Electronic Supplementary Material (ESI) for

# Efficient Monolithic Perovskite-Si Tandem Solar Cell Enabled by an Ultra-Thin Indium Tin Oxide Interlayer

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## **Materials and Methods**

#### Materials

Unless stated otherwise, all materials were purchased from Sigma Aldrich or Alfa Aesar and used as received. Methylammonium bromide (MABr), formamidinium iodide (FAI), were purchased from GreatCell Solar Materials. PbI<sub>2</sub> was purchased from TCI. 2,2',7,7'-tetrakis(N,N-di-p-methoxyphenylamine)-9,9-spirobifluorene (spiro-OMeTAD) was purchased from Luminescence technology.

#### Si bottom cell fabrication

Front-junction silicon heterojunction (SHJ) solar cells were used as the bottom cells. Double-sided polished N-type Float zone (FZ) wafers with a thickness of 280  $\mu$ m and resistivity of 1~5  $\Omega$ cm were used as substrates. For 65.1cm<sup>2</sup> tandem solar cell demonstration, front-sided polished reartextured N-type FZ wafers with a thickness of 250 μm and resistivity of 7~10 Ωcm were used purely due to the availability of silicon cells at the time. The wafers were firstly ozone cleaned followed by 1% HF dip. Afterwards, the front intrinsic/p-type amorphous silicon stack (i/p a-Si:H) and rear intrinsic/n-type (i/n) a-Si:H stack were deposited by plasma enhanced chemical vapor deposition (PECVD) in three chambers. The thickness for the i/p a-Si:H and i/n a-Si:H passivating junctions are 6nm/13nm (or 6nm/26nm) and 4nm/4nm, respectively. 70 nm Indium-tin oxide (ITO) layers were then deposited on the n-rear-side followed by Ag metallization to complete the electrode fabrication which also acts as a displaced reflector. Detail process parameters can be found in the authors' previous work (1). For evaluating the effect of varying  $\leq p \geq a$ -Si:H thickness (13nm vs 26nm) on the performance of the silicon bottom cells only, 70 nm ITO layers were deposited using a 4-inch ITO target under 30W radio frequency (RF) power in Ar at 1.5 mTorr using an AJA International sputtering system at a rate of 0.155 Å/s. 200nm thick silver metal grid with a surrounding "picture-frame" for contacting was then deposited on the ITO layer by thermal evaporation through a shadow mask.

## Tandem solar cell fabrication

For tandem fabrication, the front surface of the polished silicon solar cells received ITO (ranging from 0-5 nm) deposition without masking using a 4-inch ITO target under 30W radio frequency (RF) power in Ar at 1.5 mTorr using an AJA International sputtering system at a rate of 0.155 Å/s.

The cells were then treated in ultraviolet-ozone (UVO) cleaner for 5 min before  $SnO_2$  - electron selective layer deposition. For such deposition, the  $SnO_2$  colloidal precursor (tin(IV) oxide, 15% in H<sub>2</sub>O colloidal dispersion) was first diluted with H<sub>2</sub>O to 3.75% which was then directly spin coated on the front of the silicon solar cells at 3000 rpm for 30 s, followed by baking on a hotplate at 150 °C for 5 min in the air.

After cooling down, the SnO<sub>2</sub> coated silicon substrates were directly transferred to the N<sub>2</sub> filled glovebox for the fabrication of perovskite absorber. To prepare the perovskite precursor solution, formamidinium iodide (FAI, 1 M), lead iodide (PbI<sub>2</sub>, 1.1 M), methylammonium bromide (MABr, 0.2 M), and lead bromide (PbBr<sub>2</sub>, 0.2 M) were dissolved in a mixed solvent of N,N-dimethylformamide (DMF) and dimethyl sulfoxide (DMSO) (4:1 v/v). The precursor was spin-

coated on SnO<sub>2</sub> coated Si bottom cell at 2000 rpm for 20s (with the acceleration of 400 rpm/s), followed by 6000 rpm for 30s. 5 s prior to the end of the spinning process, 150  $\mu$ l (for 1.0 cm<sup>2</sup>), 300 ul (for 11.8 cm<sup>2</sup>) or 1 ml (for 65.1 cm<sup>2</sup>) chlorobenzene was quickly dispensed. The film was annealed at 100 °C for 10 min producing a dark brown dense perovskite film.

For the deposition of hole transport layer (HTL), spiro-OMeTAD precursor was prepared by dissolving 72.3 mg spiro-OMeTAD, 28.8  $\mu$ L, 4-tert-butylpyridine, 17.4  $\mu$ L lithium bis(trifluoromethylsulphonyl)imide solution (520 mg/mL in acetonitrile and 29  $\mu$ L FK209-cobalt(III)-TFSI solution (300 mg of FK209-cobalt(III)-TFSI in 1 ml of acetonitrile) in 1 mL chlorobenzene. The spiro-OMeTAD precursor was then deposited onto the perovskite layer by spin-coating at 3000 rpm for 30 s.

For the front transparent electrode, 10 nm of MoO<sub>3</sub> was deposited onto the spiro-OMeTAD by thermal evaporation at a rate of 0.5 Å s<sup>-1</sup> under vacuum at  $1 \times 10^{-5}$  mTorr. The transparent contact was then fabricated by sputtering 135 nm of ITO on the MoO<sub>x</sub> layer target under 30W RF power in Ar at 1.5 mTorr using an AJA International sputtering system. For the metal grid and contacting pad (in the shape of "picture frame") deposition, silver was deposited by thermal evaporation through a shadow mask to a thickness of 230 nm, 300nm or 800 nm for 1.0 cm<sup>2</sup>, 11.8 cm<sup>2</sup> and 65.1 cm<sup>2</sup> cells, respectively. For light current-voltage measurements, aperture masks of the same areas: 1.0 cm<sup>2</sup>, 11.8 cm<sup>2</sup> and 65.1 cm<sup>2</sup> were used.

The textured Polydimethylsiloxane (PDMS) layer (2, 3) was then applied on the top of the tandem device for anti-reflection and light trapping.

## Device and material characterizations

The current density-voltage (J-V) measurements of single-junction and tandem devices were performed using a solar cell current-voltage (I-V) testing system from Abet Technologies, Inc. (using class AAA solar simulator) under an illumination power of 100 mW cm<sup>-2</sup> and a scan rate of  $0.5V \text{ s}^{-1}$  for single junction Si devices or 30 mV s<sup>-1</sup> for tandem devices. Both reverse  $(V_{OC} \rightarrow J_{SC})$ and forward  $(V_{OC} \rightarrow J_{SC})$  scans were carried out in the range of 2.0 V to -0.1 V (for tandems) without light soaking. The light was calibrated using a certified reference cell. For steady-state efficiency measurements, the voltage that produced maximum power  $(V_{MPP})$  from the initial I-V scan was determined and was fixed for subsequent I-V measurements over time. The currentvoltage product from each scan was then used to calculate the steady-state efficiency. The measurements were all performed at room temperature under ambient conditions with a relative humidity around 50%.

The external quantum efficiency (EQE) measurement was carried out using the PV Measurement QXE7 Spectral Response system with monochromatic light from a xenon arc lamp. The EQE response was calibrated using two certified reference cells for 300-1000 nm and 1000-1400 nm wavelength regions, respectively. For single junction cells, no light bias was applied. For tandem devices, blue (450 nm) and near-infrared (900 nm) LED's were used to saturate the top and the bottom cell for the EQE measurement of the bottom silicon cell and top perovskite cell, respectively.

