Four-terminal perovskite on silicon tandem solar cells optimal measurement schemes

Dewi, Herlina Arianita; Wang, Hao; Li, Jia; Thway, Maung; Lin, Fen; Aberle, Armin G.; Mathews, Nripan; Mhaisalkar, Subodh Gautam; Bruno, Annalisa

2019

Dewi, H. A., Wang, H., Li, J., Thway, M., Lin, F., Abrele, A. G., . . . Bruno, A. (2020). Four-terminal perovskite on silicon tandem solar cells optimal measurement schemes. *Energy Technology*, 8(4), 1901267-. doi:10.1002/ente.201901267

<https://hdl.handle.net/10356/142482>

<https://doi.org/10.1002/ente.201901267>

This is the accepted version of the following article: Dewi, H. A., Wang, H., Li, J., Thway, M., Lin, F., Abrele, A. G., . . . Bruno, A. (2020). Four-terminal perovskite on silicon tandem solar cells optimal measurement schemes. *Energy Technology*, 8(4), 1901267-, which has been published in final form at <https://doi.org/10.1002/ente.201901267>. This article may be used for non-commercial purposes in accordance with the Wiley Self-Archiving Policy [<https://authorservices.wiley.com/authorresources/Journal-Authors/licensing/self-archiving.html>].

Downloaded on 26 Apr 2023 07:36:23 SGT

Four-Terminal Perovskite on Silicon Tandem Solar Cells Optimal Measurements Schemes

*Herlina Arianita Dewi^a, Hao Wang^a, Jia Li^a, Maung Thway^{b,c}, Fen Lin^b, Armin G. Aberle^{b,c},
Nripan Mathews^{a,d*}, Subodh Mhaisalkar^{a, d, *}, Annalisa Bruno^{a*}*

- a. Dr. H.A. Dewi, Dr H. Wang, Dr J. Li, Prof. N. Mathews, Prof. S. Mhaisalkar, Dr. A. Bruno
Energy Research Institute @ NTU (ERI@N), Nanyang Technological University,
Singapore 637553
E-mail: nripan@ntu.edu.sg; subodh@ntu.edu.sg; annalisa@ntu.edu.sg
- b. Mr. M. Thway, Dr. F. Lin, Prof. A. G. Aberle
Solar Energy Research Institute of Singapore (SERIS), National University of Singapore,
Singapore 117574
- c. Mr. M. Thway, Prof. A. G. Aberle
Department of Electrical and Computer Engineering, National University of Singapore,
Singapore 117583
- d. Prof. N. Mathews, Prof. S. Mhaisalkar
School of Materials Science & Engineering, Nanyang Technological University,
Singapore, 639798

Keywords: perovskite solar cells, silicon solar cells, tandem solar cells, measurements scheme, efficiency

Abstract

Semi-transparent perovskite solar cells and their potential integration with silicon solar cells in tandem configurations are attracting a significantly increasing interest in the photovoltaics community. Besides being highly spectrally complementary, these perovskite and silicon solar cells have very different optimal-performing sizes and consequently ideal measurement schemes for their integration in four-terminal (4T) tandem configurations need to be investigated in details. In this work, the effect of different active areas on both perovskite and silicon solar cells on their photovoltaic performances has been investigated. Furthermore, the commonly used *filtering* 4T tandem measurement scheme (named as *filtered*) has been systematically compared to the *size-matching* scheme (named as *masked*) demonstrating that employing the same top semi-transparent perovskite and bottom silicon solar cells in different measurements schemes the total 4T tandem power conversion efficiency (PCE) can differ more than 1%. The concepts presented here highlight the importance of optimal measurement schemes to assess 4T tandem PCE and rationalize the effect of compromise between the sub-cells size matching and the identification of the maximum PCE potential.

1. Introduction

In the recent years, silicon solar cells (SCs) have reached remarkable power conversion efficiencies (PCE) as high as 26.6% ^[1], closely approaching their theoretical limit of 29.4% ^[2]. Therefore, developments of alternative SCs structures and concepts are needed to overcome this limit. A straight-forward approach to increase SCs' PCE is by using multi-junction structures with different bandgaps optimized for each section of the spectrum. Perovskite based solar cells (PSCs) are potential candidate for tandem integration with silicon SCs thanks to their high PCE, as shown

by the certified record of 25.2%^[3], as well as their easy bandgap tunability^{[4] [5]} and low cost production^[6]. As a result, the development of perovskite on silicon tandem SCs has been intensive in the last few years, for both mechanical stack four terminal (4T) and monolithic two terminal (2T) configurations^[7]. The 4T configuration, where top and bottom cells have independent electrical connection, presents significant advantages on the sub-cells independent fabrication process and size selection. Moreover, the 4T tandem solar cells' PCEs results almost independent from the spectral variations and even delivering higher efficiencies when under low illuminations^[8]. A higher energy yield and lower levelized cost of electricity (LCOE) can be possibly obtained using 4T configuration as compared to the 2T counterpart^[9]. Additionally, semitransparent PSCs can be directly integrated on existing silicon PV installation. In the 4T configuration, both SCs can be easily replaced in case just one of sub-cells is degraded or damaged. Tandem SCs in 4T configuration have reached the impressive record of 27.1% PCE, employing a 0.13 cm² PSCs and a 4 cm² silicon SC^[10].

