Scaling up four-terminal bifacial tandem devices

G. Coletti[1], V. Rosca[1], L.J. Geerligs[1], A.R. Burgers[1], L. Okel[1], K. de Groot[1], N.J.J. Dekker[1], M.J. Jansen[1], M. Najafi[2], D. Zhang[2], V. Zardetto[2], I. Dogan[2], T. Aernouts[3], J. Hüpkes[4], C. Burgess[5], M. Creatore[5], R. Andriessen[2], S. Veenstra[2]

[1]TNO Energy Transition, Westerduingweg 3, 1755LE, Petten, the Netherlands

[2]TNO Energy Transition, partner in Solliance, High Tech Campus 21, 5656 AE Eindhoven, the Netherlands

[3]IMEC, partner in Solliance, Thin Film PV, Thor Park 8320, 3600 Genk, Belgium

[4]IEK5-Photovoltaics, Forschungszentrum Jülich, 52425 Jülich, Germany

[5]Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

Scientific innovation and relevance

In order to further reduce the LCOE of PV the conversion efficiency must increase beyond the practical limit of silicon technology (26% [1]). It is believed that tandem module technology, combining bottom c-Si cells with low-cost thin-film top cells, can overcome the silicon limit. Recently, bifacial glass/glass modules are gaining market share because of the increased module power output of 15-20% from the rear illumination (albedo). Therefore, the minimum efficiency target of tandem modules should consider the energy yield of bifacial c-Si modules as 'competition' and therefore aim for power output densities >30 mW/cm2. Additionally, tandem modules should demonstrate same reliability, bankability and competitive cost compared to commercial PV modules. 4T bifacial tandem modules combine the best of two worlds: tandem for best spectrum utilisation, and bifaciality for highest module power.

In this contribution we will show for the first time fully integrated bifacial and area-matched prototype bifacial tandem minimodules of 6 inch size based on technology that is scalable to large area and commercial production. To our knowledge these are the first bifacial 4T tandem mini-modules of such power density with PERC+ solar cells.

Results and conclusions

We demonstrated over 26% tandem efficiency combining a highly transparent perovskite cell (3x3 mm^2 and 17% efficiency) with a PERC+ solar cells (22% AM1.5 efficiency). At an extra rear irradiance of 20mW/m2, the bifacial bottom cell contributes an additional about 3 mW/cm2 resulting in a bifacial 4T Tandem power density of over 29 mW/cm2. Scaling up the perovskite technology, Solliance demonstrated 13.5% perovskite minimodule (100 x 100 mm2 active area) deposited on a 6 inch glass sheet. The 4T tandem device with a PERC+ cell yield 21.3% and with the MWT-SHJ cell 21.6% (see explanatory pages for data). Preliminary results from the outdoor measurements show stable performance for over 1000 hrs in at least two of the test configuration selected and early degradation onset in another. Additionally, they confirm the gain from the bifacial energy yield calculation model.

We explore the performance of 4T hybrid tandems based perovskite and bifacial c-Si solar cells. For this purpose, a 17.0 % perovskite PIN stack solar cell (3 x 3 mm^2) with a record near-infrared transmittance (average NIR transmittance of about 95%) and a 13.5% perovskite PIN stack minimodule (100x100 m2) deposited on a 6 inch glass sheet are used as top device. Both top devices are separately combined with a Metal Wrap Through Silicon HeteroJunction (MWT-SHJ) bifacial solar cell fabricated by CIC and TNO, and industrial PERC+ solar cells fabricated by Longi and AikoSolar.

Table 1 Overview of the I-V characteristics of the ST-PSC (3x3 mm2) and new PERC+ c-Si bottom cells and MWT-SHJ. A measure of the bifacial 4T tandem performance is given as STC efficiency and power density when an extra rear irradiation of 20 mW/cm2 is added. PERC+ and MWT-SHJ bifacial bottom cell efficiencies are reported as efficiency in STC and with extra rear irradiance of 20 mW/cm^2. Obviously, these values include filtering by the perovskite top cell or mini-module.