#### Tandem stability testing

For light stability testing, tandem solar cells were first encapsulated in the N<sub>2</sub> atmosphere using the glass/PIB-edge-seal/cell/glass encapsulation scheme (PIB = polyisobutylene) (4), with metal feedthroughs via the rear glass. The encapsulated devices were then placed inside a Xe environment chamber for continuous illumination (100 mW/cm<sup>2</sup>) with maximum power point tracking (MPPT) of the solar cells. The Xenon Lamp is from QUALITEST, which is similar to the most commercially available Xenon Lamp and covers the light wavelength from 200 to 3000nm. The ambient temperature and relative humidity were kept at  $25\pm5^{\circ}$ C at relative humidity of  $60\pm20\%$ , respectively. The maximum power point tracking algorithm was based on a standard perturb-and-observe MPPT measurement routine (5) implemented in a LabVIEW program. An estimate for the maximum power point (MPP) is derived from a quick initial J-V measurement. The regular algorithm perturbs the applied voltage by a double step of +/- 10 mV around the maximum power point voltage, V<sub>MPP</sub>, compares the solar cell's output power at these three voltages, and then sets the new V<sub>MPP</sub> to the one corresponding to the maximum power. It is important that the step duration is set long enough for transients to equilibrate before the power is calculated at the newly set voltage level.

For thermal stability testing, encapsulated tandem cells were directly placed on a hotplate at 60°C in a N<sub>2</sub> filled glovebox. Cell efficiencies were measured ex-situ.

#### Other measurements

A Sinton WCT-120 lifetime metrology tool was used for measuring the effective carrier lifetime, dark saturation current density  $J_0$  and the implied  $V_{OC}$  of silicon half cells (front metallization not completed) i) before ITO and ii) after ITO deposition and iii) after ITO/SnO<sub>2</sub>/perovskite deposition using the quasi-steady-state photo-conductance (QSSPC) lifetime measurement method (*6*) Negligible changes in the reflectance of the ITO and ITO/SnO<sub>2</sub>/perovskite coated half cells were noted (**Figure S15C**). Nevertheless, optical constants were adjusted accordingly during measurements and were determined experimentally by comparing the results of transient and generalised measurements (*7*) and/or two generalised measurements with different illumination profiles (*8*) The same tool was also used for measuring Suns- $V_{OC}$  of completed cells which allows pseudo-IV curve to be extracted for the determination of pseudo-FF (pFF) without the effect of series resistance. R<sub>S</sub> of the cells can also be extracted by:

$$R_{S,Suns-V_{OC}} = \frac{\Delta V}{J_{MPP}}$$
where  $\Delta V = V_{V}$  are a vector of the second second

where  $\Delta V = V_{MPP, pseudo J-V-} V_{MPP, light J-V Jsc-shifted}$ .

The cross-sectional scanning electron microscopy (SEM) images were obtained using a field emission SEM (NanoSEM 230). A FEI Themis Z double corrected STEM equipped with Gatan Quantum ER/965 GIF ultrafast Dual electron energy loss spectroscopy (EELS) system was used to investigate the multi-layered structure of the sample. The STEM EELS mapping was collected at a semi-collection angle of 74 mrad under 300 kV accelerating voltage with a screen current of 0.10 nA, and Haadf image was collected at a 115 mm camera length with a screen current of 50 pA. Before data collecting, aberration was minimized by corrector calibration. (A<sub>1</sub><5nm, A<sub>2</sub>, B<sub>2</sub> < 50 nm, A<sub>3</sub>, S<sub>3</sub>, C<sub>3</sub> < 500 nm) The TEM foil was prepared by a Thermofisher Helios G4 Plasma

FIB (PFIB) dualbeam platform following a standard lift-out protocol. (9) The sample was initially deposited with 1  $\mu$ m thick Pt protective layer on the surface, and was sequentially cut into a 2×10  $\mu$ m cantilever in the PFIB with 30 kV/15 nA voltage/current setup. Thereafter, the bar was transferred to a Mo TEM half grid by a tungsten micromanipulator, followed by a few steps of foil thinning down processes by gradually reducing the voltage and current. Finally, a 5 kV and 50 pA beam setup was used to polish both sides of lamella, the specimen is ready for imaging. FEI Velox 3.3.1 and Gatan GMS 3.5 were used for the TEM data analysis.

Conductive atomic force microscopy (c-AFM) was carried out using a Bruker dimension icon SPM (USA) with SCM-PIT-V2 probe via PeakForce TUNA mode. The samples were scanned at rate of 0.70 Hz and a resolution of 300 samples per line. NanoScope Analysis 2.0 software was used to process the AFM data.

Reflectance measurements were carried out using Perkin Elmer Lambda1050 UV/Vis/NIR spectrophotometer.

Spatially resolved photoluminescence (PL) images were taken by the BT Imaging LIS-R1 PL imaging system, which is equipped with an 805 nm short excitation wavelength laser.

To determine electron concentration, mobility and resistivity of sputtered ITO layer, Hall effect measurement was carried out using an Ecopia HMS-5000 hall effect system. Sheet resistance of the ITO layer was measured by Jandel four-point probe system with RM3 test unit. To determine the vertical conductivity of ultra-thin ITO layer, test structures of heavily doped N-type CZ silicon/ultra-thin ITO (1.7-5.0 nm) /Ag electrode (100 nm) were fabricated which were then measured by a Keithley 2636b with a four-probe station to obtain current-voltage curves.

To determine the work function ( $\Phi$ ) of ITO surface, ultraviolet photoelectron spectroscopy (UPS) was performed using an ESCALAB250Xi, Thermo Scientific, UK.  $\Phi$  is calculated according to the formula  $\Phi = hv (21.22 \text{ eV}) - E_{\text{cutoff-measured}}$  to be 21.22-15.95= 5.27eV. The energy separation from valence band to  $\Phi$  can be read off from the UPS. The result is shown as below.



Ultraviolet photoelectron spectroscopy (UPS) curve of 100 nm ITO surface. Work function ( $\Phi$ ) = hv (21.22 eV) – Ecutoff-measured.  $\Phi$  = 5.27eV. The distance from Valence band (VB) to  $\Phi$  is 3.30eV.

To determine the thickness of the ultra-thin ITO interlayer, ITO/Si test structure was measured by spectral ellipsometry (JA Woollam Inc.) and the thickness of native SiO<sub>2</sub> on Si and ITO was fitted by WVASE® software.

#### Simulations

We used a commercial software package, Sentaurus technology computer-aided design (TCAD) (10) to model energy band structure of the tandem under thermal equilibrium. Material properties for ITO and SnO<sub>2</sub> used in the modelling can be found in **Table S2** and **Table S3**. Poisson, driftdiffusion and carrier conservation equations were solved numerically until self-consistency is reached. We modelled the heterojunctions using the similar approach reported in reference. (11) For Si cell modelling, we applied models by Altermatt (12) and Auger model reported in (12) in simulation to predict silicon characteristics. Fermi statistics and Shockley-Reed-Hall models (13) were employed to compute carrier transport. We applied thermionic emission model to compute the current density and energy flux density across the interface accounting for bandgap discontinuity at the hetero-interface. The tunnelling mechanism is enabled at the tandem interface using the same approach delineated in reference. (14)

Optical simulation for tandem devices were performed using SunSolveTM ray tracing from PVLighthouse.(15) In the simulation, crystalline-silicon was treated to be a bulk and non-coherent. The simulation package does not allow for carrier recombination input. Thus 100% internal quantum efficiency is assumed for both sub-cells. The optical value (n, k) of layers were either obtained from PVLighthouse (15) or experimentally determined by fitting experimental ellipsometry data (JA Woollam Inc.) of the layers using WVASE® software.



