Evaluation of bottom cell concepts for perovskite / crystalline silicon tandems

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Abstract

In this paper, we investigate the potential performance of 4-terminal tandem cell structures based on different types of crystalline silicon (cSi) bottom cells, with a methylammonium-lead-triiodide perovskite solar cell (PSC) on top. We evaluate industrial high-efficiency 6 inch bottom cells, including several back-contact technologies, as developed at ECN. The cell types are: n-type PERT, MWT and IBC, all with diffused boron emitter and phosphorus BSF; MWT silicon heterojunction (MWT-SHJ); and cSi solar cells with polysilicon passivating contact layers on both back *and front*. We perform approximate analysis of the feasible tandem efficiency. Since the semitransparent PSC is much smaller size than the 6 inch cSi cells, we use a nearly full-area IR longpass filter, which mimicks the presence of a PSC top cell, to measure the cSi bottom cells in tandem configuration. This procedure is calibrated through a measurement of a small size version of the n-type MWT cell in actual tandem stack with the PSC layer stack as filter. Based on the best bottom cell (a 6 inch MWT-SHJ cell of 21.9% efficiency) and our best PSC top cell of 14.6% efficiency and V_{oc}=1.03 V as measured in backward I-V trace, a "virtual" tandem cell efficiency of approx. 24.7% is obtained. The tandems based on the other cSi bottom cells mostly perform "virtually" around 24.1%. We analyse in particular the potential of using cSi cells with front and rear polysilicon passivating contact layers as bottom cells. The double sided use of polysilicon allows for very high V_{oc}. When used on a standalone cSi cell, a front polysilicon layer causes a large optical loss at short wavelengths, which however falls practically completely within the absorption band of the PSC. Therefore we observe that our preliminary double-sided polysilicon cells in tandem configuration already perform quite similar to the nMWT cell ("virtual" tandem efficiency of 23.1%). By reducing thickness and doping level of the polysilicon, tandem performance exceeding 25% should become possible.

Introduction

The perovskite solar cell (PSC) has attracted an enormous amount of attention in the past years because of its cost-effective preparation processes and high conversion efficiency. In addition to its functionality as a single-junction solar cell, the PSC is also very suitable for multi-junction applications since it has a steep and tunable optical absorption edge. We have previously reported on modeling how different types of c-Si bottom cells comparatively perform in tandem devices [1]. In the present paper we extend this, including our recent higher performance industrial cSi cells, and including our recent higher performance PSC top cell. In particular we add novel types of cSi cells with polysilicon passivating contacts on both front and rear ("poly cells"), which are analyzed both experimentally and in optical simulations.

We analyze bottom cell and top cell performance separately, and combine these to arrive at a "virtual" 4-terminal tandem efficiency. For details on the calculation of the tandem efficiencies we refer to [1]. The bottom cell analysis differs from our earlier work, in that we now measure the I-V parameters of the bottom cells on full or nearly full 6 inch area under light conditions which mimic the presence of a PSC top cell. This is achieved by the application of an optical longpass filter. Consequently, the performance of different bottom cells can be analyzed without having to scale down our cells to smaller sizes. For poly cells this is necessitated because of artefacts occurring when analyzed locally.

The poly cells are particularly interesting since, thanks to excellent contact passivation, they can achieve very high Voc. In single junction use, a polysilicon front contact results in parasitic optical loss in the UV and visible wavelengths. We investigate how much of this disadvantage is removed in tandem use, and it turns out that the use of both sides polysilicon contacted cSi cells should be very promising for hybrid tandems.

The perovskite solar cell and the experimental tandem configuration

Our semitransparent perovskite top cell is processed on small area flat glass substrates. The absorber layer is deposited by spin coating to a thickness of approximately 300 nm and is composed of methylammonium-lead-triiodide $CH_3NH_3PbI_3$ (MAPI), i.e., with a bandgap of approx. 1.6 eV. Details are described elsewhere [1, 2].To reduce reflection losses, an anti-reflection textured glass sheet is added on top of the device, and index matching liquid applied between the two glass substrates (Fig. 1).

