Electronic Supplementary Material (ESI) for Journal of Materials Chemistry A.

Supporting Information

Reduced energy loss enabled by thiophene-based interlayer for high performance and stable perovskite solar cells

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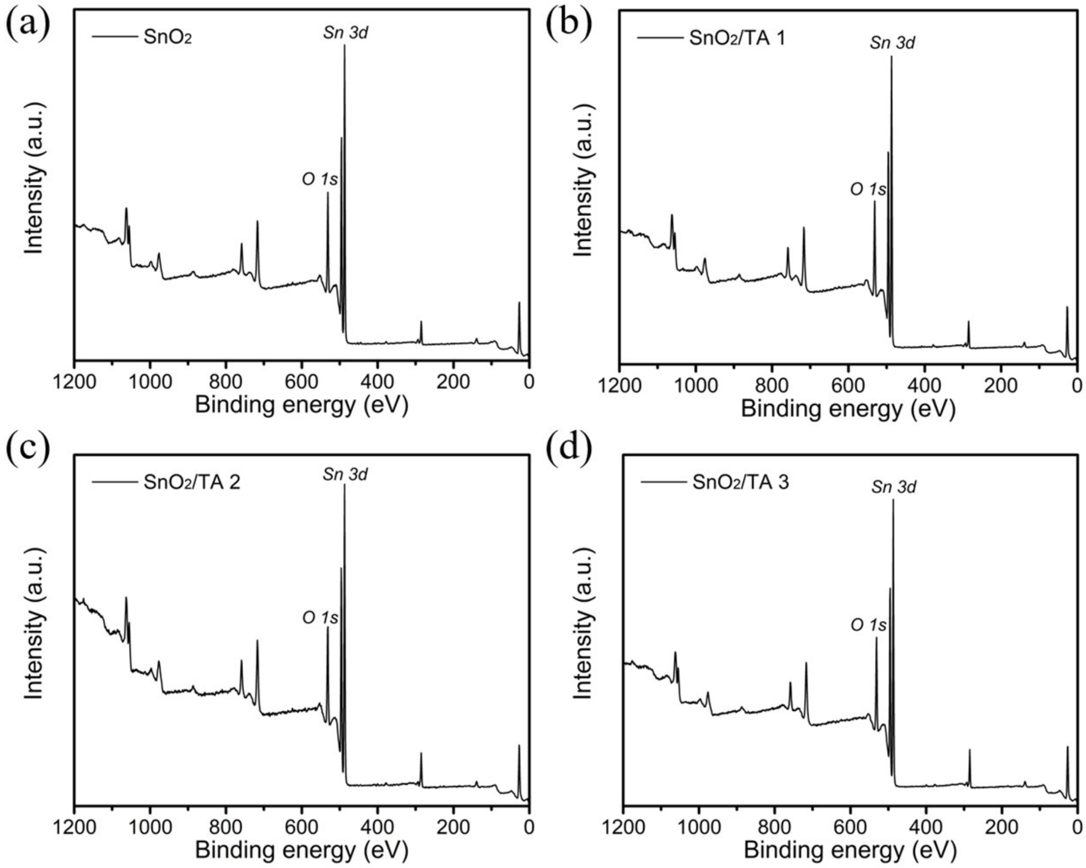

Figure S1 XPS spectra for the pristine SnO_2 and TA interlayers modified SnO_2 ETLs