Fig. S1 WVASE optically modelling for determining thicknesses of ultra-thin ITO showing good agreement between modelled (black dashed lines) and experimental (green solid lines) (A, C, E, G) amplitude  $\Psi$ ; (red solid lines) (B, D, F, H) phase difference  $\Delta$  components of (A, B) 1.0 nm; (C, D) 1.7 nm; (E, F) 2.4nm; (G, H) 3.5 nm and (I, J) 5.0 nm thick ITO.



**Fig. S2 Electron energy loss spectroscopy (EELS) analysis of the multi-layered device structure**. (A) EELS spectrum imaging of the selected region (including  $\text{SnO}_2$ /ultra-thin (1.7 nm) ITO/native oxide/Si), and (B) EELS spectrum of each layer extracted from the region marked by the corresponding rectangle, respectively. Sn (#1) has a delayed M<sub>4,5</sub> edge at 485 eV, overlapping with O K edge at 532 eV corresponding to the yellow rectangle region (SnO<sub>2</sub> layer). The second spectrum (#2) was extracted from ITO corresponding to the blue rectangle region where a prominent In M<sub>4,5</sub> delayed edge start rising at 443 eV. The third spectrum (#3) from the red rectangle shows a sharp O-K edge and Si-K edge only at 532 eV and 1839 eV, respectively, indicating the presence of a native oxide layer. The last spectrum (#4) demonstrates Si-K edge only, and the concentration of the p-type dopants is too low beyond the detection capacity of the EELS detector and therefore is missing in the spectrum. The spectra of layers were used to carry out multiple linear least squares (MLLS) (*16*) fitting for the EELS mapping as shown in **Figure 1D**.



**Fig. S3 Film uniformity check for the 1.7nm ITO over a large area.** (A, B, & C) High-angle annular dark-field (HAADF) STEM cross-sectional images of the interfacing stack for 3 points (indicated in photo) from the edge of a 4-inch round tandem. (D, E & F). Energy dispersive spectroscopy (EDS) mapping of 3 cross-sectional STEM images taken from 3 points (indicated in photo) across a 4-inch round tandem.



Fig. S4 Conductive atomic force microscopy (c-AFM) of (A) 1.0 nm (B) and 1.7 nm (C) ITO on silicon half-cell.



Fig. S5 STEM image of the 1nm ITO on silicon under (A) 0-degree tilt whereby "islanding" overlaps and (B) 16degree tilt whereby islands (highlighted by red arrows) become distinguishable showing non-continuous nature of the film.



**Fig. S6 Extraction of pseudo-FF (pFF) and Rs.** Light current-density vs voltage (*J-V*) ( $J_{SC}$ -shifted) and Suns- $V_{OC}$  curves of Si-perovskite test cells (without anti-reflection coating) with different ITO interlayer thickness at (A) 0 nm; (B) 1.0 nm; (C) 1.7 nm; (D) 2.4 nm; (E) 3.5 nm; (F) 5.0 nm. Details for calculating pseudo-FF (pFF) and R<sub>s</sub> can be found in the Experimental Section.



**Fig. S7 Optical simulation of effect of varying the thickness of ultra-thin ITO interlayer thickness.** Simulated EQE's of perovskite silicon tandem devices prior to the application of front anti-reflection (AR) layer.



Fig. S8 Effect of the thickness of the ITO inter-layer on the parasitic resistance of  $1 \text{ cm}^2$  tandem solar cells. (A) R<sub>s</sub> (B) R<sub>sH</sub> extracted from the light JV curves. The highest value is a maximum value. The highest bar is the 75th percentile value. The middle bar is the median value. The square mark is for the average. The lowest bar is the 25th percentile value. The lowest value is the minimum.,



**Fig. S9 Ultra-thin ITO lateral and vertical conductivity measurement** (A) Sheet resistance of the ultra-thin ITO layer at different thicknesses. (B) Dark current-voltage measurements of n++ CZ Si/ultra-thin ITO/Ag test structure for determining vertical conductivity.



Fig. S10 Dark current-voltage (IV) characteristics of the testing tandem devices with different ITO thicknesses.



**Fig. S11 Effect of varying ITO thickness on the number of shunted cell.** J-V curve of the 1cm<sup>2</sup> tandem devices with ITO interlayer thickness equal to (A) 1.7, (B) 3.5, and (C) 5nm showing the number of shunted and low VOC cells increase with ITO thickness.



**Fig. S12 Sensitivity to ITO thickness in small (0.09 cm<sup>2</sup>) perovskite-Si tandem devices.** Distribution of (A) PCE, (B) J<sub>SC</sub>, (C) FF, (D) V<sub>OC</sub> (E) R<sub>S</sub> (F) R<sub>SH</sub> based on 16 devices for each condition showing much lesser sensitivity to ITO thickness as the shunting is not severe in smaller devices.



**Fig. S13 Energy band diagram of the tandem device that includes a 1.5nm native oxide** and a zoom in of the ITO/SiO<sub>2</sub>/a-Si:H recombination stack showing trap assisted tunnelling is still feasible. Solid and hollow red dots denote electron and hole, respectively.



**Fig. S14 Photoluminescence (PL) images** of Si half cells (front and rear metallization not completed) with varying ITO interlayer thickness (A) before ITO deposition, (B) after ITO deposition, (C) after UVO treatment and SnO<sub>2</sub> deposition and (D) after UVO treatment, SnO<sub>2</sub> and perovskite deposition. (E) Associated averaged PL intensities.



Fig. S15 Measured (A) effective carrier lifetimes and (B) implied  $V_{OC}$ 's of silicon half cells (front metallisation not completed) with varying ITO interlayer thickness before ITO deposition, after ITO deposition and after ITO/SnO<sub>2</sub>/perovskite deposition. (C) Reflectance of silicon half cells before ITO deposition, after ITO deposition and after ITO/SnO<sub>2</sub>/perovskite deposition showing negligible differences informing choice of optical constants used for carrier lifetime measurements.



Fig. S16 Carrier injection dependent lifetime curves for Si half wafers with varying ITO interlayer thickness showing similar shapes.



**Fig. S17** Device performance of single junction heterojunction solar cell with 13nm to 26 nm a-Si:H junction thickness. (A) Device structure, (B) *J-V* characteristics, and (C) EQE of the single junction heterojunction solar cell with 13 nm or 26 nm thick  $\langle p \rangle$  a-Si:H layer. Please note that the cells were prepared for tandem cell fabrication, not optimized for single junction. For the purpose of obtaining its JV curve, we applied rudimentary metallization



**Fig. S18 The effect of increasing the thickness of < p> a-Si:H layers.** *J*-*V* characteristics of the perovskite-Si tandem test cell with 1.7nm thick ITO interface layer and 13 nm or 26 nm thick < p> a-Si:H layer without AR.



Fig. S19 The effect of the thickness of ITO interface layer (0nm, 1.0nm, 1.7nm, 2.4nm, 3.5nm and 5.0nm) with a 26 nm <p> a-Si: H layer. Distribution of (A) PCE, (B)  $J_{SC}$ , (C) FF, (D)  $V_{OC}$  of the 1cm<sup>2</sup> perovskite-Si tandem solar cell with 26 nm <p> a-Si: H layer and different thickness ITO interface layer.



