECA; (c) Mixture of less ECA and more poly-ECA; (d) Most of poly-ECA; (e) Molecular structures with numbered carbon atoms.

The assignment of ^{13}C NMR spectra of monomer ECA (abbreviated as m) and poly-ECA (abbreviated as p) were labelled in the Figure, and molecular structures of the ECA and poly-ECA with the carbon numbers were also provided in Figure S1. We can clearly see reaction processes with the polymerization time extending.

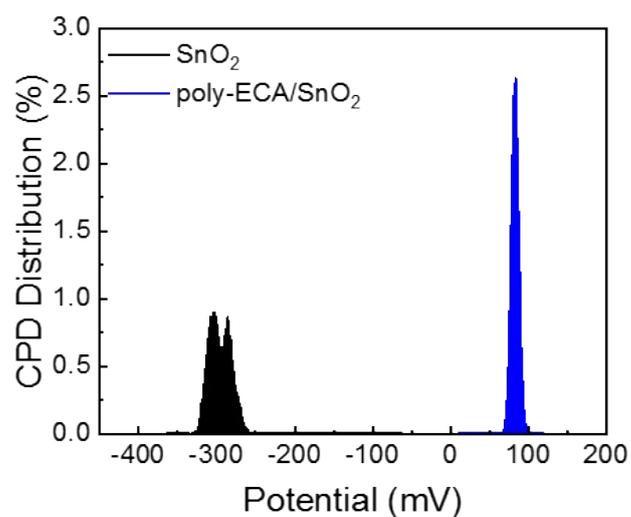


Figure S2. CPD distribution of SnO₂ films before and after spin-coating of ECA solution.

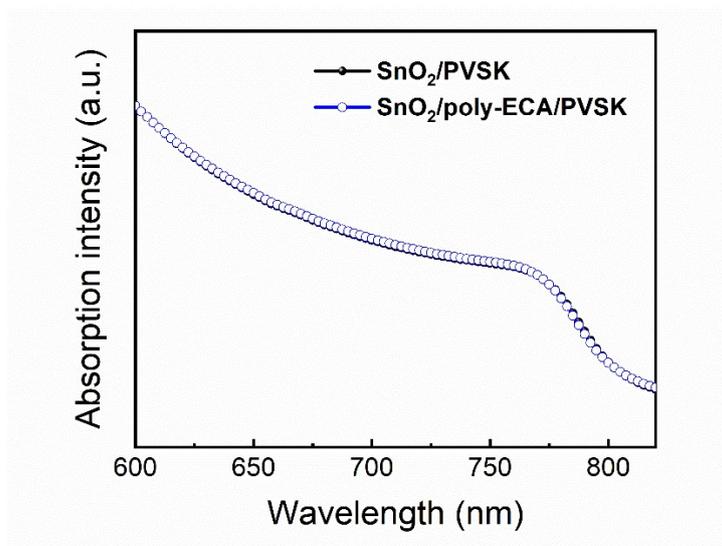


Figure S3. UV-visible spectra of perovskite films on SnO₂ and SnO₂/poly-ECA substrates.

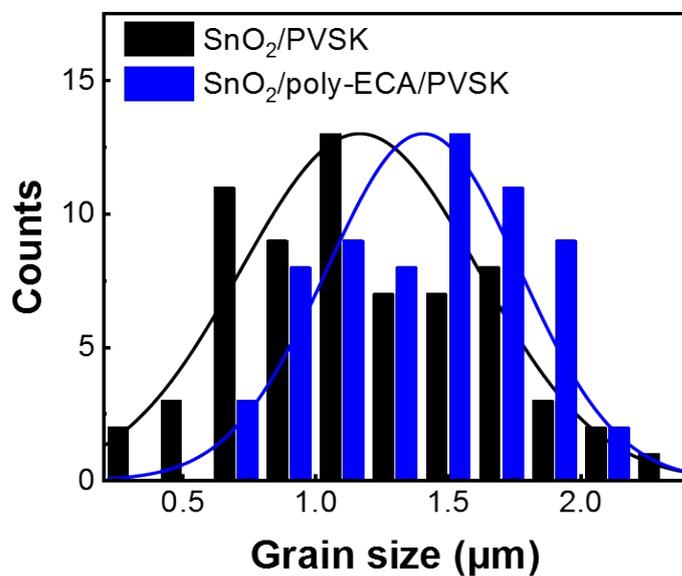


Figure S4. Statistical distribution of grain sizes in SEM images of perovskite films fabricated on different SnO₂ substrates.

