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Supporting information

Highly Efficient Semi-Transparent Perovskite Solar Cells for Four Terminal Perovskite-Silicon Tandems

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Table S1. Summary of 4T perovskite/silicon tandem efficiencies

Perovskite top cell	Bandgap (eV)	Silicon	Perovskite PCE (%)	Silicon PCE (%)	PCE (%)	Size top (cm ²)	Size bottom (cm ²)	Ref
MAPbI ₃	1.55	SHJ	6.2	7.2	13.4	0.25	4	¹
MAPbI ₃	1.55	Multi-Si	12.7	4.3	17	0.39	0.39	²
MAPbI ₃	1.55	SHJ	10.4	7.8	18.2	0.16	4	³
MAPbI ₃	1.55	c-Si	12.3	5.7	18.0	0.39	0.39	⁴
MAPbI ₃	1.55	PERL	12.2	7.9	20.1	0.16	4	⁵
MAPbI ₃	1.55	SHJ	16.5	6.5	23	0.075	4	⁶
MAPbI ₃	1.55	SHJ	16.4	8.8	25.2	0.25	4	⁷
CsMAFAPbI _{3-x} Br _x	1.63	IBC-SHJ	16.6	7.9	24.5	0.36	4	⁸
FA _{0.83} Cs _{0.17} Pb(I _{0.6} Br _{0.4}) ₃	1.74	SHJ	15.1	7.3	22.4	0.09	4	⁹
RbCsMAFAPbI _{3-x} Br _x	1.74	IBC	16	10.4	26.4	0.16	4	¹⁰
FAMAPbI _{3-x} Br _x	1.65	SHJ	16.2	9.4	25.6	0.25	4	¹¹
CsFAPbI _{3-x} Br _x	1.55		15.2	8	23.2	1.03	1.03	
MAPbI ₃	1.55	IBC (c-Si)	12.0	8.2	20.2	4	4	¹²
			14.4	8.2	22.6	0.13	4	
MAPbI ₃	1.55	PERL	17.1	9.6	26.9	0.1	1	¹³
		IBC	17.1	8.1	25.2			
CsFAPbIBr	1.56	IBC (c-Si)	15.3	8.6	23.9	4	4	¹⁴
			16.7	8.6	25.3	0.13	4	
CH ₃ NH ₃ PbI _{3-x} Cl _x	1.55	c-Si	13.3	3.7	17	0.07	-	¹⁵
Cs _{0.15} (CH ₅ N ₂) _{0.85} Pb(I _{0.71} Br _{0.29}) ₃	1.72	IBC (c-Si)	13.8	13.3	27.1	0.13	4	¹⁶
			12.1	13.3	25.3	4	4	
Cs _{0.05} (MA _{0.17} FA _{0.83}) _{0.95} Pb(I _{0.9} Br _{0.1}) ₃	1.55	IBC (c-Si)	15.7	10	25.7	0.09	-	¹⁷

Figure S1. (a) PESA measurement of 1.58 eV and 1.72 eV perovskite thin films on FTO substrates, (b) Schematic band diagram of perovskite solar cells showing good energy alignment between both 1.58 eV and 1.72 eV perovskites and the charge transport layers (p-SnO₂, m-TiO₂, spiro-OMeTAD) used in the devices. The schematized band alignment guarantees an efficient charge injection at the interfaces between perovskite and ETL and HTL.

Figure S2. XRD data obtained from 1.58 eV and 1.72 eV perovskite films deposited on glass. The 1.72 eV perovskite phase stability is proved by the absence of the characteristic δ -phase peak at 11.8° in the XRD pattern¹⁸⁻¹⁹.

Table S2. Steady state photoluminescence quenching efficiency for 1.58 eV and 1.72 eV perovskite with the two different electron transport layers: m-TiO₂ and p-SnO₂

Perovskite	Quenching efficiency (%)	
	m-TiO ₂	p-SnO ₂
1.58 eV	98	93
1.72 eV	99	96

Figure S3. Transparency of glass/FTO substrates with different sheet resistance of (a) 14 Ω/cm (black) and (b) 7 Ω/cm (green). The 14 Ω/cm FTO shows better transparency over the whole visible and infrared wavelength region.