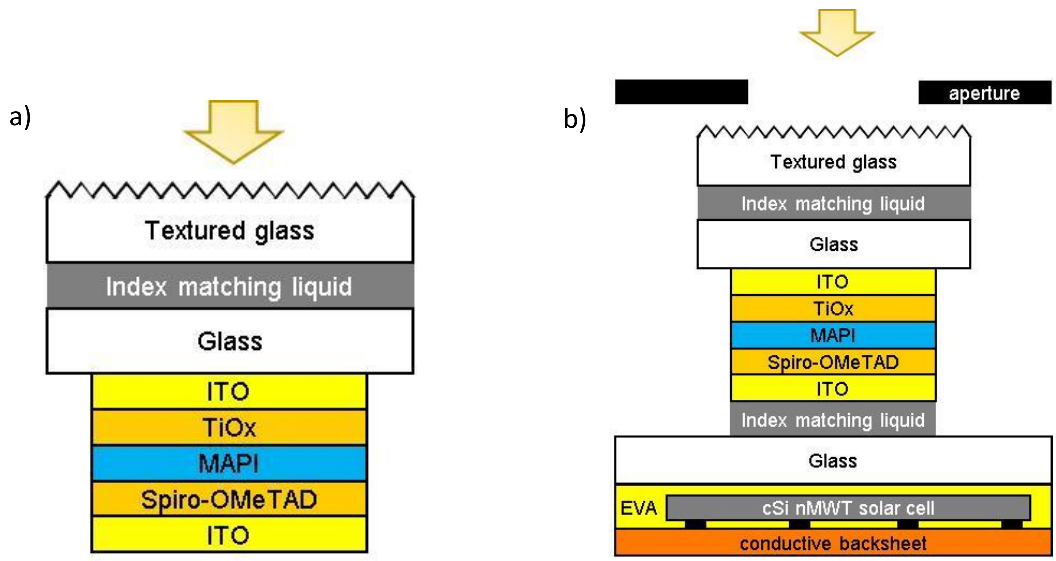

Fig. 1. a) Top cell configuration for single junction PSC measurement. b) Tandem configuration for measurement of the filtered J_{sc} of a small nMWT bottom cell. Aperture size 25×25 mm^2.

As reported previously [1], optical modeling results are in excellent correspondence with the measured reflection/transmission curves of the PSC stack, and with the measured reflection curve of the encapsulated bottom cell, leading us to have confidence in the further optical modeling results described in this paper. The cSi n-type MWT (nMWT) cell size in the tandem configuration in Fig. 1 is 39×39 mm^2, and the aperture size is 25×25 mm^2. The PSC cell area is 4×4 mm^2, but a larger area of the same layer stack is used as filter for the bottom cell measurement (Fig. 1b).

The best semitransparent PSC produced thus far at Solliance and measured according to Fig. 1a resulted in 14.6% efficiency with a V_{oc} of 1.03 V. This result was obtained in backward I-V scan, i.e., from V_{oc} to I_{sc} condition. Measuring the PSC efficiency during extended tracking at maximum power point (mpp) was not possible due to evaporation of the index matching liquid. This preliminary PSC result will be used as top cell efficiency in our tandem "virtual" efficiency evaluations below. Note that efficiency may be reduced at larger device area, e.g. due to monolithic interconnection.

The silicon solar cells

A variety of high-performance n-type cSi solar cells were evaluated. With one exception these cells are all processed at ECN on industrial 6 inch n-type Cz wafers using industry-compatible high-throughput equipment and processes. These cells are:

- n-PERT cell ("n-Pasha") [3], with front and back contact grids for tabbed interconnection, and printed fire-through (FT) fine line metallization.
- nMWT (metal-wrap-through) version of the n-Pasha cell. Processing is very similar [4].

- IBC (interdigitated back contact) cell with front floating emitter, named “Mercury” [5]. Processing is similar to n-Pasha, but this cell has a higher efficiency potential.
- MWT-silicon heterojunction (MWT-SHJ) cell 1, using amorphous silicon emitter and BSF, TCO with front silver paste and rear sputtered silver [6].
- MWT-SHJ cell 2, produced in collaboration by ECN and Choshu Industry Co. [7].
- poly cell 1, with front and rear polysilicon contacts and fire-through metallization.
- poly cell 2, with front and rear polysilicon contacts, contacted by TCO.

The poly cells were recently processed in the context of collaborative development on polysilicon passivating contacts with Tempress Systems BV [8]. Due to the preliminary nature of this cell process development, their V_{oc} is still relatively modest. However, these cells have a very high V_{oc} potential. In these preliminary tests we obtained over 700 mV implied V_{oc} on both sides textured wafer before metallization, a best J_o of 3 fA/cm^2 for n-poly on a textured surface and 6 fA/cm^2 for p-poly on polished surface. The poly cell has good thermal robustness, even allowing standard fire-through metallization.

Experimental analysis of the silicon solar cells under filtered conditions

Fig. 2 shows the spectral response of nMWT and poly cells, compared to the transmission of the perovskite stack, suggesting that the short wavelength optical loss due to the polysilicon may not be a significant concern in tandem operation.