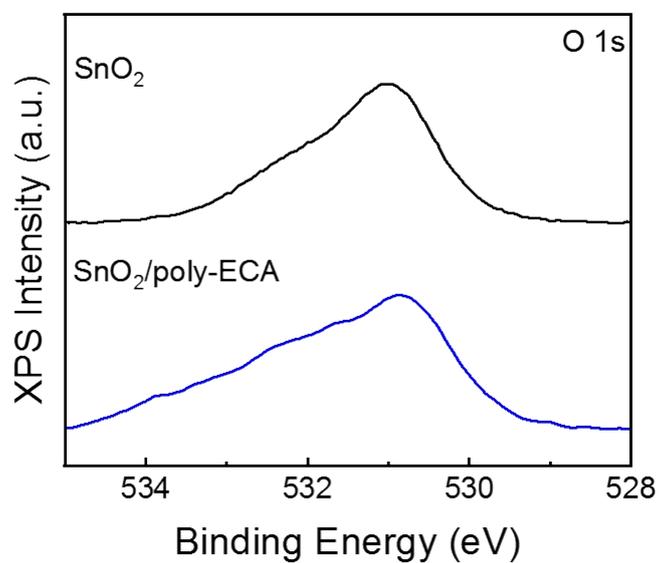


Figure S5. XPS spectra for O 1s orbitals of pristine and ECA modified SnO₂ films.

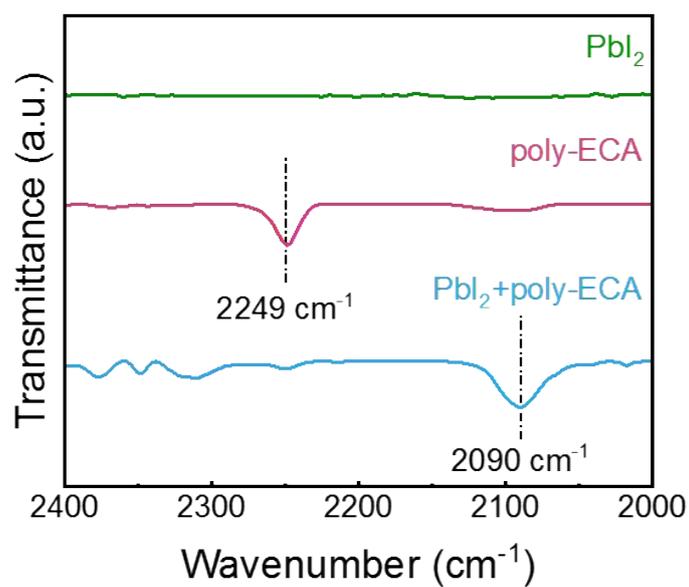


Figure S6. FTIR spectra of PbI_2 , poly-ECA powder and their mixture.

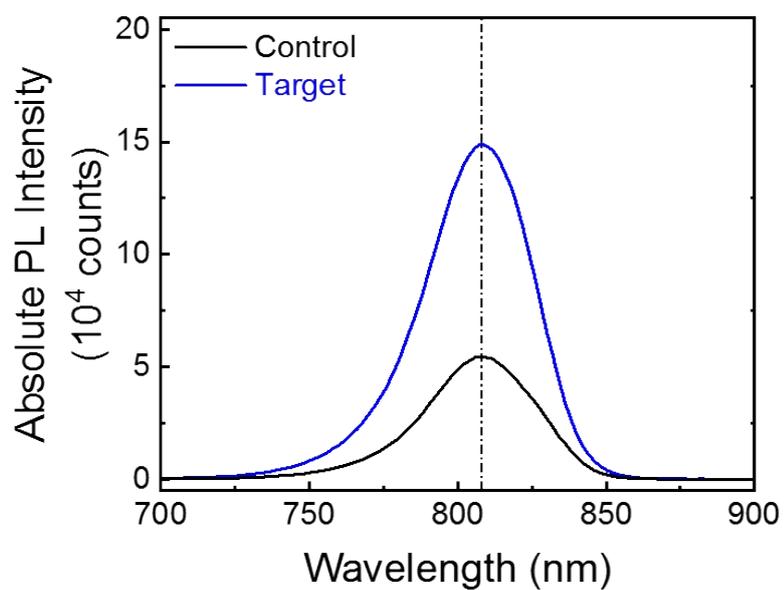


Figure S7. Steady-state PL intensity of control and target perovskite films.