Fig. S20 Optical simulations of perovskite-Si tandems. (A, C) Simulated EQE's and (B, D) loss breakdowns for (A, B) n-i-p and (C, D) p-i-n tandems



Fig. S21 Photo of an encapsulated 1cm<sup>2</sup> perovskite-Si tandem solar cell. (A) Front-, (B) rear-, and (C) sideview.



Fig. S22 Preliminary thermal stability testing of an un-encapsulated 1.0 cm<sup>2</sup> perovskite-Si tandem cell at 60 °C in N<sub>2</sub>.

Device polarity	Si bottom cell	Interface	Higher bandgap perovskite solar cell		$J_{SC}$ (mA/cm <sup>2</sup> )	FF (%)	Eff. (%)	Area (cm <sup>2</sup> )	Ref.
NIP	Homo junction (p+ front emitter /n-Si/n++ rear BSF)	n++Si	mp-TiO2/MAPbI3/Spiro-OMeTAD/AgNW/LiF	1.58	11.5	75	13.7	1.0	(17)
NIP	SHJ (a-Si(p) front / n-Si)	ITO	ALD SnO <sub>2</sub> /MA <sub>X</sub> FA <sub>1-X</sub> PbI <sub>Y</sub> Br <sub>3-Y</sub> /Spiro-OMeTAD/MoO <sub>X</sub> /ITO/LiF	1.80	13.0	78	18.0	0.16	(18)
NIP	SHJ (a-Si(p) front / n-Si)	IZO	PCBM/PEIE/MAPbI <sub>3</sub> /Spiro-OMeTAD/MoO <sub>X</sub> /ITO/IO:H/ARF	1.70 1.69	16.1 15.9	70 78	19.2 21.2	1.22 0.17	(19)
NIP	SHJ (a-Si(p) front / n-Si)	IZO	PEIE/PCBM/MAPbI <sub>3</sub> /Spiro-OMeTAD/MoO <sub>X</sub> /IO:H/ITO	1.72	16.4	72	$20.5^{+}$	1.43	(20)
NIP	Homo junction (p+ front emitter /n-Si/n++ rear BSF)	ZTO	Sputtered c-TiO <sub>2</sub> /mp-TiO <sub>2</sub> /MAPbI <sub>3</sub> /Spiro- OMeTAD/MoO <sub>X</sub> /ITO/IO:H/ARF	1.64	15.3	65	16.3	1.43	(21)
PIN	SHJ (a-Si(p) rear / n-Si)	ITO	NiO/FA0.83Cs0.17Pb(I0.83Br0.17)3/LiF/PC60BM/SnO2/ZTO/ITO /Ag/LiF	1.65	18.1	79	23.6*	0.99	(22)
NIP	SHJ (a-Si(p) front / n-Si)	nc- Si:H(p+)/nc- Si:H(n+)	C60/Cs0.19MA0.81PbI3/Spiro-OMeTAD/MoOx/IZO/MgF2	1.75 1.78 1.77	16.8 16.5 16.5	77 74 65	$22.0^+$ $21.2^+$ $18.0^+$	0.25 1.43 13.0	(23)
NIP	Homo junction (p+ front emitter /n-Si/n++ rear BSF)	Al <sub>2</sub> O <sub>3</sub> /SiN <sub>X</sub> /I TO	c-TiO <sub>2</sub> /mp-TiO <sub>2</sub> /Cs <sub>0.07</sub> Rb <sub>0.03</sub> FA <sub>0.765</sub> MA <sub>0.135</sub> PbI <sub>2.55</sub> Br <sub>0.45</sub> /Spiro- OMeTAD/MoOx/IZO/ARF	1.75	17.6	74	22.5+	1.0	(24)
NIP	SHJ (a-Si(p) front / n-Si)	ITO (80nm)	SnO <sub>2</sub> /MA <sub>0.37</sub> FA <sub>0.48</sub> Cs <sub>0.15</sub> PbI <sub>2.01</sub> Br <sub>0.99</sub> /Spiro-OMeTAD/MoO <sub>X</sub> /ITO/LiF	1.70	15.3	79	20.6	0.03	(25)
NIP	Homo junction (p+ front emitter /n-Si/n++ rear PERL)	None	SnO2/MAPbI3/Spiro-OMeTAD/MoO3/ITO/ARF	1.68 1.69	16.1 15.6	78 68	20.5 <sup>+</sup> 17.1 <sup>+</sup>	4.0	(26)
PIN	SHJ (a-Si(p) rear / n-Si)	nc- Si:H(n+)/nc- Si:H(p+)	Spiro-TTB/CsxFA1-xPb(I,Br)3/LiF/C60/SnO2/IZO/Ag/MgF2	1.79	19.5	73	25.2**	1.42	(27)
PIN	SHJ (a-Si(p) rear / n-Si)	ITO	PTAA/FA0.83Cs0.17Pb(I0.83Br0.17)3/C60/SnO2/ZTO/ITO/Ag/ PDMS	1.77	18.4	77	25.0	1.0	(28)
NIP	Homo junction (p+ front emitter /n-Si/n++ rear PERL)	None	SnO <sub>2</sub> /(FAPbI <sub>3</sub> ) <sub>0.83</sub> (MAPbI <sub>3</sub> ) <sub>0.17</sub> /Spiro-OMeTAD/MoO <sub>3</sub> /ITO/ARF	1.74	16.2	78	21.8+	16.0	(2)
NIP	SHJ (nc-SiO <sub>X</sub> :H(p) front / n-Si)	ITO (80nm)	SnO <sub>2</sub> /MAFACsPbIBr/Spiro-OMeTAD/MoO <sub>X</sub> /ITO/ARC	1.78	17.8	75	22.8+	0.13	(29)
NIP	SHJ (a-Si(p) front / n-Si)	ITO (80nm)	SnO <sub>2</sub> /FA <sub>0.5</sub> MA <sub>0.38</sub> Cs <sub>0.12</sub> PbI <sub>2.04</sub> Br <sub>0.96</sub> /Spiro-OMeTAD/MoO <sub>X</sub> /ITO	1.66	16.5	81	22.2	0.06	(30)
PIN	SHJ (a-Si(p) rear / n-Si)	ITO	PTAA/Cs <sub>0.15</sub> (FA <sub>0.83</sub> MA <sub>0.17</sub> ) <sub>0.85</sub> Pb(I <sub>0.8</sub> Br <sub>0.2</sub> ) <sub>3</sub> /ICBA/C <sub>60</sub> /SnO <sub>2</sub> /IZO/Cu/Mg F <sub>2</sub>	1.80	17.8	79	25.4	0.42	(31)
PIN	SHJ (a-Si(p) rear / n-Si / nc-SiOx:H(n) FSF)	ITO	PTAA/Cs <sub>0.05</sub> (FA <sub>0.83</sub> MA <sub>0.17</sub> ) <sub>0.95</sub> Pb(I <sub>0.83</sub> Br <sub>0.17</sub> ) <sub>3</sub> /ICBA/C <sub>60</sub> /SnO <sub>2</sub> /IZO/Ag/P DMS	1.76	18.5	78	25.5	0.77	(32)
?	?	?	?	1.80	19.8	79	28.0*	1.03	(33)
NIP	SHJ (nc-SiO <sub>X</sub> :H(p) front / n-Si)	ITO (40nm)	SnO <sub>2</sub> /MAFACsPbIBr/Spiro-OMeTAD/MoO <sub>X</sub> /ITO/Au/PDMS	1.75	16.9	74	21.9	0.13	(34)
	SHJ (poly-Si (p+) front / n-Si)	None	c-TiO <sub>2</sub> /mp-TiO <sub>2</sub> /	1.76	17.8	78	24.5	1.0	
NIP	Homo junction (p+ front emitter /n-Si/n+ rear BSF)	None	PMMA/PCBM/Cs <sub>0.05</sub> Rb <sub>0.05</sub> FA <sub>0.765</sub> MA <sub>0.135</sub> PbI <sub>2.55</sub> Br <sub>0.45</sub> /PTAA for SHJ or Spiro-OMeTAD for homo-junction Si/MoO <sub>X</sub> /IZO/Au/PDMS	1.70	17.2	79	22.9+	1.0	(35)
NIP	SHJ (a-Si(p) rear / n-Si)	ITO (80nm)	SnO <sub>2</sub> /MAFACsPbIBr/Spiro-OMeTAD/MoO <sub>x</sub> /ITO/Au	1.83	16.0	70	20.4	0.13	(36)
PIN	SHJ (nc-SiO <sub>X</sub> :H(n) front / n-Si)	ITO	F4-TCNQ:polyTPD/ Cs <sub>0.05</sub> (FA <sub>0.83</sub> MA <sub>0.17</sub> ) <sub>0.95</sub> Pb(I <sub>1- <sub>X</sub>Br<sub>X</sub>)<sub>3</sub>/ETL/Buffer/ITO/Ag /ARC</sub>	1.79	19.0	75	25.2*	1.0	(37)
PIN	SHJ (nc-SiC(n) front/SiO <sub>X</sub> / p-Si)	nc-Si:H (p+)	Spiro-TTB/CsFAPbIBr/LiF/C60/SnO2/IZO/Ag/MgF2	1.74	19.5	75	25.1	1.42	(38)