The best performing PSCs have active areas between 0.07 cm² and 0.16 cm²^[11]. Even though the ability to fabricate semi-transparent large area PSCs has been demonstrated, the efficiencies above 0.25 cm² are consistently lower mostly due to the perovskite and transporting layers reduced uniformity and the increased sheet resistance of the electrodes when the sizes are scaled up. A proper electrode design, including pattern and metal grids, is important to minimize the effect on contact geometry and sheet resistance for large area PSCs^[12] and fabricate PSCs module reaching PCE ranging from 17% (for 30cm²)^[13] up to 12.6% (50.6 cm²)^[14] and 10.74% (70 cm²)^[15] for opaque PSCs. Instead semi-transparent PSCs the PCE reached 15.3% over 4 cm²^[16] and 14.96% for 11.7 cm²^[17]. On the contrary, silicon SCs are mainly fabricated on relatively large area wafers (usually in 24 inch² or 36 inch²). In attempt to match the silicon SCs size with semi-transparent PSCs, conventional small-area silicon SCs are fabricated using laser-cut process

from full-size silicon wafer. The main drawbacks for the laser-cut process on Si SCs are the formation of defects on the cutting side and the consequent exposure of non-passivated area leading to a major V_{oc} reduction. Due to the different high-PCEs optimum sizes for the PSCs and silicon SCs, a size compromise between two sub-cells is critical to achieve high 4T tandem SCs PCE.

This work aims at investigating the effect of different active areas of PSCs and silicon SCs on their photovoltaic parameters and consequently establishing suitable measurement schemes for 4T tandem solar cells. We fabricated both opaque and semi-transparent 1.2 cm^2 PSCs and studied their photovoltaic parameters with different aperture areas. Large area opaque PSCs showed stable PCEs (17.5%-18%) when measured with shadow masks ranging from 0.09 cm^2 to 1 cm^2 . Differently, a substantial PCEs drop from 16.8% to 10.8% has been measured for the semi-transparent PSCs in the same masking conditions. This significant drop in photovoltaic performances observed for semi-transparent PSCs is driven by the increased sheet resistance of the transparent electrodes over larger area. Moreover, the commonly used *filtered* 4T tandem measurement ^[10, 18] has been compared to a size-matching *masked* scheme. In the *filtered* scheme, the 4T tandem PCE is evaluated by summing up the optimal PCEs of the small area PSC and the large area silicon SC shadowed by a comparable sized large area PSC. Instead, in the *masked* scheme, the 4T tandem PCE is evaluated by summing up the PCEs of the small area PSC and the one of the silicon SCs shadowed by the PSCs and masked to match the small area PSCs. Using same top semi-transparent PSC and bottom silicon SC, the total 4T tandem PCE is more than 1% higher employing *filtered* scheme respect to the *masked* one. This study, for the first time, rationalizes the effect of the measurement scheme on the 4T tandem performances and provides insight between size matching compromise and the real 4T tandem PCE potential.

2. Sub-cells, Area Variation

2.1. PSC top cell

The PSCs fabricated in this work employed the triple cations $\text{Cs}_{0.05}(\text{MA}_{0.17}\text{FA}_{0.83})_{0.95}\text{Pb}(\text{I}_{0.83}\text{Br}_{0.17})_3$ perovskite as absorber material as it can provide decent stability, high reproducibility and good matching bandgap with silicon SCs^[19]. The field emission scanning electron microscope (FESEM) top view image, **Figure S1a**, reveals the compact morphology of perovskite surface which can guarantee good performances and uniform contact with Spiro-OMeTAD hole transport material (HTM). The opaque planar PSCs layers structure consist of Fluorine doped Tin Oxide (FTO)/ SnO_2 /perovskite/Spiro-OmeTAD/Au, as shown in **Figure 1a**. The semi-transparent PSCs, **Figure 1b**, has have very similar device architecture just including sputtered indium tin oxide (ITO) and a thin Ag buffer layer^[20] top electrode instead of the opaque gold electrode. The semi-transparent PSCs have an average transparency of higher than 72% in the infrared region, **Figure S1b**. Detail characterizations and optimization processes of the perovskite absorber and charge transport layers have been reported in our previous work^[8].

In this work both small and larger area PSCs have been fabricated with electrode area of 0.2 cm^2 and 1.2 cm^2 respectively (**Figure S2a**). When both the 0.2 cm^2 and the 1.2 cm^2 opaque PSCs, prepared in the same batch, have been masked with and active area of 0.09 cm^2 can reach a PCE of 18.9% and 17.8% respectively, **Figure S2b**. As expected, these results confirm that in principle matching size between metal mask and contact electrode is preferable to minimize losses and achieve better photovoltaic performance. However, hereafter we purposely focus on the larger area PSCs to understand the effect of different active areas on the PSCs photovoltaic behavior. Metal masks with different apertures (0.09 cm^2 , 0.16 cm^2 , 0.25 cm^2 , 1 cm^2) have been used to investigate the effect of different active areas on both opaque and semi-transparent 1.2 cm^2 PSCs