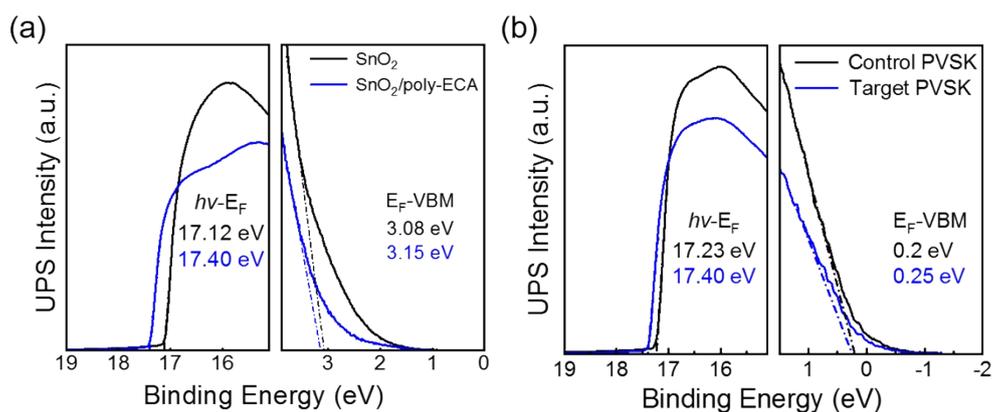


Figure S8. UPS spectra for (a) pristine and ECA modified SnO₂ films and (b) control and target perovskite films.

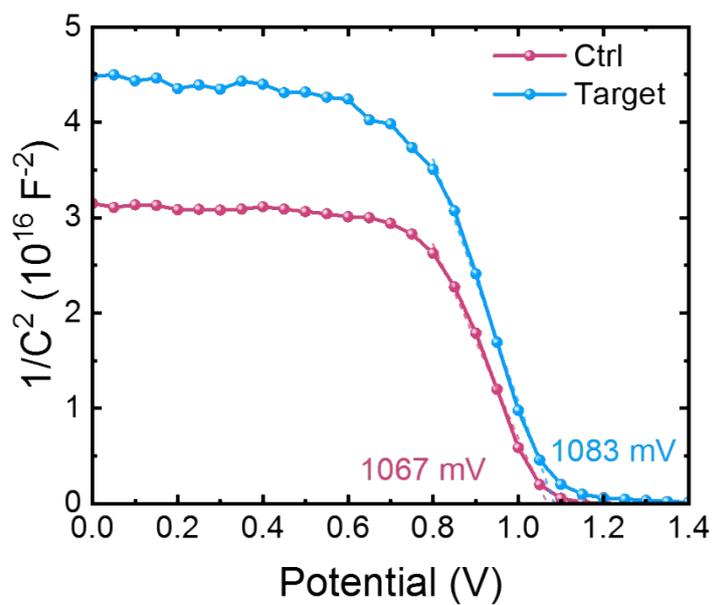


Figure S9. Mott-Schottky curves of control and target F-PSCs.

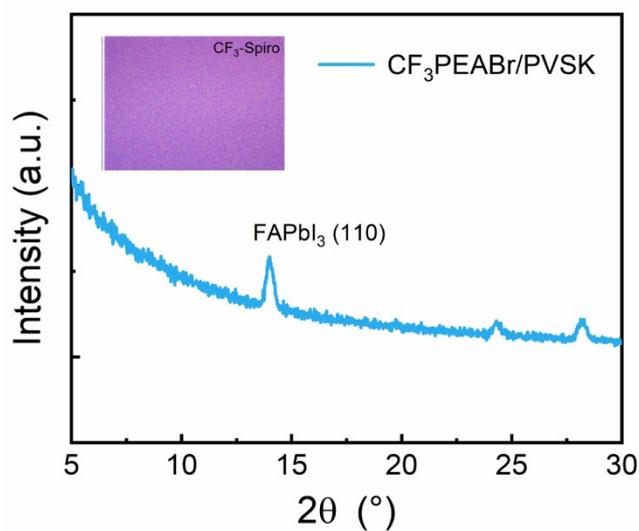


Figure S10. XRD patterns of CF₃PEABr/PVSK. Inset: Optical image of Spiro-OMeTAD layer on CF₃PEABr/PVSK