**Table S1:** Summary of reported monolithic perovskite-silicon tandem devices.

PIN	Homo junction (n+ front emitter /p-Si/rear Al- BSF)	ITO	PTAA/(FAPbI <sub>3</sub> ) <sub>0.8</sub> (MAPbBr <sub>3</sub> ) <sub>0.2</sub> /PCBM/ZnO/IZO)/Ag/LiF		16.1	80	21.2	0.27	(39)
PIN	SHJ (a-Si(p) rear / n-Si)	ITO	NiO/Cs <sub>0.17</sub> FA <sub>0.83</sub> PbI <sub>0.83</sub> Br <sub>0.17</sub> /C <sub>60</sub> /SnO <sub>2</sub> /ITO/Ag/MgF <sub>2</sub>		17.5	75	22.6	57.4	(40)
PIN	SHI $(2-Si(n) \operatorname{rear} / n-Si)$	ITO	$PT \wedge \Lambda/Cso \alpha_2(M \wedge \alpha_2 F \wedge \alpha_2) Ph(I_0 \alpha_2 Bro \alpha_2) / Cco/SnO2/IZO/A \alpha/I iF$	1.77	19.2	77	26.0	0.77	(AI)
1 113	5115 (a-51(p) Ical / II-51)	110	1 TAA/CS0.05(IMA0.831 A0.1/)1 0(10.83D10.1/)3/C60/S102/120/Ag/Ell		17.8	78	25.0	0.77	(71)
NIP	Homo junction (p+ front emitter /n-Si/n++ rear PERL)	None	SnO <sub>2</sub> /(FAPbI <sub>3</sub> ) <sub>0.83</sub> (MAPbI <sub>3</sub> ) <sub>0.17</sub> /Spiro- OMeTAD/MoO <sub>3</sub> /ITO/Ag/(Ba,Sr) <sub>2</sub> SiO <sub>4</sub> :Eu <sup>2+</sup> :PDMS	1.73	16.5	81	23.0+	4.0	(3)
NIP	SHJ (a-Si(p) front / n-Si)	ITO	TiO <sub>2</sub> /mp-TiO <sub>2</sub> /PCBM:PMMA/FA <sub>0.75</sub> Cs <sub>0.25</sub> Pb(I <sub>0.8</sub> Br <sub>0.2</sub> ) <sub>3</sub> /Spiro- OMeTAD/ITO/MgF <sub>2</sub>	1.84	15.3	77	21.6+	0.249	(42)
PIN	SHJ (a-Si(p+) rear/ n-Si)	ITO	PTAA/Cs <sub>0.1</sub> MA <sub>0.9</sub> Pb(I <sub>0.9</sub> Br <sub>0.1</sub> ) <sub>3</sub> /C <sub>60</sub> /SnO <sub>2</sub> /ITO/Ag/PDMS	1.82	19.2	75	26.1+	0.42	(43)
PIN	SHJ (a-Si(p+) rear/ n-Si)	InOx	$NiO_{X}/Cs_{0.05}MA_{0.15}FA_{0.8}PbI_{2.25}Br_{0.75}/LiF/C_{60}/SnO_{2}/IZO/Ag/MgF_{2}$	1.78	19.0	75	25.7*	0.832	(44)
PIN	SHJ (a-Si(p+) rear/ n-Si)	ITO	NiO <sub>X</sub> /Poly-TPD/PFN/Cs <sub>x</sub> FA <sub>1-x</sub> PbI <sub>y</sub> Br <sub>1-</sub>	1.87	19.1	75	27.0+	1.0	(45)
			$y^+$ MAPOCI3/LIF/C60/SIIO2/ZIO/IZO/Ag/PDMIS	1.8/	18.3	80	25.8*	1.0	
PIN	SHJ (a-Si(p+) rear/ n-Si)	ITO	PTAA/PEA(10.25SCN0.75):FA0.65MA0.20CS0.15Pb(10.8Bf0.2)3/C60/PEIE/11O/ Ag	1.82	18.9	76	26.2*	1.001	(46)
PIN	SHJ (a-Si(p+) rear/ n-Si)	ITO	PTAA/PFN/ FA <sub>0.75</sub> Cs <sub>0.25</sub> Pb(I <sub>0.8</sub> Br <sub>0.2</sub> ) <sub>3</sub> /C <sub>60</sub> /SnO <sub>x</sub> /ITO/MgF <sub>2</sub>	1.77	17.7	80	25.1*	0.25	(47)
PIN	SHJ (a-Si(p+) rear/ n-Si/a-Si(i)/a-Si:H)	ITO	$NiOx/PTAA/(MAPb(I_{0.75}Br_{0.25})_3/C_{60}/SnO_2/IZO/MgF_2$	1.76	19.2	70	24.1+	1.0	(48)
PIN	SHJ (a-Si(p+) rear/ n-Si/a-Si(i)/nc-SiOx(n))	Nc- Si:H(n+)/Spi ro-TTB	Spiro-TTB/FACsMAPbI3-xBrx/C60/SnO2/IZO	1.73	19.8	73	25.1	1.0	(49)
PIN	SHJ (a-Si(p+) rear/ n-Si/a-Si(i)/nc-SiOx(n))	ITO	PTAA(or SAM)/ Cs0.05(FA0.77MA0.23)0.95Pb(I0.77Br0.23)3/LiF/C60/SnO2/IZO/LiF	1.90	19.3	80	29.15*	1.06	(50)
PIN	SHJ (a-Si(p+) rear/ n-Si/a-Si:H(i)/nc-Si(n))	ITO	NiOx/FACsMAPbI <sub>3-x</sub> Br <sub>x</sub> /C60/SnO2/IZO/MgF <sub>2</sub>	1.80	18.5	76	25.2*	0.832	(51)
?	?	?	? 1.		20.26	77	29.5*	1.212	(52)
PIN	SHJ (a-Si(p+) rear/ n-Si(CZ) /a-Si(i)/nc- SiOx(n))	ITO	2PACz/Cs0.05(FA0.77MA0.23)0.95Pb(I0.77Br0.23)3/LiF/C60/SnO2/IZO/LiF		17.8	81	27.9	1.0	(53)
PIN	SHJ (a-Si(p+) rear/ n-Si/a-Si(i)/a-Si:H(n))	ITO	$SAM/Cs_{0.15}MA_{0.15}FA_{0.70}Pb(I_{0.80}Br_{0.20})_3/C_{60}/SnO_2/IZO/MgF_2$		19.6	76	27.4	1.03	(54)
NIP	SHJ (a-Si(p) front / n-Si)	ITO (40nm)	SnO <sub>2</sub> /MAFACsPbIBr/Spiro-OMeTAD/MoO <sub>X</sub> /ITO/Au		16.9	74	24.2	0.86	(55)
NIP	SHJ (a-Si(p) front / n-Si)	ITO	C <sub>60</sub> -anchored a-NbO <sub>x</sub> / Cs <sub>0.05</sub> MA <sub>0.15</sub> FA <sub>0.8</sub> Pb(I <sub>0.75</sub> Br <sub>0.25</sub> ) <sub>3</sub> /Spiro- TTB/TPBI/VOx/IZO/MgF <sub>2</sub>		19.5	76	27.1	1.03	(56)
				1.88	19.6	76	28.2	0.84*	
PIN	SHJ (a-Si(p+) rear / n-Si)	ITO	2-PACz/FACsMAPbI <sub>3-x</sub> Br <sub>x</sub> /LiF/C <sub>60</sub> /SnO <sub>2</sub> /IZO/MgF <sub>2</sub>	1.87	19.6	79	28.9	1.03	(57)
				1.88	19.1	76	27.1	3.8	
PIN	SHJ (poly-Si (n+) front+SiO <sub>2</sub> / n-Si/ p+ rear PERC)	ITO	2-PACz/CsFAPb(IBrCl) <sub>3</sub> /LiF/C <sub>60</sub> /SnO <sub>2</sub> /IZO/LiF	1.80	17.1	69	21.3	1.01	(58)
NIP	Homo junction (p+ front emitter /n-Si/SiOx-p- poly rear TOPCON)	None	SnO2/Cs0.05FA0.8MA0.15PbI2.55Br0.45 /Spiro-OMeTAD/MoO3/ITO/Au	1.78	14.4	67	17.3	25.0	(59)
NIP	SHJ (a-Si(p) front / n-Si)	ITO (10nm)	SnO <sub>2</sub> /Cs <sub>0.22</sub> FA <sub>0.78</sub> Pb(I <sub>0.85</sub> Br <sub>0.15</sub> ) <sub>3</sub> /Spiro-OMeTAD/MoO <sub>3</sub> /ITO/Au	1.85	18.0	81	27.0	0.16	(60)
PIN	SHJ (poly-Si (n+) front / n-Si/p+ Si rear)	ITO	NiO <sub>X</sub> /Poly-TPD/ Cs <sub>0.22</sub> FA <sub>0.78</sub> Pb(Cl <sub>0.03</sub> Br <sub>0.15</sub> Br <sub>0.85</sub> ) <sub>3</sub> /C <sub>60</sub> /SnO <sub>X</sub> /IZO/Au/SiO <sub>2</sub> /PTFE	1.79	19.7	78	27.6	1.0	(61)
PIN	SHJ (a-Si(n) front / n-Si)	IZO	2-PACz/ Cs0.05FA0.8MA0.15Pb(I0.755Br0.255)3/MgFx/C60/SnO2/IZO	1.91	19.8	78	29.3	1.0	(62)
PIN	SHJ (Q-ANTUM Technology Silicon)	IZO	SAM/CsFAPb(IBrCl)3/C60/SnO2/IZO/LiF	1.91	19.3	78	28.8	1.006	(63)
PIN	SHJ (a-Si(p+) rear/ n-Si/a-Si(i)/a-Si:H(n))	ITO	PTAA/ FAxMA1-xPb(IyBr1-y)3/C60/SnO2/IZO/Ag/Al/PDMS		19.0	80	27.6	0.5	(64)