performances, **Figure 1c-f**. The opaque and semitransparent PSCs show a very different behavior under the same masking conditions. Indeed, the opaque PSCs show relatively stable PCE, ranging from 18.0% and 17.5%, regardless of different active areas, while a substantial PCE drop from 16.8% and 10.8% has been observed for active areas scaling up from 0.09 cm² and 1 cm² for semi-transparent PSCs counterpart, **Figure 1d**. The J-V curves are reported in **Figure 1e** and **Figure 1f** and the photovoltaic figures-of-merit for each condition can be found in **Table 1**. Both opaque and semi-transparent PSCs measured under progressively larger shadow masks show consistently higher V_{oc} due to the reduced charge recombination in the larger shaded areas, in agreement with previous published work ^[21]. At the same time, the J_{sc} in opaque PSCs remains quite constant, while gradual J_{sc} decrease can be monitored in larger areas semi-transparent PSCs counterpart. Even more significantly, a FF decrease can be observed in larger semi-transparent PSCs as compared to opaque PSCs. These results prove that the large variation of FF is due to lower conductivity of sputtered ITO as compared to opaque Au electrode. The transparent top ITO contact, sputtered at room temperature and low power (25 W) without undergo any post-annealing to avoid damage of the underlying perovskite and Spiro-OMeTAD, present a relatively high ITO sheet resistance of ~30 ohm sq⁻¹. Indeed, also semi-transparent PSCs fabricated using commercial ITO substrates with higher conductivity (7 ohm sq⁻¹ instead 14 ohm sq⁻¹ of the FTO) and comparable transparency (**Figure S3a**) even delivering a higher PCE of 17.2%, suffered from a substantial drop PCE to 11.8% over 1 cm² (**Figure S3b**). Improvement in large area PSCs can be further pursued through proper substrate and electrode patterning to form module connection. ^[14] Specifically for semi-transparent PSCs, design of suitable metal grid to minimize sputtered ITO sheet resistance loss while maintaining a high overall PSC transparency needs to be explored. On the other hand, it is worth to highlight that the consistency of the other photovoltaic parameters

when the sizes are scaled up in the both opaque and semi-transparent cells confirms the good quality of our perovskite film and charge transport interlayer over a large area.

Figure 1. Opaque and Semi-transparent 1.2 cm² Perovskite Solar Cells Photovoltaic Performances : Cross section FESEM of (a) opaque and (b) semi-transparent PSCs. Each of individual layers are tainted with different color. (c) Schematic of PSCs illuminated by light on specific active area as defined by a square shaped metal mask. Different shadow mask sizes are used to study the effect of size on the photovoltaics parameters (d) PCEs of both opaque and semi-transparent PSCs versus masking sizes. J-V curves of (e) opaque and (f) semi-transparent PSCs using different measurement size. Insets show the schematic of the respective PSCs structure

Table 1. Photovoltaic summary of top perovskite using different masking size

Top Electrode	Cell Size (cm ²)	Masking area (cm ²)	V _{oc} (V)	J _{sc} (mA cm ⁻²)	FF (%)	PCE (%)
Au	0.2	0.09	1.15	21.18	77.8	18.9
Au	1.2	0.09	1.11	21.38	75.0	17.8
		0.16	1.12	20.90	76.4	17.9
		0.25	1.14	20.91	75.7	18.0
		1	1.18	21.13	70.0	17.5
ITO	1.2	0.09	1.05	20.48	78.1	16.8
		0.16	1.05	20.45	74.4	16.0
		0.25	1.07	20.03	70.8	15.2
		1	1.14	19.18	49.5	10.8

The opaque and semi-transparent un-encapsulated PSCs' stability has been also measured under 1 sun constant illumination at ambient condition (70% RH) confirming the good PSCs quality. Indeed, un-encapsulated opaque and semi-transparent PSCs show just a ~7% and ~5% PCE relative drop respectively, **Figure 2a**, after 600 s continuous illumination without any cooling system. The enhanced stability of semi-transparent PSC proves that presence of ITO can help to protect the underlying perovskite from environmental damage ^[22]. Moreover, the semi-transparent PSCs shows good shelf-life-stability when stored at inert environment as well as controlled humidity, 30% RH, as proved by only ~10% PCE degradation after 6 months (**Figure 2b**).

Figure 2. Opaque and Semi-transparent 1.2 cm² Perovskite Solar Cells Stability. (a) Opaque and semi-transparent PSCs stability under 1 sun constant illumination at 70% RH without any encapsulation. (b) Semi-transparent PSCs shelf-life stability under various storage conditions (inert and 30% RH). The PSCs are periodically taken out for measurement under ambient environment of 70% RH

2.2. Silicon SC bottom cell

As a rule of thumb, the most red-wavelength efficient c-Si SCs will be the most suitable ones for tandem integration. Hence, the record Si SCs structures as interdigitated back-contacted (IBC) ^[10, 23] or Silicon heterojunction (SHJ) ^[24] will allow to reach the highest PCE for perovskite on Si tandem SCs at relative high production costs. On the other hand, the common industrialized structures such as passivated emitters rear contact (PERC) SC will be able to reach slightly lower PCE but instead will allow to maintaining the production costs significantly lower.