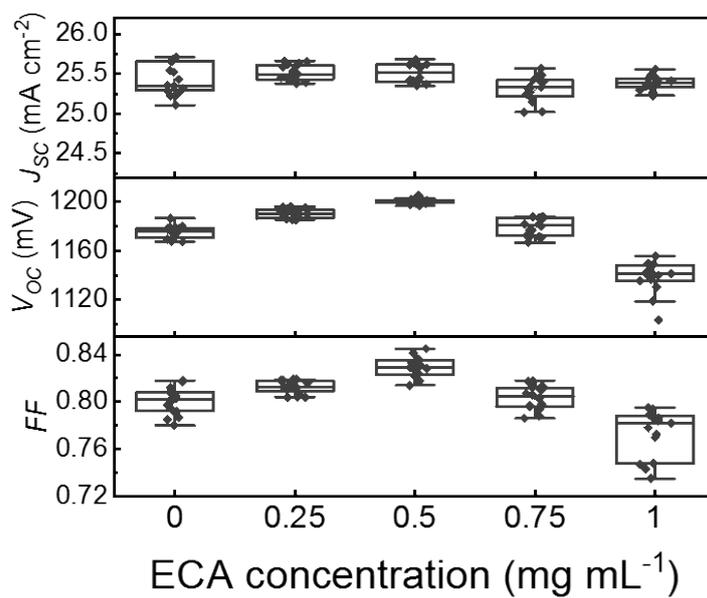


Figure S11. Statistical distribution of photovoltaic parameters (J_{sc} , V_{oc} and FF) of F-PSCs with different concentrations of ECA.