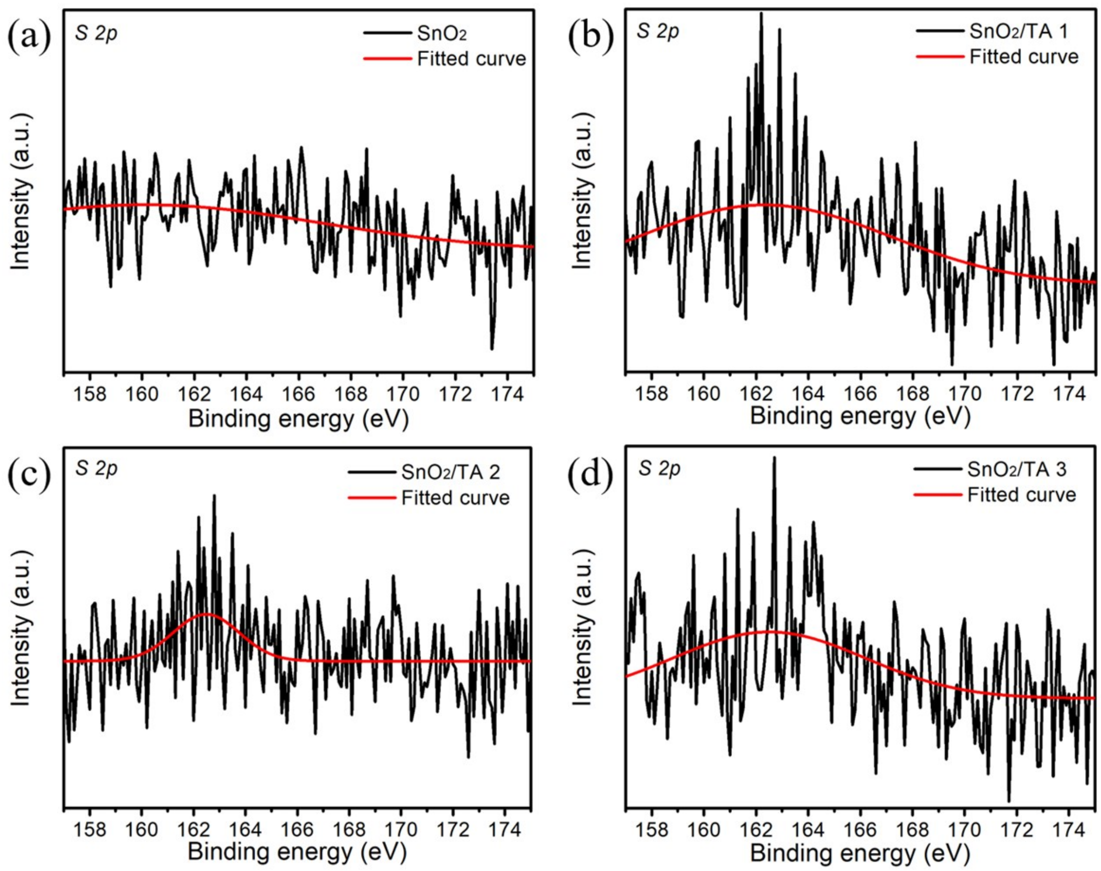

Figure S2 XPS spectra for the pristine SnO_2 and TA interlayers modified SnO_2 ETLs.