				1.78	17.6	68	21.1	65.1	WOIK
NIP	SHJ (a-Si(p) front / n-Si)	ITO (1.7nm)	nm) SnO <sub>2</sub> /(FAPbI <sub>3</sub> ) <sub>0.83</sub> (MABr <sub>3</sub> ) <sub>0.17</sub> /Spiro-OMeTAD/MoO <sub>3</sub> /ITO/Ag	1.77 18.0	76	24.2	11.8	THIS	
				1.82	18.1	82	27.2	1.0	This
?	?	?	?	1.98	20.2	81	32.5*	1.014	(68)
?	?	?	?	1.91	20.5	80	31.3*	1.167	(68)
?	?	?	?	1.89	17.8	79	26.8*	274.22	(67)
PIN	SHJ (a-Si(p+) rear/ n-Si/a-Si(i)/nc-SiOx(n))	ITO	Me-4PACz/2PACz/ Cs0.05(FA0.79MA0.21)0.95Pb(I0.79Br0.21)3/LiF/C60/SnO2/IZO/LiF	1.90	19.5	79	29.8*	1.016	(66)
PIN	SHJ (a-Si(p+) rear/ n-Si/a-Si(i)/nc-SiOx(n))		NiOx/2PACz/FAMACsPbIBr/LiF/C60/SnO2/IZO/LiF	1.79	20.1	80	28.8	1.2	(65)
		ITO		1.85	17.5	71	22.1	11.9	

SHJ = Silicon heterojunction solar cells,  $MA = CH_3NH_3$ ,  $FA = HC(NH_2)_2$ + steady-state, \* certified or independently verified, N/P: not reported.

Parameters	Values	Ref.
Relative permittivity	3.2	(69)
Density of states (cm <sup>-3</sup> )	1.03×10 <sup>21</sup>	
Bandgap (eV)	3.33	Measured in this work
Conductive band (eV)	5.24	Calculate in this work
Valence band (eV)	8.57	
Work function (eV)	5.27	
Electron concentration (cm <sup>-3</sup> )	2.89×10 <sup>20</sup>	Measured in this work
Carrier mobility (cm <sup>2</sup> V <sup>-1</sup> s <sup>-1</sup> )	50.3	]
Resistivity ( $\Omega$ cm) for 100nm ITO	4.28×10 <sup>-4</sup>	

Table S2: Material properties of ITO

 Table S3: Material properties SnO2

Parameters	Values	Ref.
Relative permittivity	9.86	
Density of states (cm <sup>-3</sup> )	$2.42 \times 10^{19}$	(70)
Bandgap (eV)	3.79	
Thickness (µm)	0.015	Measured in this work
Conductive band (eV)	4.31	
Work function (eV)	4.36	(70)
Electron concentration (cm <sup>-3</sup> )	$3.3 \times 10^{18}$	
Carrier mobility (cm <sup>2</sup> V <sup>-1</sup> s <sup>-1</sup> )	1.9×10 <sup>-3</sup>	

ITO	•	Lifetime (ms)	Implied Voc (mV)				
(nm)	After ITO	After ITO/SnO <sub>2</sub> /perovskite	After ITO	After ITO/SnO <sub>2</sub> /perovskite			
0	13.5±0.6	13.6±0.6	726±1	725±2			
1	$10.9 \pm 0.2$	10.6±0.4	726±1	724±3			
1.7	14.5±0.6	14.8±0.4	726±1	727±1			
3.5	$11.4 \pm 0.2$	10.9±0.2	727±1	725±2			
5	$10.5 \pm 0.3$	10.4±0.2	725±3	725±3			

**Table S4:** Measured effective carrier lifetimes and implied  $V_{OC}$ 's of ITO or ITO/SnO<sub>2</sub>/perovskite coated silicon half cells (front metallisation not completed)

**Table S5:** Measured dark saturation current density  $J_0$  of Si half wafer (front and rear metallisation not completed) before and after ITO deposition with varying thickness.