Figure S4. 1.58 eV perovskite concentration variation. Statistic of photovoltaic parameters and of (a) PCE, (b) J_{sc} , (c) V_{oc} , and (d) FF, and (e) Cross section FESEM of 1.58 eV perovskite device using various precursors concentrations of 1.35 M, 1.5 M, and 1.8 M. The perovskite film thicknesses for 1.35 M, 1.5 M, and 1.8 M precursor concentrations are ~350 nm, ~500 nm, and ~700 nm respectively.

Figure S5. Transparency curves of the 1.58 eV semi-transparent PSCs using ITO sputter powers ranging from 25 to 30 W.

Table S3. Photovoltaic parameters of semi-transparent PSCs using different ITO sputter powers ranging from 25 to 30 W.

ITO Sputtering power (W)	V _{oc} (V)	J _{sc} (mA/cm ²)	FF (%)	PCE (%)
30	1.005	9.56	51.46	4.94
28	0.924	18.48	45.47	7.77
25	1.013	19.24	67.90	13.24

Figure S6. Transparency curves of 1.58 eV semi-transparent PSCs individual layers. Transparency curves of 1.58 eV semi-transparent PSCs individual layers: Left panel: top FTO+SnO₂, middle: 1.58 eV perovskite layer and Bottom: Spiro. Right panel: Top: Ag, Middle: ITO and Bottom: p-SnO₂/1.58 eV semi-transparent PSCs.

Figure S7. Transparency curves of the (a) 1.58 eV (deep red) and (b) 1.72 eV (purple) PSCs for both p-SnO₂ (solid lines) and m-TiO₂ (dotted lines)

Figure S8. Schematic of n-type monoPoly™ silicon bottom cell. The 1 cm² active area localized grown silicon are fabricated with front side SiN_x/AlO_x and rear side SiN_x passivation.

Figure S9. J-V curve and EQE of 4T tandem based on 1.58 eV and 1.72 eV PSCs using m-TiO₂ configuration and Si SC. (a) J-V curve of 1.58 eV PSCs (deep red circles), stand-alone Si-SC (blue circles), ‘1.58 eV filtered’ Si-SC (green circles); (b) J-V curve of 1.72 eV PSCs (purple circles), stand-alone Si-SC (blue circles), ‘1.72 eV filtered’ Si-SC (green circles). Insets in (a) and (b) show the schematic of mechanical stack 4T tandems using their respective top PSCs bandgaps. EQE curves of 4T tandems: (c) 1.58 eV PSC (deep red), ‘1.58 eV filtered’ Si-SCs (green), Stand-alone Si-SCs (blue); (d) 1.72 eV PSC (purple), ‘1.72 eV filtered’ Si-SCs (green), Stand-alone Si-SCs (blue).

Table S4. Photovoltaic summary of semi-transparent perovskite (1.58 eV and 1.72 eV), silicon, and tandem perovskite/silicon measured using m-TiO₂ device structure

SCs	V _{oc} (V)	J _{sc} (mA/cm ²)	FF (%)	PCE (%)
Si unfiltered	0.66	40.2	79.0	21.1
Si filtered (1.58 eV)	0.62	14.7	81.2	7.4
Perovskite (1.58 eV)	1.09	21.1	74.7	17.2
4T tandem (1.58 eV)				24.6
Si filtered (1.72 eV)	0.62	15.8	81.3	8.0
Perovskite (1.72 eV)	1.10	18.0	74.1	14.7
4T tandem (1.72 eV)				22.7

Figure S10. Photovoltaic parameters of stand-alone Si-SCs (blue), filtered Si SCs (green), and perovskite 1.58 eV SCs (deep red) under different illumination intensity. (a) J_{sc} , (b) FF, and (c) V_{oc}

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