The c-Si SC used in this study is a conventional PERC n-type c-Si bifacial SC, also known as n-type front and back contact (nFAB). The small area bottom SCs have been fabricated through laser cutting process of the 6" silicon wafer to obtain a relatively matching size with the top semi-transparent PSCs ^[25]. The reference initial 6" silicon SC has V_{oc} of 0.66 V, J_{sc} of 40.03 mA cm⁻², FF of 79.8 %, and PCE of 21.1%. The small-area silicon SCs have significant inferior performance respect to the reference silicon SC, mostly due to the additional charges recombination introduced

by laser damage and the increased area of non-passivated cell edges, which can significantly affecting the V_{oc} [26]. Silicon SCs with different sizes have been fabricated to determine optimum silicon SCs to compromise the effect of side-edge defect and ratio between side-edge and active area. The best performing conditions compromising the V_{oc} drops and the performances corresponds to the silicon SCs of 1 cm x 2 cm (2 cm^2) with PCE of 19.6%. Further enhancement of the small area silicon bottom SCs could be done by developing direct localized grown small size silicon fabrication to minimize laser cutting defect [27].

3. Four Terminal (4T) Perovskite/Silicon Tandem SCs

Here, we study the photovoltaics performances of 4T perovskite/silicon tandem SCs highlighting the effect of different measurements schemes. The 4T tandem PCEs have been evaluated by mechanically stacking the top semi-transparent PSC directly above the silicon SC bottom cell. The visible wavelength spectrum is mainly utilized by perovskite top cell, leaving infrared region to be harvested by the silicon bottom cell, **Figure 3a**.

Although it is preferable to have size matching between top and bottom sub-cells in practical application, several factors need to be considered and size matching compromises are necessary to evaluate the potential and real tandem PCEs. Here, two different measurement schemes, denoted as *filtered* and *masked* are compared to analyze the 4T tandem PCE. In the *filtered* method, the 4T tandem PCE is evaluated by summing up the PCEs of small area PSC with the one of the 2 cm^2 silicon SC shadowed by a PSC with a size comparable to the silicon SC. Instead, in the *masked* scheme, the 4T tandem PCE is evaluated by summing up the PCEs of the small area PSC and of the silicon SCs shadowed by the PSCs and masked to match the small area PSCs.

The *filtered* scheme is the most commonly used measurement method to understand full potential of perovskite/silicon tandem ^[10, 18a-c]. An optical perovskite filter which has identical stack and transparency as our champion top semi-transparent PSCs (PCE 17.7% ^[8]) has been fabricated (**Figure 3b**). The *shadowed filtered* silicon SC, as a consequence of reduced light spectrum, shows a J_{sc} reduction (from 39.94 mA cm⁻² to 15.41 mA cm⁻²) and 30 mV V_{oc} drop (**Figure 3c**) resulting in a *shadowed filtered* silicon SC PCE of 7.0%. Combining our champion 17.7% semi-transparent PSCs and the *shadowed filtered* Silicon SC PCEs, a 4T tandem PCE as high as 24.7% can be achieved using this *filtered* scheme. A full summary of individual photovoltaic parameters of the individual sub-cells and of the 4T tandem by employing *filtered* scheme is shown in **Table 2**.

Figure 3. Filtered and Masked 4T Tandem Measurements Schemes. (a) Schematic of 4T perovskite/silicon tandem SC. (b) 4T tandem measurement using *filtered* scheme. Active areas for semi-transparent PSC and silicon SC are 0.09 cm² and 2 cm² respectively (c) J-V curves of 4T tandem using *filtered* scheme Semi-transparent PSC (deep red), *stand-alone* silicon SC (black), *shadowed filtered* silicon (green). (d) 4T tandem measurement using *masked* scheme. Shadow

metal mask with active area of 0.09 cm^2 is used to define the active area for both semi-transparent PSC and silicon SC. (e) J-V curves of 4T tandem using *masked* scheme. Semi-transparent PSC (deep red), *stand-alone* silicon SC (black) *masked* silicon SC (blue), *shadowed masked* silicon (purple).

Table 2. Photovoltaic paremetres and PCEs of semi-transparent PSC, *stand-alone* silicon SC, *shadowed filtered* silicon SC, and 4T tandem SC by employing *filtered* measurement scheme

Cell	Active Area (cm^2)	V_{oc} (V)	J_{sc} (mA cm^{-2})	FF (%)	PCE (%)
<i>stand-alone</i> silicon SC	2	0.631	39.94	77.78	19.6
<i>shadowed filtered</i> silicon SC	2	0.598	15.41	76.02	7.0
PSC	0.09	1.060	21.52	77.48	17.7
4T tandem PCE using <i>filtered</i> scheme					24.7