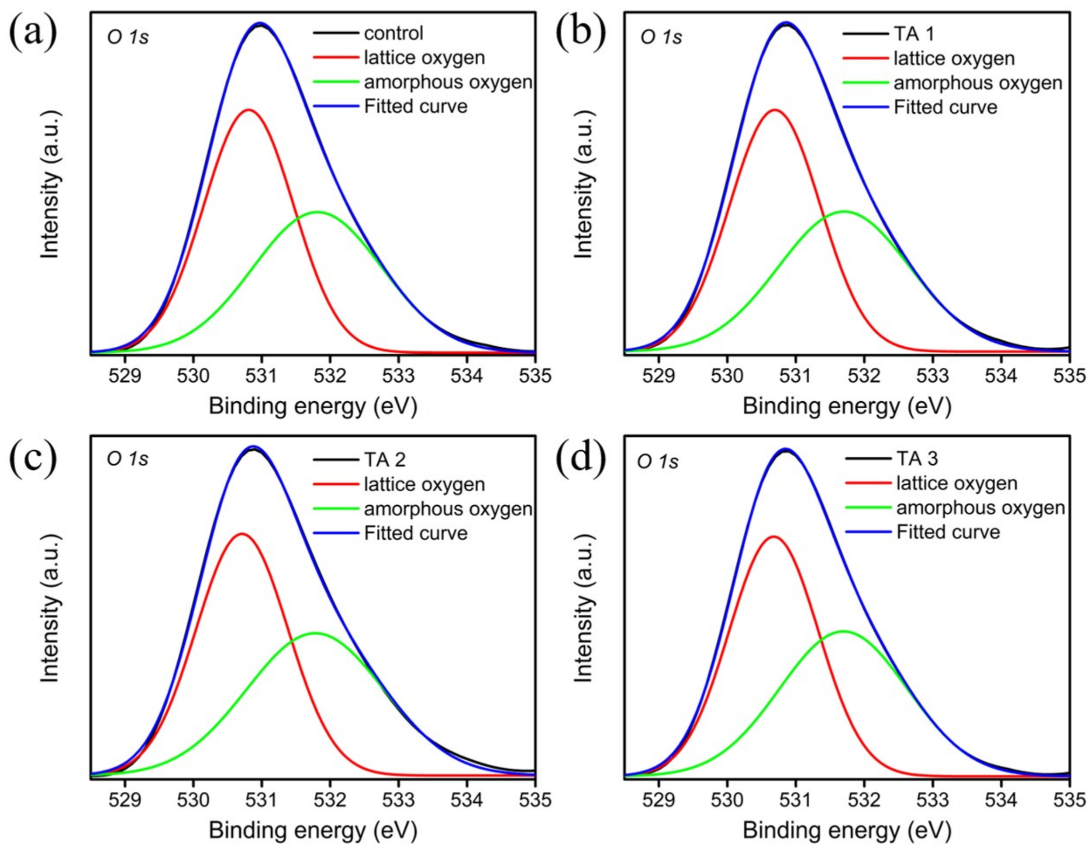

Figure S3 O 1s core-level spectra of a) SnO_2; b) SnO_2/TA 1; c) SnO_2/TA 2; d) SnO_2/TA 3 ETLs.