ITO	J₀ (A/cm²)					
(nm)	Before ITO	After ITO				
0		2.3E-15				
1.0	2.3E-15	3.8E-15				
1.7		1.8E-15				
3.5		3.5E-15				
5.0		2.7E-15				

# Reference

- 1. M. Köhler *et al.*, A silicon carbide-based highly transparent passivating contact for crystalline silicon solar cells approaching efficiencies of 24%. *Nature Energy* **6**, 529–537 (2021).
- 2. J. Zheng *et al.*, 21.8% Efficient Monolithic Perovskite/Homo-Junction-Silicon Tandem Solar Cell on 16 cm2. *ACS Energy Letters* **3**, 2299-2300 (2018).
- 3. J. Zheng *et al.*, Large Area 23%-Efficient Monolithic Perovskite/Homo-Junction-Silicon Tandem Solar Cell With Enhanced UV Stability Using Down-Shifting Material. *ACS Energy Letters* **4**, 2623-2631 (2019).
- 4. L. Shi *et al.*, Gas chromatography–mass spectrometry analyses of encapsulated stable perovskite solar cells. *Science* **368**, (2020).
- 5. A. Czudek *et al.*, Transient Analysis during maximum power point tracking (TRAMPPT) to assess dynamic response of perovskite solar cells. *arXiv preprint arXiv:.05028*, (2019).
- 6. R. A. Sinton, A. Cuevas, M. Stuckings, in *Conference Record of the Twenty Fifth IEEE Photovoltaic Specialists Conference-1996.* (IEEE, 1996), pp. 457-460.
- 7. D. MacDonald, A. Cuevas, K. McIntosh, L. Barbosa, D. De Ceuster, paper presented at the Proceedings of the 20th European Photovoltaic Solar Energy Conference, 2005.
- 8. T. Trupke, R. Bardos, M. Abbott, Self-consistent calibration of photoluminescence and photoconductance lifetime measurements. *Applied Physics Letters* **87**, 184102 (2005).

- 9. L. A. Giannuzzi, F. A. Stevie, A review of focused ion beam milling techniques for TEM specimen preparation. *Micron* **30**, 197-204 (1999).
- 10. T. Sentaurus, Technology computer aided design (TCAD). *Synopsys, Zürich, Switzerland.*
- 11. J. Zhao *et al.*, Advanced interface modelling of n-Si/HNO3 doped graphene solar cells to identify pathways to high efficiency. *Applied Surface Science* **434**, 102-111 (2018).
- 12. P. P. Altermatt, Models for numerical device simulations of crystalline silicon solar cells—a review. *Journal of computational electronics* **10**, 314 (2011).
- 13. R. N. Hall, Electron-hole recombination in germanium. *Physical review* 87, 387 (1952).
- 14. H. Steinkemper, F. Feldmann, M. Bivour, M. Hermle, Numerical simulation of carrierselective electron contacts featuring tunnel oxides. *IEEE Journal of Photovoltaics* **5**, 1348-1356 (2015).
- 15. PVlighthouse https://www.pvlighthouse.com.au. (2022).
- 16. R. Egerton, in *Electron Energy-Loss Spectroscopy in the Electron Microscope*. (Springer, 2011), pp. 231-291.
- 17. J. P. Mailoa *et al.*, A 2-terminal perovskite/silicon multijunction solar cell enabled by a silicon tunnel junction. *Applied Physics Letters* **106**, 121105 (2015).
- 18. S. Albrecht *et al.*, Monolithic perovskite/silicon-heterojunction tandem solar cells processed at low temperature. *Energy Environ. Sci.* **9**, 81-88 (2016).
- 19. J. Werner *et al.*, Efficient Monolithic Perovskite/Silicon Tandem Solar Cell with Cell Area >1 cm(2). *J Phys Chem Lett* **7**, 161-166 (2016).
- 20. J. Werner *et al.*, Efficient Near-Infrared-Transparent Perovskite Solar Cells Enabling Direct Comparison of 4-Terminal and Monolithic Perovskite/Silicon Tandem Cells. *ACS Energy Letters*, 474-480 (2016).
- 21. J. Werner *et al.*, Zinc tin oxide as high-temperature stable recombination layer for mesoscopic perovskite/silicon monolithic tandem solar cells. *Applied Physics Letters* **109**, 233902 (2016).
- 22. K. A. Bush *et al.*, 23.6%-efficient monolithic perovskite/silicon tandem solar cells with improved stability. *Nature Energy* **2**, 17009 (2017).
- 23. F. Sahli *et al.*, Improved Optics in Monolithic Perovskite/Silicon Tandem Solar Cells with a Nanocrystalline Silicon Recombination Junction. *Advanced Energy Materials*, 1701609 (2017).
- 24. Y. Wu *et al.*, Monolithic perovskite/silicon-homojunction tandem solar cell with over 22% efficiency. *Energy Environ. Sci.* **10**, 2472-2479 (2017).
- 25. R. Fan *et al.*, Toward Full Solution Processed Perovskite/Si Monolithic Tandem Solar Device With PCE Exceeding 20%. *Solar RRL* **1**, 1700149 (2017).
- 26. J. Zheng *et al.*, Large area efficient interface layer free monolithic perovskite/homojunction-silicon tandem solar cell with over 20% efficiency. *Energy & Environmental Science* **11**, 2432-2443 (2018).
- 27. F. Sahli *et al.*, Fully textured monolithic perovskite/silicon tandem solar cells with 25.2% power conversion efficiency. *Nature materials* **17**, 820–826 (2018).
- K. A. Bush *et al.*, Minimizing Current and Voltage Losses to Reach 25%-Efficient Monolithic Two-Terminal Perovskite-Silicon Tandem Solar Cells. *ACS Energy Letters* 3, 2173–2180 (2018).
- 29. S. Zhu *et al.*, Solvent Engineering to Balance Light Absorbance and Transmittance in Perovskite for Tandem Solar Cells. *Solar RRL*, 1800176 (2018).