Figure 3d shows the *masked* scheme, which is considered as a size matching tandem operating condition. Due to fact that PSC and silicon SCs have their best operating conditions for significantly different active area, this *masked* scheme condition is intrinsically more complicated to be realized. The same optical perovskite filter in previous *filtered* method has been used to shadow the Si SCs and shadow metal masks with aperture area of 0.09 cm^2 have been used to determine the active area for both sub-cells. As starting point, in order to understand the effect of masking the silicon SCs, we have measured the photovoltaics parameters of the 2 cm^2 silicon SC with (*masked*) and without (*stand-alone*) the 0.09 cm^2 mask. A shown in **Table 3** and **Figure 3e**, the *masked* silicon SC shows a significant reduction of $V_{oc} \sim 100 \text{ mV}$, due to the increased charge recombination in the shaded area while J_{sc} and FF display very marginally decrease. The *shadowed masked*-silicon SC shows a total V_{oc} loss of 130 mV ($\sim 100 \text{ mV}$ purely due to masking and $\sim 30 \text{ mV}$ to the of reduced light spectrum), and the J_{sc} drop (from 39.78 mA cm^{-2} to 15.36 mA cm^{-2}), as compared to the reference *masked* silicon SC, showing a drop consistent to what has been observed in the previous *filtered* scheme. Using this *masked* scheme, a PCE of 5.8% can be obtained for *shadowed masked* silicon SC, hence resulting on final 4T tandem PCE of 23.5%. The details of individual figures of merit and PCE, by employing *masked* scheme, are shown in **Table 3**.

Table 3. Photovoltaic summary of semi-transparent PSC, *stand-alone* silicon SC, *masked* silicon SC, *shadowed masked* silicon SC, and 4T tandem PCE by employing *masked* measurement scheme

Cell	Active Area (cm ²)	V _{oc} (V)	J _{sc} (mA cm ⁻²)	FF (%)	PCE (%)
	2				
<i>stand-alone</i> silicon SC		0.631	39.94	77.78	19.6
<i>masked</i> silicon SC	0.09	0.539	39.78	76.07	16.4
<i>shadowed masked</i> silicon SC	0.09	0.507	15.36	74.84	5.8
PSC	0.09	1.060	21.52	77.48	17.7
4T tandem PCE using <i>masked</i> scheme					23.5

Using same top semi-transparent PSCs and bottom silicon SC, the total 4T tandem PCE is more than 1% higher employing the *filtered* measurement scheme as compared to the *masked* one, mostly due to the different sizes optimum conditions for the two SCs. We can then conclude that the J_{sc} values are comparable by using both *masked* and *filtered* schemes while the other photovoltaic parameters (V_{oc} and FF) are strongly affected by the charge recombination of the shaded area. The *filtered* scheme can give a better idea on the full potential of the 4T tandem SC, using the two sub-cells at their best operating conditions. On the other hand, the *masked* scheme will give a more tangible indication of their simultaneous working conditions. At this stage of tandem development, PSCs and silicon SC size matching is still an issue to reach high PCE, consequently the measurements scheme selection is important. Although on the long term with further improvement of the semi-transparent large area PSC, we believe that these two methods will converge to a similar value.

4. Conclusion

This work demonstrates the effects of PSCs and silicon SCs active area sizes on their photovoltaics parameters and on the 4T tandem PCE measurements. Using the same top PSC and bottom silicon SC, the 4T tandem PCEs can differ over 1% using two different measurement

schemes. Indeed PCEs of 23.5% and 24.7% have been achieved by using *filtered* and *masked* measurement schemes respectively. The lower PCE for *masked* scheme is a consequence of additional charge recombination effects in the shaded area of silicon SCs. The commonly used *filtered* scheme indicates the maximum 4T tandem PCE potential (with the given top and bottom cells), while the size-matching *masked* scheme spotlights the performance under real operating conditions. Our results highlights the importance of suitable tandem measurement schemes to compromise size matching and 4T tandem PCE.

5. Experimental Section

Perovskite solar cell (PSC) fabrication

Fluorine doped tin oxide (FTO) or indium tin oxide (ITO) glass substrates were cleaned in decon soap solution followed by deionized water and ethanol. The low temperature planar SnO_2 (p- SnO_2) was prepared using 0.1 M $\text{SnCl}_{2.2}\text{H}_2\text{O}$ (Sigma Aldrich) doped with 8% InCl_3 (Sigma Aldrich) in ethanol. $\text{Cs}_{0.05}(\text{MA}_{0.17}\text{FA}_{0.83})_{0.95}\text{Pb}(\text{I}_{0.83}\text{Br}_{0.17})_3$ perovskite precursor solution was prepared following previous published report ^[19a]. The dissolved perovskite solution was spin-coated at 1000 rpm for 10 s followed immediately by 6000 rpm for 17 s. Spiro-OMeTAD (70 mg/mL in chlorobenzene) doped with 4-*tert*-butylpyridine, lithium bis(trifluoromethylsulphonyl) imide, and FK209 was spin-coated at 5000 rpm for 30 s. Gold back contact (100 nm) was deposited using thermal evaporation for opaque perovskite cell. While for semi-transparent perovskite cell, indium tin oxide (ITO) was deposited using DC sputter at 25 W power to form transparent electrode.

Silicon SC fabrication

The fabrication of the silicon SC bottom cell followed the standard procedure of industrial n-type bifacial silicon SC with boron diffused emitter and phosphorus diffused back surface field. An n-type 6-inch pseudo-square silicon wafer ($180\text{ }\mu\text{m}$, $2\text{ }\Omega\text{ cm}^{-1}$) was used as a starting substrate. The finished cell was passivated with $\text{AlO}_x/\text{SiN}_x$ stack on the front and SiN_x on the rear, deposited using plasma enhanced chemical vapor deposition (PECVD). On top of the dielectric layers of both sides, H-pattern grids are screen-printed and fired quickly at high temperatures. In order to achieve a better size match with the semi-transparent PSC, the finished 6-inch silicon cell was then laser cut from the rear side into various-size cells.