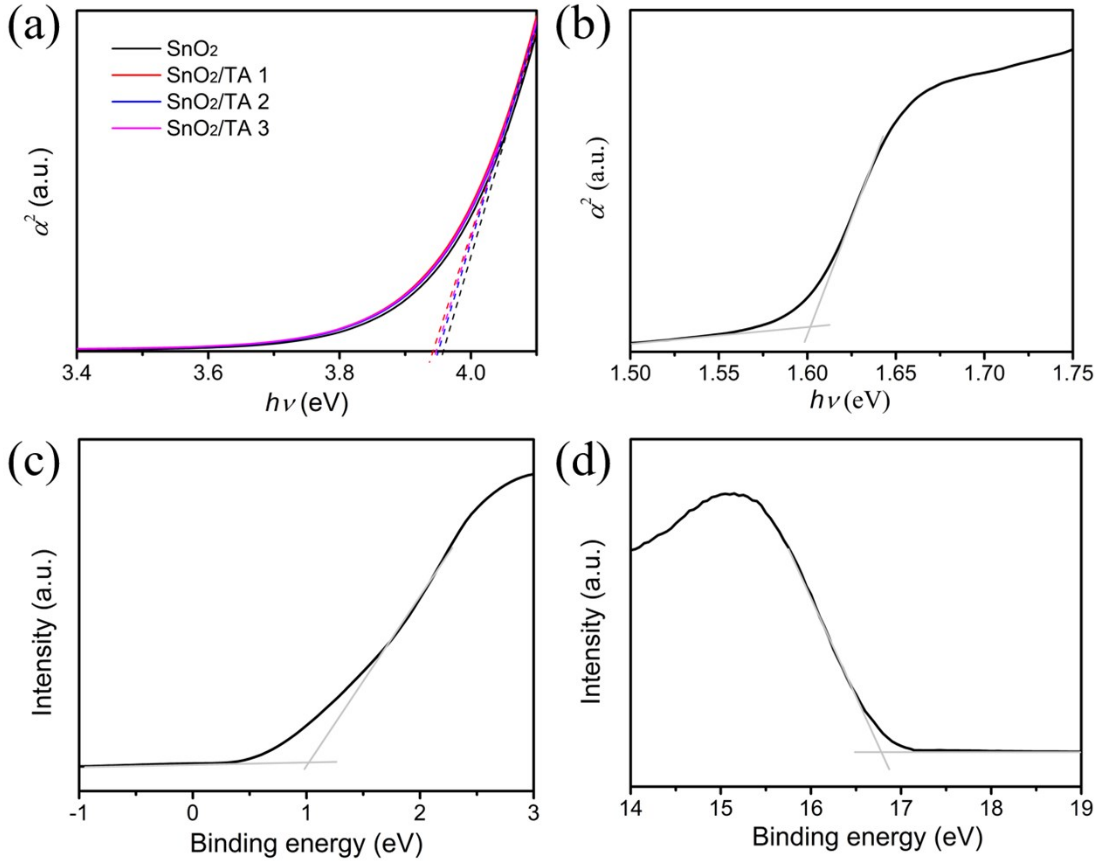

Figure S4 a) Optical bandgap of SnO_2 surface with different TA interlayers modifications. b) Optical bandgap of perovskite film. UPS onset (c) and second electron cutoff (d) binding energy of perovskite film.

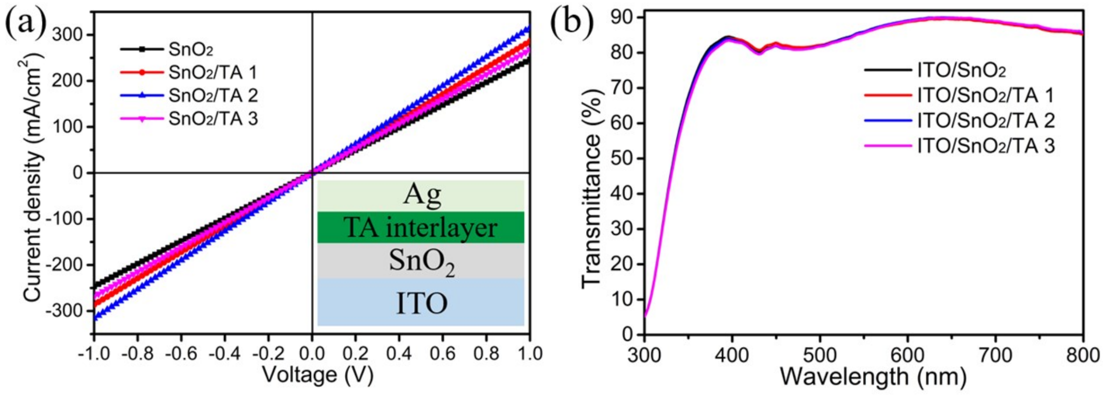

Figure S5 a) Dark current-voltage characteristics of devices shown as inset in the figure. b) Transmittance spectra of the pristine SnO_2 and TA interlayers modified SnO_2 ETLs.