- 30. Z. Qiu *et al.*, Monolithic perovskite/Si tandem solar cells exceeding 22% efficiency via optimizing top cell absorber. *Nano Energy* **53**, 798-807 (2018).
- 31. B. Chen *et al.*, Grain Engineering for Perovskite/Silicon Monolithic Tandem Solar Cells with Efficiency of 25.4%. *Joule* **3**, 177-190 (2019).
- 32. M. Jošt *et al.*, Textured interfaces in monolithic perovskite/silicon tandem solar cells: Advanced light management for improved efficiency and energy yield. *Energy & Environmental Science* **11**, 3511-3523 (2018).
- 33. C. Case, in *Organic, Hybrid, and Perovskite Photovoltaics XIX*. (International Society for Optics and Photonics, 2018), vol. 10737, pp. 107370I.
- 34. F. Hou *et al.*, Inverted pyramidally-textured PDMS antireflective foils for perovskite/silicon tandem solar cells with flat top cell. *Nano Energy* **56**, 234-240 (2019).
- 35. H. Shen *et al.*, In situ recombination junction between p-Si and TiO2 enables highefficiency monolithic perovskite/Si tandem cells. *Science Advances* **4**, eaau9711 (2018).
- 36. F. Hou *et al.*, Monolithic Perovskite/Silicon-Heterojunction Tandem Solar Cells with Open-Circuit Voltage of over 1.8 V. *ACS Applied Energy Materials* **2**, 243-249 (2019).
- 37. L. Mazzarella *et al.*, Infrared Light Management Using a Nanocrystalline Silicon Oxide Interlayer in Monolithic Perovskite/Silicon Heterojunction Tandem Solar Cells with Efficiency above 25%. *Advanced Energy Materials*, 1803241 (2019).
- 38. G. Nogay *et al.*, 25.1%-Efficient Monolithic Perovskite/Silicon Tandem Solar Cell Based on a p-type Mono-crystalline Textured Silicon Wafer and High Temperature Passivating Contacts. *ACS Energy Letters*, (2019).
- 39. C. U. Kim *et al.*, Optimization of device design for low cost and high efficiency planar monolithic perovskite/silicon tandem solar cells. *Nano Energy* **60**, 213-221 (2019).
- 40. B. Kamino *et al.*, Low Temperature Screen-Print Metallization for the Scale Up of 2-Terminal Perovskite-Silicon Tandems. *ACS Applied Energy Materials* **2**, 3815-3821 (2019).
- 41. E. Köhnen *et al.*, Highly efficient monolithic perovskite silicon tandem solar cells: analyzing the influence of current mismatch on device performance. *Sustainable Energy* & *Fuels* **3**, 1995-2005 (2019).
- 42. A. J. Bett *et al.*, Two-terminal Perovskite silicon tandem solar cells with a high-Bandgap Perovskite absorber enabling voltages over 1.8 V. *Progress in Photovoltaics: Research and Applications* **28**, 99-110 (2019).
- 43. B. Chen *et al.*, Blade-Coated Perovskites on Textured Silicon for 26%-Efficient Monolithic Perovskite/Silicon Tandem Solar Cells. *Joule* **4**, 850-864 (2020).
- 44. Y. Hou *et al.*, Efficient tandem solar cells with solution-processed perovskite on textured crystalline silicon. *Science* **367**, 1135-1140 (2020).
- 45. J. Xu *et al.*, Triple-halide wide–band gap perovskites with suppressed phase segregation for efficient tandems. *Science* **367**, 1097-1104 (2020).
- 46. D. Kim *et al.*, Efficient, stable silicon tandem cells enabled by anion-engineered widebandgap perovskites. *Science* **368**, 155-160 (2020).
- 47. P. S. C. Schulze *et al.*, 25.1% High-Efficient Monolithic Perovskite Silicon Tandem Solar Cell with a High Band Gap Perovskite Absorber. *Solar RRL* **4**, 2000152 (2020).
- 48. A. S. Subbiah *et al.*, High-Performance Perovskite Single-Junction and Textured Perovskite/Silicon Tandem Solar Cells via Slot-Die-Coating. *ACS Energy Letters* **5**, 3034-3040 (2020).
- 49. E. Aydin *et al.*, Interplay between temperature and bandgap energies on the outdoor performance of perovskite/silicon tandem solar cells. *Nature Energy* **5**, 851–859 (2020).

- 50. A. Al-Ashouri *et al.*, Monolithic perovskite/silicon tandem solar cell with> 29% efficiency by enhanced hole extraction. *Science* **370**, 1300-1309 (2020).
- 51. M. De Bastiani *et al.*, Efficient bifacial monolithic perovskite/silicon tandem solar cells via bandgap engineering. *Nature Energy* **6**, 167–175 (2021).
- 52. M. A. Green *et al.*, Solar cell efficiency tables (Version 58). *Progress in Photovoltaics: Research Applications* **29**, 11 (2021).
- 53. E. Köhnen *et al.*, 27.9% Efficient Monolithic Perovskite/Silicon Tandem Solar Cells on Industry Compatible Bottom Cells. *Solar RRL* **5**, 2100244 (2021).
- 54. F. H. Isikgor *et al.*, Concurrent cationic and anionic perovskite defect passivation enables 27.4% perovskite/silicon tandems with suppression of halide segregation. **5**, 1566-1586 (2021).
- 55. F. Hou *et al.*, Control Perovskite Crystals Vertical Growth for Obtaining High Performance Monolithic Perovskite/Silicon Heterojunction Tandem Solar Cells with Voc of 1.93 V. *Solar RRL* **5**, 2100357 (2021).
- 56. E. Aydin *et al.*, Ligand-bridged charge extraction and enhanced quantum efficiency enable efficient n–i–p perovskite/silicon tandem solar cells. *Energy & Environmental Science* **14**, 4377-4390 (2021).
- 57. J. Liu *et al.*, 28.2%-efficient, outdoor-stable perovskite/silicon tandem solar cell. *Joule* **5**, 3169-3186 (2021).
- 58. S. Mariotti *et al.*, Monolithic Perovskite/Silicon Tandem Solar Cells fabricated using industrial p-type POLO/PERC Silicon Bottom Cell Technology. *Solar RRL*, **6**, 2101066 (2022).
- J. Y. Hyun *et al.*, Perovskite/Silicon Tandem Solar Cells with a Voc of 1784 mV Based on an Industrially Feasible 25 cm<sup>2</sup> TOPCon Silicon Cell. *ACS Applied Energy Materials*, 5, 5449-5456 (2022).
- 60. L. Wang *et al.*, Strain Modulation for Light-Stable n-i-p Perovskite/Silicon Tandem Solar Cells. *Advanced Materials*, **34**, 2201315 (2022).
- 61. Y. Wu *et al.*, 27.6% Perovskite/c Si Tandem Solar Cells Using Industrial Fabricated TOPCon Device. *Advanced Energy Materials*, **12**, 2200821 (2022).
- 62. J. Liu *et al.*, Efficient and stable perovskite-silicon tandem solar cells through contact displacement by MgFx. *Science* **377**, 302-306 (2022).
- 63. K. Sveinbjörnsson *et al.*, Monolithic Perovskite/Silicon Tandem Solar Cell with 28.7% Efficiency Using Industrial Silicon Bottom Cells. *ACS Energy Letters*, 2654-2656 (2022).
- 64. B. Chen *et al.*, A Two-Step Solution-Processed Wide-Bandgap Perovskite for Monolithic Silicon-Based Tandem Solar Cells with >27% Efficiency. *ACS Energy Letters* 7, 2771-2780 (2022).
- 65. L. Mao *et al.*, Fully Textured, Production-line Compatible Monolithic Perovskite/Silicon Tandem Solar Cells Approaching 29% Efficiency. *Advanced Materials*, **34**, 2206193 (2022).
- 66. P. Tockhorn *et al.*, Nano-optical designs enhance monolithic perovskite/silicon tandem solar cells toward 29.8% efficiency. (2022) https://doi.org/10.21203/rs.3.rs-1439562/v1.
- 67. M. A. Green *et al.*, Solar cell efficiency tables (Version 60). *Progress in Photovoltaics: Research and Applications*, **30**, 687-701 (2022).
- 68. NREL, https://www.nrel.gov/pv/cell-efficiency.html (Accessed January 10, 2023).
- 69. Y.-C. Lin, L.-Y. Chen, F.-C. Chiu, Lossy mode resonance-based glucose sensor with high-κ dielectric film. *Crystals* **9**, 450 (2019).

70. Q. Jiang *et al.*, Enhanced electron extraction using SnO2 for high-efficiency planarstructure HC(NH2)2PbI3-based perovskite solar cells. *Nature Energy* **2**, 16177 (2016).