Single cell results		η [%]	**4T tandem efficiency (monofacial) [%]**	**Power density Bifi200 [mW/cm2]**
ST-PSC	Backward scan	17.3		
	Forward scan	17.0		
	Top cell (3x3 mm2) – 5min MPP tracking	**17.0**		
PERC+	Front single junction	22		
	Filtered bottom cell	9.2	**26.2**	
	Bottom cell rear	16.1		
	Filtered bottom cell front + rear 20 mW/cm2			12.4
	4T Tandem Front + rear 20 mW/cm2			**29.4**
MWT-SHJ	*Front single junction*	*22.8*		

Corresponding author: gianluca.coletti@tno.nl

Bifacial (Presented at EUPVSEC 2019)	*Filtered bottom cell*	*9.5*	*26.5*	
	Bottom cell rear	*19.1*		
	Filtered bottom cell front + rear 20 mW/cm2			*13.5*
	4T Tandem Front + rear 20 mW/cm2			*30.5*

Table 2 Overview of the I-V characteristics of the ST-PSC (100x100 mm2) and PERC+ c-Si bottom cells and MWT-SHJ (record result as reference). A measure of the bifacial 4T tandem performance is given as STC efficiency and power density when an extra rear irradiation of 20 mW/cm2 is added. PERC+ and MWT-SHJ bifacial bottom cell efficiencies are reported as efficiency in STC and with extra rear irradiance of 20 mW/cm2 *obviously these values include filtering by the perovskite top cell or mini-module.*

Mini module results	Description	η [%]	**4T tandem efficiency (monofacial) [%]**	**Power density Bifi200 [mW/cm2]**
ST-PSC	Top minimodule (100x100 mm2) – 5min MPP tracking	**13.5**		
PERC+	Front single junction	22		
	Filtered bottom cell	7.8	**21.3**	
	Bottom cell rear	16.1		
	Filtered bottom cell front + rear 20 mW/cm2			11
	4T Tandem Front + rear 20 mW/cm2			**24.5**
MWT-SHJ Bifacial	Front single junction	22.8		
	Filtered bottom cell	8.1	**21.6**	
	Bottom cell rear	19.1		
	Filtered bottom cell front + rear 20 mW/cm2			11.9
	4T Tandem Front + rear 20 mW/cm2			**25.4**

Despite the performance of the single junction silicon devices are not matched yet by the tandem stack, these first large area 4T tandem minimodules demonstrate the progress in the scalability to industrial relevant areas. Most of the loss observed in the bottom device is due to the relatively lower transparency of the scale up device in the NIR region, as the top minimodule does not implement yet the highly transparent TCOs of the single cell reported in Table I.

Four terminal tandem bifacial minimodules

For the four terminal tandem bifacial minimodules we used perovskite mini-modules fabricated on 6 inch substrates using scalable deposition methods (sputter coating, slot die coating and spatial-ALD) in combination with a laser scribed monolithic interconnection process. The 6 inch glass sheet features a fully interconnected 100x100 mm^2 perovskite minimodule, consisting of 31 monolithically interconnected cells. Next, the semi-transparent mini-modules were encapsulated with the bottom bifacial PERC+ solar cells of industrial 6 inch (M2) size. For this, an adapted lamination process had to be developed.

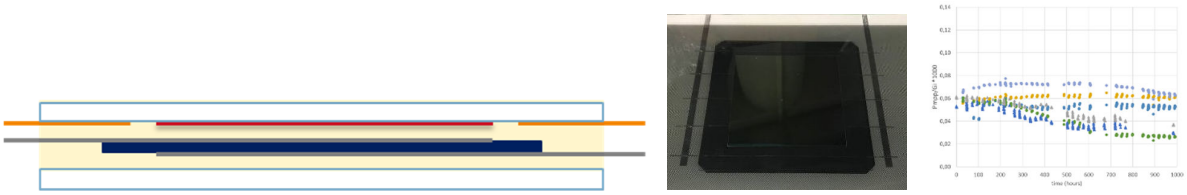

Figure 1. Left: Schematic layout of the 4T tandem minimodule. Centre: First prototype of a stack of 6 inch 4T tandem stack with a perovskite module on top of a single laminated silicon cell. Right: Preliminary outdoor data of the 2x2 cm2 Tandem minimodules

Outdoor measurements

Preliminary outdoor data from a previous prototype of perovskite minimodules with 6 monolithic interconnected cells and a PERC+ silicon bottom device are reported in Fig. 3. The data up to 1000 hrs are reported. Only the power corresponding to an irradiance between 90 and 110 mW/cm2 is reported here, to monitor the stability of the power output in constant irradiation conditions. The results correspond to two generations of minimodules build and 3 different versions of Pk fabrication. 1000 hrs stability is achieved on at least two configurations while early to late degradation onset is visible in others. At the conference extended measurement time and comparisons with the BigEye modelling will be reported.

Corresponding author: gianluca.coletti@tno.nl