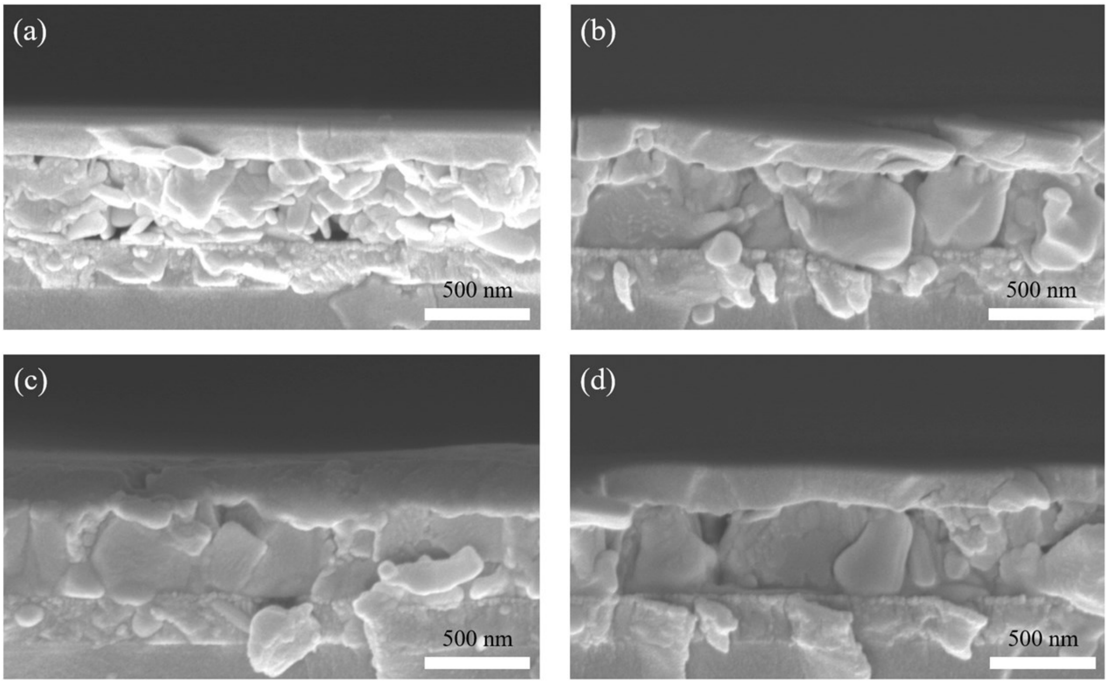

Figure S6 Cross-sectional SEM images of the control sample (a), TA 1 interlayer modified sample (b), TA 2 interlayer modified sample (c), and TA 3 interlayer modified sample.