Characterizations

Transmission (T) spectra were recorded using UV-Vis-NIR Spectrophotometer (UV3600, Shimadzu) equipped with an integrating sphere (300-1200 nm wavelength). Cross section images of the opaque and semi-transparent PSCs were recorded using a Field Emission Scanning Electron Microscope (FESEM, JEOL JSM-7600F). Photocurrent-voltage characteristics of both PSCs and silicon SCs were recorded using digital dial source meter (Keithley 2612 sourcemeter). The J-V measurements were measured using San-EI Electric, XEC-301S solar simulator under standard simulated AM1.5G illumination and the light intensity was calibrated using standard reference silicon cell. As indicated, square shapes shadow metal masks with various apertures sizes were used for determine active area.

Supporting Information

Supporting Information is available from the Wiley Online Library.

Acknowledgements

This research is supported by the National Research Foundation, Prime Minister's Office, Singapore under Energy Innovation Research Program (Grant number, NRF2015EWT-EIRP003-004 and NRF-CRP14-2014-03 and Solar CRP: S18-1176-SCRP).

References

- [1] aK. Yoshikawa, W. Yoshida, T. Irie, H. Kawasaki, K. Konishi, H. Ishibashi, T. Asatani, D. Adachi, M. Kanematsu, H. Uzu, K. Yamamoto, *Solar Energy Materials and Solar Cells* **2017**, *173*, 37-42; bK. Yoshikawa, H. Kawasaki, W. Yoshida, T. Irie, K. Konishi, K. Nakano, T. Uto, D. Adachi, M. Kanematsu, H. Uzu, K. Yamamoto, *Nature Energy* **2017**, *2*, 17032.
- [2] A. Richter, M. Hermle, S. W. Glunz, *IEEE Journal of Photovoltaics* **2013**, *3*, 1184-1191.
- [3] NREL, in http://www.nrel.gov/ncpv/images/efficiency_chart.jpg.
- [4] aA. Bruno, D. Cortecchia, X. Y. Chin, K. Fu, P. P. Boix, S. Mhaisalkar, C. Soci, *Advanced Energy Materials* **2017**, 1700265; bP. P. Boix, K. Nonomura, N. Mathews, S. G. Mhaisalkar, *Materials Today* **2014**, *17*, 16-23; cS. A. Kulkarni, T. Baikie, P. P. Boix, N. Yantara, N. Mathews, S. Mhaisalkar, *Journal of Materials Chemistry A* **2014**, *2*, 9221-9225; dT. M. Koh, V. Shanmugam, J. Schlipf, L. Oesinghaus, P. Müller-Buschbaum, N. Ramakrishnan, V. Swamy, N. Mathews, P. P. Boix, S. G. Mhaisalkar, *Advanced Materials* **2016**, *28*, 3653-3661.
- [5] E. J. Juarez-Perez, R. S. Sanchez, L. Badia, G. Garcia-Belmonte, Y. S. Kang, I. Mora-Sero, J. Bisquert, *The Journal of Physical Chemistry Letters* **2014**, *5*, 2390-2394.
- [6] aD. P. McMeekin, G. Sadoughi, W. Rehman, G. E. Eperon, M. Saliba, M. T. Hörantner, A. Haghighirad, N. Sakai, L. Korte, B. Rech, M. B. Johnston, L. M. Herz, H. J. Snaith, *Science* **2016**, *351*, 151-155; bG. E. Eperon, M. T. Hörantner, H. J. Snaith, *Nature Reviews Chemistry* **2017**, *1*, 0095.
- [7] J. Werner, B. Niesen, C. Ballif, *Advanced Materials Interfaces* **2018**, *5*, 1700731.
- [8] H. A. Dewi, H. Wang, J. Li, M. Thway, R. Sridharan, R. Stangl, F. Lin, A. G. Aberle, N. Mathews, A. Bruno, S. Mhaisalkar, *ACS Applied Materials & Interfaces* **2019**, *11*, 34178-34187.
- [9] aL. Haohui, Z. Ren, Z. Liu, A. Aberle, T. Buonassisi, I. M. Peters, *Opt. Express* **2015**, *23*; bS. E. Sofia, J. P. Mailoa, D. N. Weiss, B. J. Stanbery, T. Buonassisi, I. M. Peters, *Nature Energy* **2018**, *3*, 387-394.
- [10] M. Jaysankar, B. A. L. Raul, J. Bastos, C. Burgess, C. Weijtens, M. Creatore, T. Aernouts, Y. Kuang, R. Gehlhaar, A. Hadipour, J. Poortmans, *ACS Energy Letters* **2019**, *4*, 259-264.
- [11] aQ. Jiang, Y. Zhao, X. Zhang, X. Yang, Y. Chen, Z. Chu, Q. Ye, X. Li, Z. Yin, J. You, *Nature Photonics* **2019**, *13*, 460-466; bW. S. Yang, B.-W. Park, E. H. Jung, N. J. Jeon, Y. C. Kim, D. U. Lee, S. S. Shin, J. Seo, E. K. Kim, J. H. Noh, S. I. Seok, *Science* **2017**, *356*, 1376-1379.
- [12] aL. Gao, L. Chen, S. Huang, X. Li, G. Yang, *ACS Applied Energy Materials* **2019**, *2*, 3851-3859; bB. Wilkinson, N. L. Chang, M. A. Green, A. W. Y. Ho-Baillie, *Progress in Photovoltaics: Research and Applications* **2018**, *26*, 659-674; cM. Zhang, B. Wilkinson, Y. Liao, J. Zheng, C. F. J. Lau, J. Kim, J. Bing, M. A. Green, S. Huang, A. W.-Y. Ho-Baillie, *Joule* **2018**, *2*, 2694-2705.
- [13] E. H. Jung, N. J. Jeon, E. Y. Park, C. S. Moon, T. J. Shin, T. Y. Yang, J. H. Noh, J. Seo, *Nature* **2019**, *567*, 511-515.