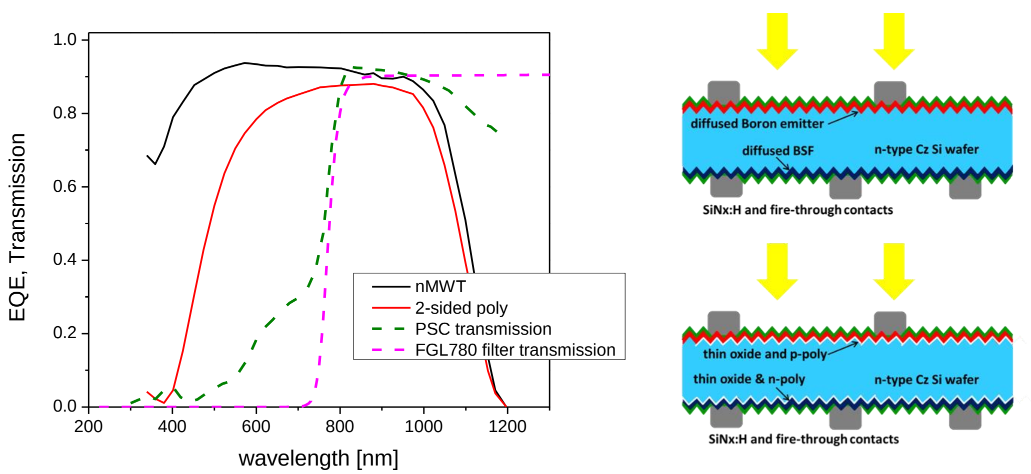

Fig. 2 .left: EQE of diffused and poly cells compared. Transmission of the PSC stack and longpass filter compared. Right: schematic cross section of the two cell types.

To evaluate bottom cell performance, often local J_{sc} or local SR is evaluated as in Fig. 1b. However, we found that the apparent performance of the poly cells is much reduced in such a locally illuminated measurement. Therefore we followed a different approach. The J_{sc} of all 6 inch cSi cells was evaluated under a longpass filter (filter response shown in Fig. 2). The illumination intensity was set based on the J_{sc}-measurement of the small nMWT cell under the PSC stack (Fig 1b), to give the same J_{sc} from the 6 inch nMWT cell. Because the longpass filter was slightly smaller than the cell size, masked measurements (210 cm^2) were used. Since masking affected V_{oc} (reduction) and FF (enhancement), V_{oc} and FF were obtained from full area measurements at the same J_{sc} under a grey filter.

The results are given in Table 1 and Fig. 3. The poly cells show a (“virtual”) gain in tandem operation of approx. 7%$_{abs}$, in contrast to the 3-3.5%$_{abs}$ gain for the other cells. This amounts to the polysilicon cells reaching nearly the same tandem performance as the other cells, despite their preliminary nature and therefore still relatively poor performance.

We emphasize that this procedure yields only approximate results. For example, because the optical properties of the various bottom cells differ, the illumination “calibration” based on the nMWT measurements is not fully reliable. Also, a change in the optics of the bottom cell can slightly change the

J_{sc} generated in the top cell. Finally, the PSC stack transmits some light around 600-700 nm which the longpass filter blocks, which could be relevant for the poly cells. This is analyzed in the next section.

Table 1 cSi bottom cells evaluated. Single junction I-V data without spectral mismatch correction. The procedure for the filtered I-V characteristics and "virtual" tandem efficiency yields only approximate results. The PSC efficiency used for the virtual tandem efficiency is based on backward I-V trace, i.e., not on an extended mpp-tracking.

	single junction AM1.5				**filtered I-V characteristics**				**virtual tandem efficiency**
	Jsc (mA/cm2)	Voc (V)	FF	eta (%)	Jsc (mA/cm2)	Voc (V)	FF	eta (%)	
n-Pasha	39.1	0.660	0.792	20.45	18.5	0.640	0.800	9.50	24.1
nMWT	40.2	0.659	0.771	20.43	18.7	0.636	0.782	9.31	23.9
IBC	41.0	0.655	0.784	21.06	18.9	0.634	0.791	9.48	24.1
MWT-SHJ (1)	35.9	0.733	0.756	19.91	16.4	0.711	0.761	8.90	23.5
MWT-SHJ (2)	39.2	0.723	0.774	21.93	18.6	0.704	0.774	10.13	24.7
poly 1, FT	32.8	0.673	0.723	15.96	17.5	0.656	0.741	8.53	23.1
poly 2, TCO	30.0*	0.682	0.754	15.45	15.8	0.664	0.763	8.01	22.6

* Jsc reduction compared to the poly 1 cell is partly due to a front grid with large metallization coverage