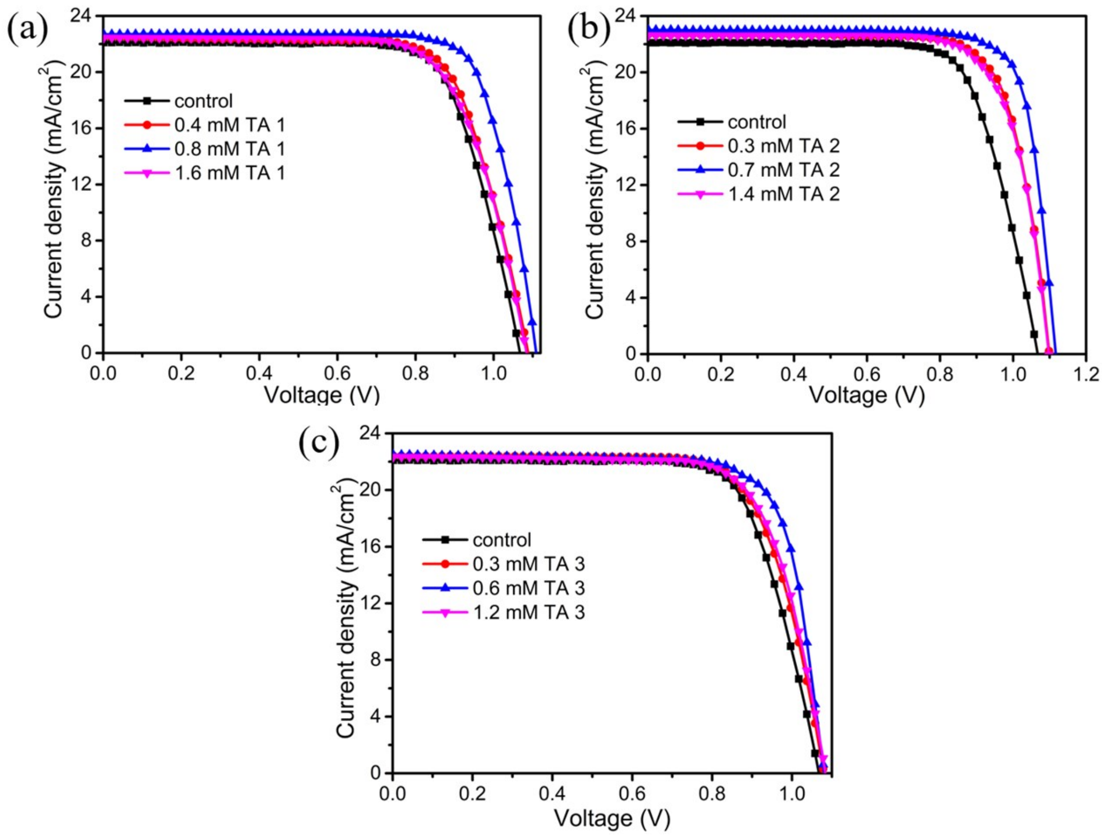

Figure S7 Current density-voltage (*J-V*) curves for modified PVSCs under different condition: modified with TA 1 (a), TA 2 (b) and TA 3 (c) interlayers with different solution concentrations.

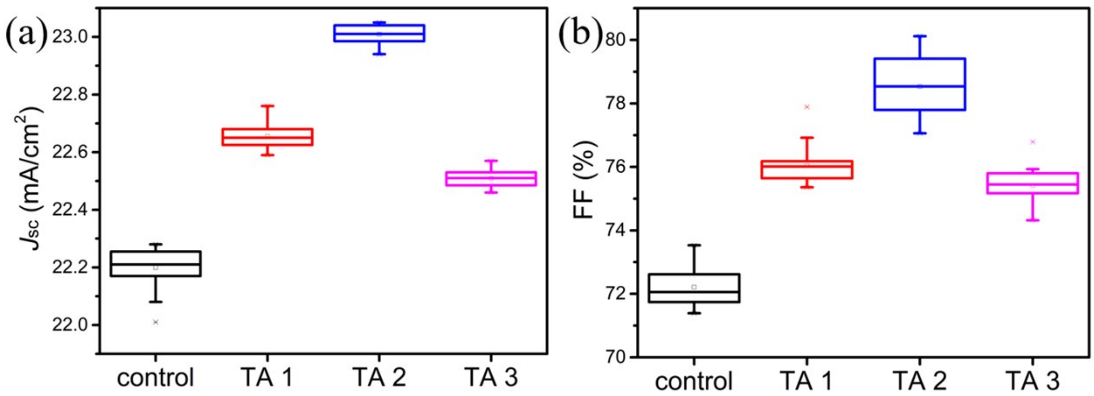

Figure S8 Statistics of J_{SC} and FF distributions.

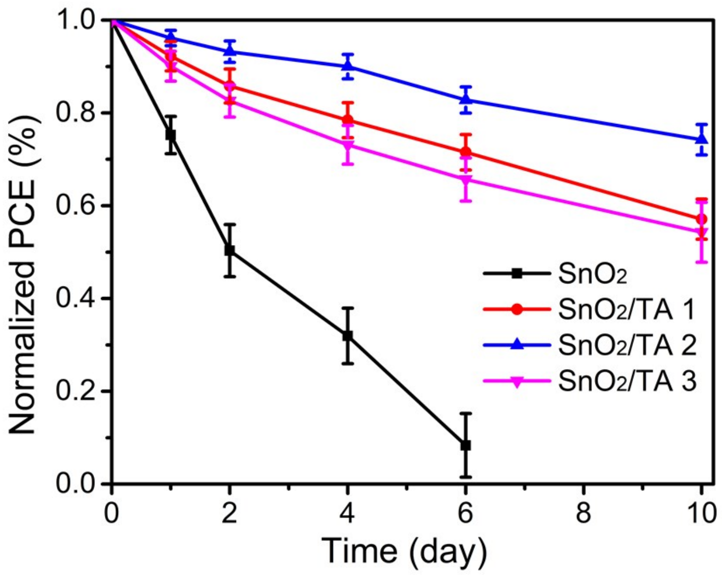

Figure S9 Long-term stability test for unencapsulated PVSCs exposed to the ambient condition (RH: ≈ 70%).