- [14] A. Agresti, S. Pescetelli, A. L. Palma, A. E. Del Rio Castillo, D. Konios, G. Kakavelakis, S. Razza, L. Cinà, E. Kymakis, F. Bonaccorso, A. Di Carlo, *ACS Energy Letters* **2017**, *2*, 279-287.
- [15] A. Priyadarshi, L. J. Haur, P. Murray, D. Fu, S. Kulkarni, G. Xing, T. C. Sum, N. Mathews, S. G. Mhaisalkar, *Energy & Environmental Science* **2016**, *9*, 3687-3692.
- [16] M. Jaysankar, M. Filipic, B. Zielinski, R. Schmager, W. Song, W. Qiu, U. W. Paetzold, T. Aernouts, M. Debucquoy, R. Gehlhaar, J. Poortmans, *Energy & Environmental Science* **2018**, *11*, 1489-1498.
- [17] K.-M. Lee, K.-S. Chen, J.-R. Wu, Y.-D. Lin, S.-M. Yu, S. H. Chang, *Nanoscale* **2018**, *10*, 17699-17704.
- [18] aT. Duong, Y. Wu, H. Shen, J. Peng, X. Fu, D. Jacobs, E.-C. Wang, T. C. Kho, K. C. Fong, M. Stocks, E. Franklin, A. Blakers, N. Zin, K. McIntosh, W. Li, Y.-B. Cheng, T. P. White, K. Weber, K. Catchpole, *Advanced Energy Materials* **2017**, *7*, 1700228; bC. O. Ramirez Quiroz, Y. Shen, M. Salvador, K. Forberich, N. Schrenker, G. D. Spyropoulos, T. Heumuller, B. Wilkinson, T. Kirchartz, E. Spiecker, P. J. Verlinden, X. Zhang, M. A. Green, A. Ho-Baillie, C. J. Brabec, *Journal of Materials Chemistry A* **2018**, *6*, 3583-3592; cM. Jaysankar, W. Qiu, M. van Eerden, T. Aernouts, R. Gehlhaar, M. Debucquoy, U. W. Paetzold, J. Poortmans, *Advanced Energy Materials* **2017**, *7*, 1602807; dM. Jaysankar, B. A. L. Raul, J. Bastos, C. H. Burgess, C. Weijtens, M. Creatore, T. Aernouts, Y. Kuang, R. Gehlhaar, A. Hadipour, J. Poortmans, *ACS Energy Letters* **2018**, *4*.
- [19] aM. Saliba, T. Matsui, J.-Y. Seo, K. Domanski, J.-P. Correa-Baena, M. K. Nazeeruddin, S. M. Zakeeruddin, W. Tress, A. Abate, A. Hagfeldt, M. Gratzel, *Energy & Environmental Science* **2016**, *9*, 1989-1997; bW. Jérémie, N. Bjoern, B. Christophe, *Advanced Materials Interfaces* **2018**, *5*, 1700731.
- [20] A. Guchhait, H. A. Dewi, S. W. Leow, H. Wang, G. Han, F. B. Suhaimi, S. Mhaisalkar, L. H. Wong, N. Mathews, *ACS Energy Letters* **2017**, *2*, 807-812.
- [21] aD. Kiermasch, L. Gil-Escrig, H. J. Bolink, K. Tvingstedt, *Joule* **2019**, *3*, 16-26; bC. Tong, W. Ji, D. Li, A. Mei, Y. Hu, Y. Rong, H. Han, *Journal of Materials Chemistry A* **2019**, *7*, 10942-10948.
- [22] K. A. Bush, C. D. Bailie, Y. Chen, A. R. Bowring, W. Wang, W. Ma, T. Leijtens, F. Moghadam, M. D. McGehee, *Advanced Materials* **2016**, *28*, 3937-3943.
- [23] aM. Jaysankar, M. Filipič, B. Zielinski, R. Schmager, W. Song, W. Qiu, U. W. Paetzold, T. Aernouts, M. Debucquoy, R. Gehlhaar, J. Poortmans, *Energy & Environmental Science* **2018**, *11*, 1489-1498; bD. Zhang, M. Najafi, V. Zardetto, M. Dörenkämper, X. Zhou, S. Veenstra, L. J. Geerligs, T. Aernouts, R. Andriessen, *Solar Energy Materials and Solar Cells* **2018**, *188*, 1-5.
- [24] aE. Köhnen, M. Jošt, A. B. Morales-Vilches, P. Tockhorn, A. Al-Ashouri, B. Macco, L. Kegelmann, L. Korte, B. Rech, R. Schlatmann, B. Stannowski, S. Albrecht, *Sustainable Energy & Fuels* **2019**, *3*, 1995-2005; bL. Mazzarella, Y.-H. Lin, S. Kirner, A. B. Morales-Vilches, L. Korte, S. Albrecht, E. Crossland, B. Stannowski, C. Case, H. J. Snaith, R. Schlatmann, *Advanced Energy Materials* **2019**, *9*, 1803241; cZ. Wang, X. Zhu, S. Zuo, M. Chen, C. Zhang, C. Wang, X. Ren, Z. Yang, Z. Liu, X. Xu, Q. Chang, S. Yang, F. Meng, Z. Liu, N. Yuan, J. Ding, S. Liu, D. Yang, *Advanced Functional Materials*, *n/a*, 1908298.
- [25] X. Yan, N. Chen, F. B. Suhaimi, L. Zhang, X. Gong, X. Zhang, S. Duttagupta, *Appl. Opt.* **2019**, *58*, E1-E6.
- [26] F. J. Ramos, S. Jutteau, J. Posada, A. Bercegol, A. Rebai, T. Guillemot, R. Bodeux, N. Schneider, N. Loones, D. Ory, C. Broussillou, G. Goaer, L. Lombez, J. Rousset, *Scientific reports* **2018**, *8*, 16139-16139.
- [27] aM. Thway, T. Liu, R. Sridharan, M. Huang, X. Ren Ng, H. Arianita Dewi, H. Wang, A. Bruno, N. Mathews, S. Duttagupta, R. Arnold Stangl, S. Jin Chua, A. Aberle, F. Lin, *Small-area Passivated Contact monoPoly TM Silicon Solar Cells for Tandem Device Integration*, **2019**; bH. A. Dewi, H. Wang, J. Li, M. Thway, R. Sridharan, R. Stangl, F. Lin, A. G. Aberle, N. Mathews, A. Bruno, S. G. Mhaisalkar, *ACS Applied Materials & Interfaces* **2019**.