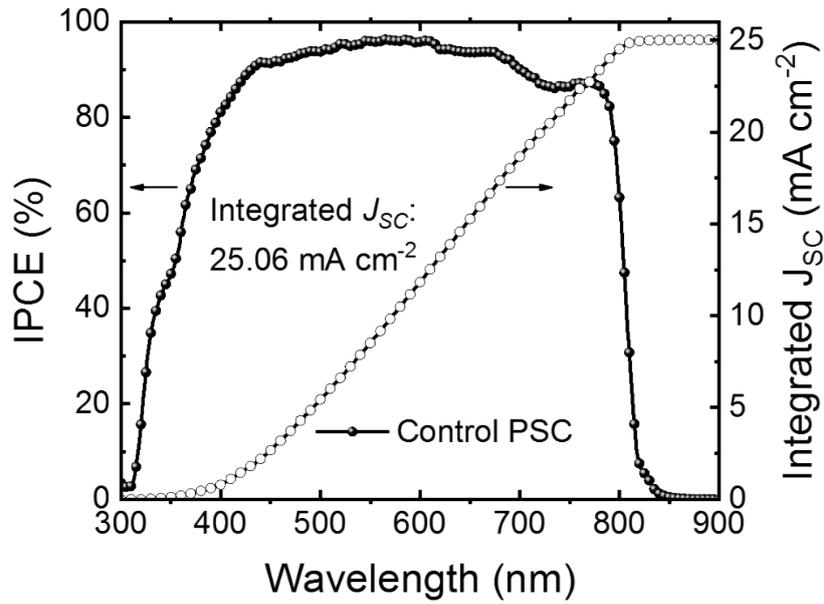


Figure S12. EQE spectra of the Control PSC

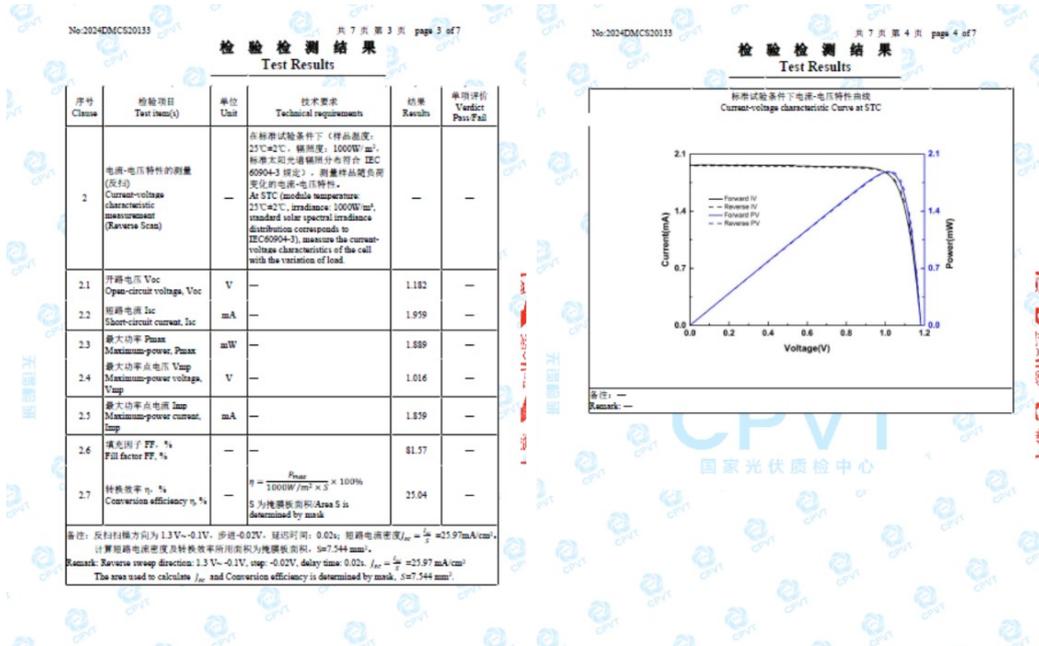


Figure S13. Certification report of champion F-PSCs in this work.

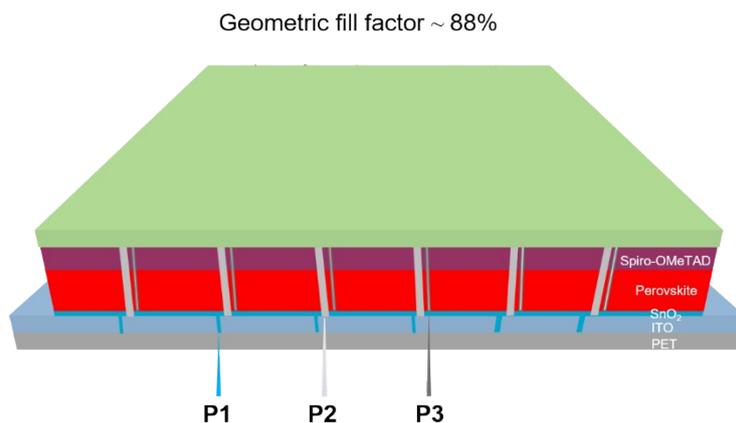


Figure S14. Schematic diagram of the structure of the flexible minimodule

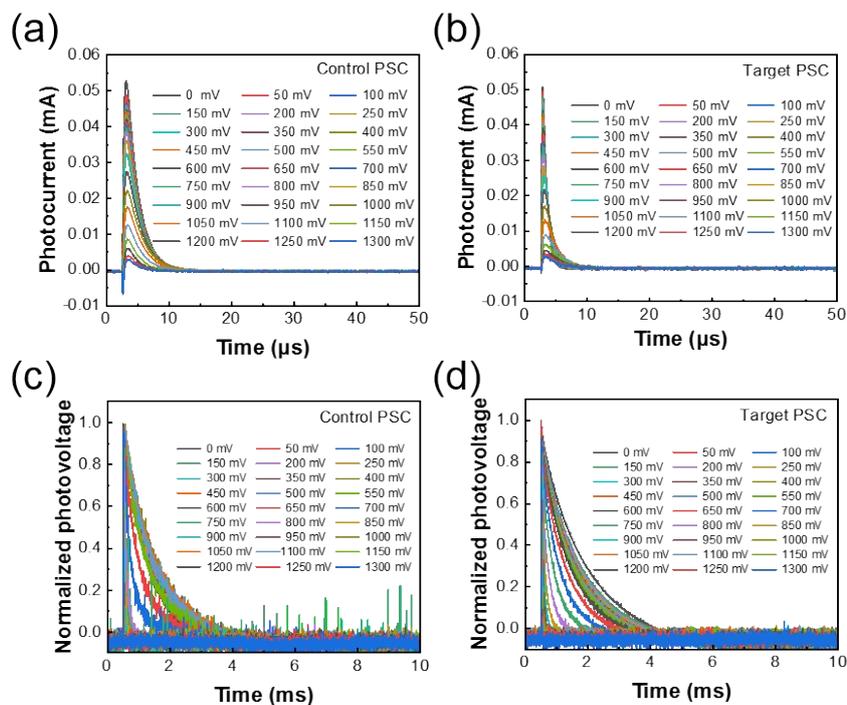


Figure S15. TPC curves of (a) control PSC, (b) target PSC and TPV curves of (c) control PSC and (d) target PSC at different bias voltage.