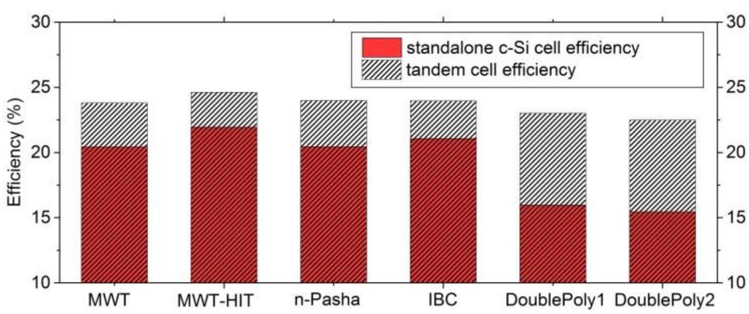

Fig. 3. Tandems based on different cSi bottom cells evaluated.

Modeling of polysilicon-passivated bottom cells in tandem use

The preliminary poly cells have thick (200 nm) and highly doped polysilicon layers. The free carrier absorption (FCA) is therefore significant as can be seen in Fig. 2 (from comparison to the nMWT EQE curve beyond 1000 nm) and Fig. 4. Thinner and lower doped layers are possible. In view of this, and because the longpass filter deviates from the real PSC transmission, we have optically modeled the expected performance of tandems for a variety of polysilicon layer thicknesses and doping levels.

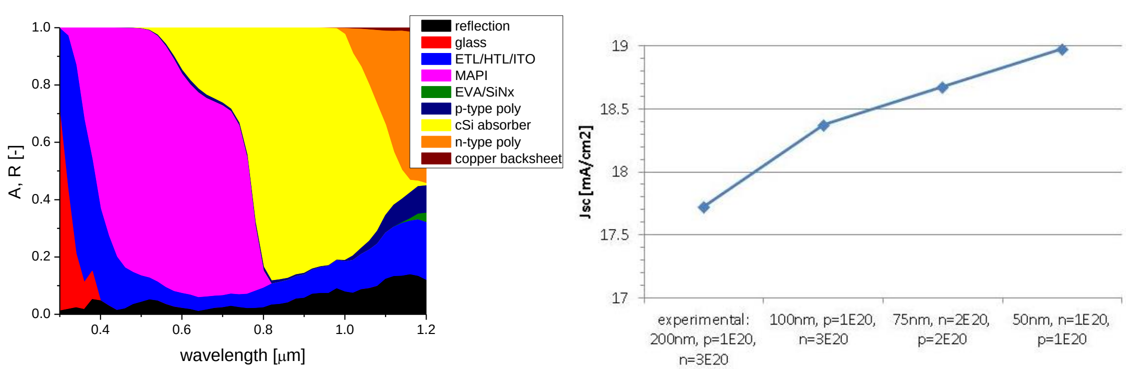

Fig. 4 .Left: optical model of the tandem based on the 2-sided poly FT cell. Right: illustration of the benefit of thinner and lower doped poly layers.

Fig. 4 shows modeling results of the experimental poly 1 cell of the previous section. The modeled absorption in the cSi corresponds to 17.7 mA/cm^2 matching well the experimental filtered J_{sc} of 17.5 mA/cm^2. The loss from the polysilicon is largely due to FCA; there is very little short wavelength loss in the front polysilicon layer (0.17 mA/cm^2). As polysilicon doping levels and thicknesses are reduced, the modeled J_{sc} increases to more than 18.5 mA/cm^2. Of course, sheet resistance of the poly layers will concurrently increase and additional conductive layers or a denser metallisation grid may be required for a good FF.

To illustrate the potential, a poly bottom cell with J_{sc}=18.7 mA/cm^2 that at the same time achieves the high V_{oc} potential of this technology, e.g. over 700 mV, would increase its bottom cell efficiency in Table 1 by 2%$_{abs}$ to 10.5%, and, assuming a FF of 80%, increase the tandem efficiency to 25.1%.

Finally, we note that we have analyzed only MAPI as the absorber in the PSC. A larger bandgap perovskite absorber may be beneficial for stability of the PSC, but may change the tandem performance. We have not looked into this yet.

Conclusion

We have evaluated perovskite/cSi tandems based on actual full 6 inch size n-type bottom cells, produced with low-cost industrial processes. We find particularly interesting and promising results for novel cells with polysilicon passivating contact layers on both sides. An approximate virtual tandem efficiency of 24.7% is found based on our best semitransparent perovskite cell (with backward I-V trace for efficiency measurement) and a 21.9% MWT-SHJ cell produced in collaboration with Choshu Industry Co. Efficiencies above 25% appear within reach, also with improved low-cost polysilicon-passivated 6 inch Cz cells.

Acknowledgements

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