Table of Content

Keywords: perovskite solar cells, silicon solar cells, tandem solar cells, efficiency

*Herlina Arianita Dewi^a, Hao Wang^a, Jia Li^a, Maung Thway^{b,c}, Fen Lin^b, Armin G. Aberle^{b,c},
Nripan Mathews^{a,d,*}, Subodh Mhaisalkar^{a,d,*}, Annalisa Bruno^{a*}*

Four Terminal Perovskite on Silicon Tandem Solar Cells Optimal Measurements Schemes

Four terminals tandem measurement schemes: perovskite-silicon tandem solar cells have received an increasing interest in the photovoltaic community. In this study, effects of both perovskite and silicon solar cells active area sizes on their photovoltaic performances have been investigated. Different measurement schemes for a 4T tandem have been compared to correlate the maximum PCE potential of and the one in real operating conditions.

Supporting Information

Four Terminal Perovskite on Silicon Tandem Solar Cells Optimal Measurements Schemes

*Herlina Arianita Dewi^a, Hao Wang^a, Jia Li^a, Maung Thway^{b,c}, Fen Lin^b, Armin G. Aberle^{b,c},
Nripan Mathews^{a,d*}, Subodh Mhaisalkar^{a, d,*}, Annalisa Bruno^{a*}*

- a. Dr. H.A. Dewi, Dr H. Wang, Dr J. Li, Prof. N. Mathews, Prof. S. Mhaisalkar, Dr. A. Bruno
Energy Research Institute @ NTU (ERI@N), Nanyang Technological University,
Singapore 637553
E-mail: nripan@ntu.edu.sg; subodh@ntu.edu.sg; annalisa@ntu.edu.sg
- b. Mr. M. Thway, Dr. F. Lin, Prof. A. G. Aberle
Solar Energy Research Institute of Singapore (SERIS), National University of Singapore,
Singapore 117574
- c. Mr. M. Thway, Prof. A. G. Aberle
Department of Electrical and Computer Engineering, National University of Singapore,
Singapore 117583
- d. Prof. N. Mathews, Prof. S. Mhaisalkar
School of Materials Science & Engineering, Nanyang Technological University,
Singapore, 639798

Keywords: perovskite solar cells, silicon solar cells, tandem solar cells, measurements scheme, efficiency

Figure S1. (a) Top view FESEM of perovskite film, showing compact perovskite surface, (b) Semi-transparent PSC transparency, showing higher than 72% infrared transparency.

Figure S2. (a) Photographs of opaque PSCs fabricated on big area (top) and small area (bottom). (b) J-V curve and photovoltaic parameters of the respective opaque PSCs. Metal mask with aperture area of 0.09 cm^2 is used to define the active area

Figure S3. (a) Transparency curve of ITO and FTO substrates. (b) J-V performance of semi-transparent PSCs using commercial ITO as bottom electrode. Inset shows the schematic of perovskite solar cell.