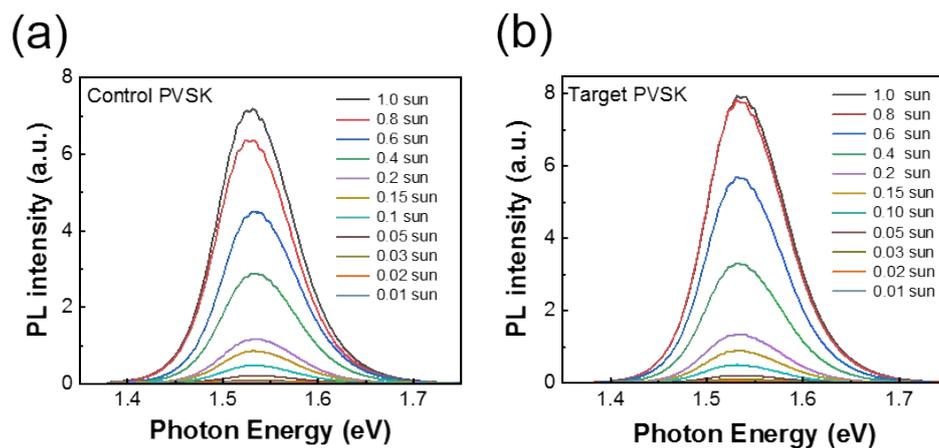


Figure S16. Absolute PL spectra of (a) control and (b) target ITO/SnO₂/(ECA)/PVSK stacks.

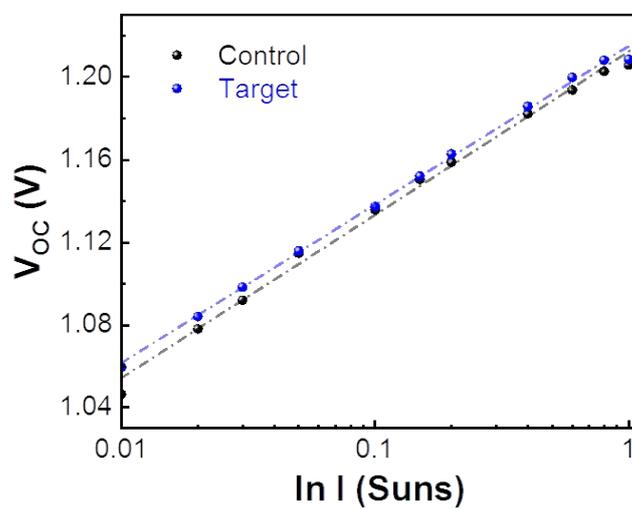


Figure S17. Open-circuit voltage at different light illumination of champion control and target devices.

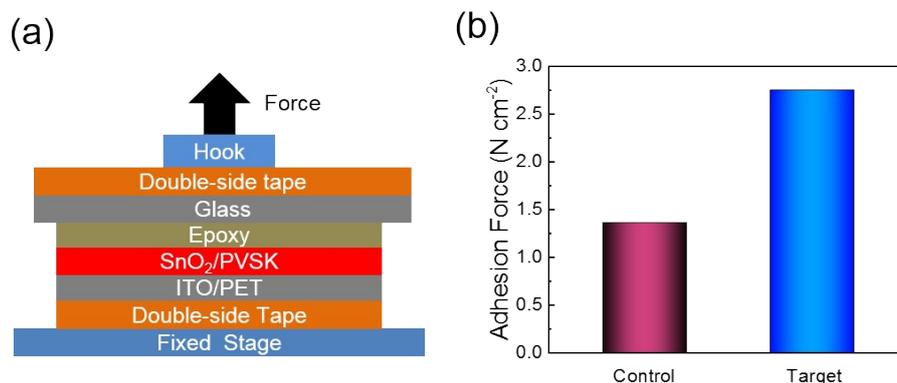


Figure S18. (a) Schematic illustration of the adhesion force measurement system; (b) adhesion force between perovskite absorber and SnO₂ substrate of control and target devices. Detailed procedure was given here. A thin epoxy film was doctor-bladed on the top of SnO₂(poly-ECA)/perovskite (PVSK), then similar size ultra-clear glass was put on the epoxy film surface. After the epoxy film was solidified, the hook was stuck on the center of the ultra-clear glass by double-side tape. The samples were fixed and tension meter was used to measure the adhesion force.