Table S1 The FWHM of characteristic peaks for $MAPbI_3$ films grown on pristine SnO_2 and TA interlayers modified SnO_2 ETL substrates.

Samples	Peak position (degree)	plane	FWHM (nm)
$SnO_2/MAPbI_3$	14.18	(110)	0.124
	28.52	(220)	0.139
	31.97	(310)	0.169
SnO_2/TA 1/$MAPbI_3$	14.18	(110)	0.099
	28.52	(220)	0.133
	31.97	(310)	0.167
SnO_2/TA 2/$MAPbI_3$	14.18	(110)	0.097
	28.52	(220)	0.072
	31.97	(310)	0.161
SnO_2/TA 3/$MAPbI_3$	14.18	(110)	0.105
	28.52	(220)	0.138
	31.97	(310)	0.168

Table S2 Summary of bi-exponential fitting results of the TRPL spectra.

Samples	A_1 (%)	τ_1 (ns)	A_2 (%)	τ_2 (ns)	τ_{ave} (ns)
ITO/SnO_2/$MAPbI_3$	9.38	95.49	90.62	9.22	53.86
ITO/ SnO_2/TA 1/$MAPbI_3$	10.15	72.98	89.85	8.93	39.68
ITO/ SnO_2/TA 2/$MAPbI_3$	5.53	52.23	94.47	7.10	20.67
ITO/ SnO_2/TA 3/$MAPbI_3$	11.60	84.88	88.40	9.02	50.93

The curves are fitted by the bi-exponential decay model:

$$y = A_1 \exp\left(-\frac{x}{\tau_1}\right) + A_2 \exp\left(-\frac{x}{\tau_2}\right) + y_0 \qquad (1)$$

where τ_1 and τ_2 are the lifetimes for the fast and slow recombination, respectively. The average lifetime τ_{ave} is calculated according to the equation:

$$\tau_{ave} = \frac{A_1 {\tau_1}^2 + A_2 {\tau_2}^2}{A_1 \tau_1 + A_2 \tau_2} \qquad (2)$$

Table S3 Average photovoltaic parameters of PVSCs modified by TA 1 interlayer with different concentrations (20 devices from different batches for each condition).

Concentration (mM)	J_{SC} (mA/cm^2)	V_{OC} (V)	FF (%)	PCE (%)
0	22.20	1.071	72.21	17.16
0.4	22.51	1.092	73.68	18.10
0.8	22.66	1.107	76.04	19.06
1.6	22.47	1.085	73.53	17.92

Table S4 Average photovoltaic parameters of PVSCs modified by TA 2 interlayer with different concentrations (20 devices from different batches for each condition).

Concentration (mM)	J_{SC} (mA/cm^2)	V_{OC} (V)	FF (%)	PCE (%)
0	22.20	1.071	72.21	17.16
0.3	22.68	1.095	76.38	18.97
0.7	22.99	1.112	78.53	20.08
1.4	22.61	1.085	74.79	18.35

Table S5 Average photovoltaic parameters of PVSCs modified by TA 3 interlayer with different concentration (20 devices from different batches for each condition).

Concentration (mM)	J_{SC} (mA/cm^2)	V_{OC} (V)	FF (%)	PCE (%)
0	22.20	1.071	72.21	17.16
0.3	22.40	1.076	73.64	17.76
0.6	22.51	1.079	75.42	18.31
1.2	22.36	1.074	73.02	17.54