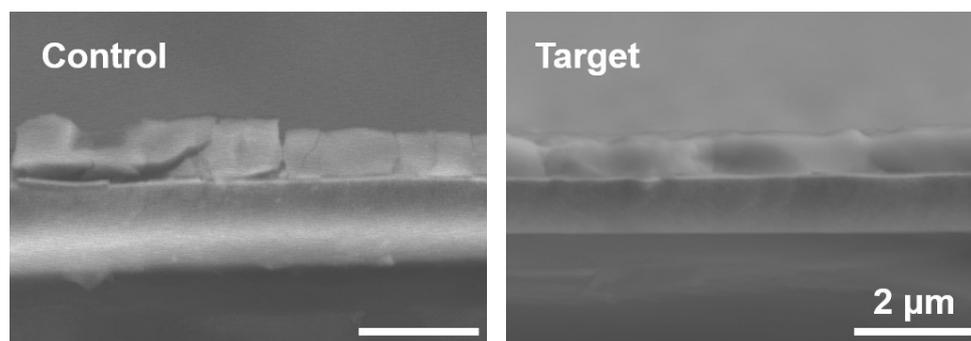


Figure S19. Cross-sectional SEM images of the Control (SnO₂/perovskite) and Target (SnO₂-poly-ECA/perovskite) samples after 10,000 bending cycles (radius: 10 mm).

Table S1. TRPL lifetime of control and target perovskite films.

Sample	A_1	τ_1/ns	A_2	τ_2/ns	$\tau_{\text{ave}}/\text{ns}$
Control	0.3940 ± 0.005	305 ± 4	0.5874 ± 0.005	1064 ± 6	759
Target	0.5465 ± 0.006	507 ± 7	0.3478 ± 0.006	2091 ± 33	1123

Table S2. Pseudo V_{OC} and FF obtained from pseudo $J-V$ curves of control and target stacks.

Stack	p- V_{OC}/mV	p-FF
Control	1205	0.87
Target	1209	0.88

Table S3. Nanoscratching testing results of the Control and Target

		Critical scratch load (mN)	
		Control	Target
Testing times	1	5.143	6.813
	2	5.067	6.130
	3	5.111	7.107
Average value		5.107	6.683

Table S4. Summary of benchmarking mechanical durabilities including bending radius, cycle numbers and efficiency retention in recent years

Bending radius	Cycle numbers	Efficiency retention	Ref.
2 mm	8000	91%	[S1]
3 mm	8000	84.65%	[S2]
3 mm	8000	80%	[S3]
3 mm	10000	95%	[S4]
3 mm	10000	94.10%	[S5]
3 mm	10000	88.90%	[S6]
4 mm	1000	92.20%	[S7]
4 mm	1000	92.60%	[S8]

4 mm	4000	90%	[S9]
4 mm	4000	97%	[S10]
4 mm	10000	87.60%	[S11]
4 mm	10000	90.00%	[S12]
5 mm	1000	92%	[S13]
5 mm	1000	92%	[S14]
5 mm	1000	96%	[S15]
5 mm	2000	89%	[S16]
5 mm	5000	90.10%	[S17]
5 mm	5000	75%	[S18]
5 mm	5000	93%	[S19]
5 mm	5000	93%	[S20]
5 mm	6000	96.56%	[S21]
5 mm	6000	90%	[S22]
5 mm	8000	74%	[S23]
5 mm	10000	91%	[S24]
5 mm	10000	71%	[S25]
5 mm	10000	85.10%	[S26]
5 mm	10000	92%	[S27]
5 mm	10000	96%	[S28]
5 mm	10000	90%	[S29]
5 mm	10000	86%	[S30]
5 mm	10000	80%	[S31]
5 mm	10000	81%	[S32]
5 mm	20000	92%	[S33]
5 mm	25000	92.30%	[S34]
6 mm	5000	90.80%	[S35]
6 mm	20000	86.70%	[S36]
6 mm	20000	90%	[S37]
7 mm	5000	73%	[S38]
7 mm	5000	84%	[S39]
10 mm	5000	95.30%	[S40]
10 mm	10000	95%	Our work

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