MODULE INTERCONNECTION WITH ALTERNATE P- AND N-TYPE SI SOLAR CELLS

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ABSTRACT: We present a novel type of module with innovative interconnection of industrial solar cells enabling the simplification of module fabrication. The solar cells used for such interconnections are bifacial screen printed cells processed with industrial firing through PECVD SiN_x technology. Our developed cell process, using BBr_3-diffusion, can be applied on p-type as well as on n-type silicon wafers. For the p-type device the B-diffused region serves as a back surface field, for the n-type device as a front emitter. The innovative interconnection is based on the alternate interconnection of both front junction devices with the opposite base polarities. This allows not only a simpler interconnection of the cells from rear to rear and front to front (and not from rear to front) but also enables a closer assembly, if necessary.

Three bifacial glass/glass prototype modules were processed using this interconnection sequence at three different module manufacturers and tested under outdoor conditions, proving our concept to work well. The daily, averaged power output was up to 30% higher than for a module with a monofacial geometry.

Keywords: bifacial, solar cell interconnection, module technology

1 INTRODUCTION

Standard module technology is based on the interconnection of monofacial p-type silicon (Si) solar cells. Interconnections have to join the rear of one cell to the front of the neighbouring one which is not a very simple process. In order to simplify module fabrication (and for other reasons such as aesthetic aspects) some cell concepts combine both contacts on the rear of the cell [1]. These cell concepts, however, generally require more complex and complicated process steps compared to standard screen printed solar cells.

We, on the other hand, present industrially feasible bifacial solar cells for which the processing sequence is very close to that of standard screen printed solar cells using firing through SiN_x technology [2,3,4]. These cells can be used for a simplified interconnection in module fabrication. In addition, the bifacial character of the modules allows an increased power output of up to 30% in average over one day.

2 BIFACIAL SOLAR CELLS WITH FRONT JUNCTION USING P- AND N-TYPE SUBSTRATES

Bifacial solar cells are devices that allow light penetration from front and rear side. Such devices have been already under development from the early 60's and can be found in many configurations, such as double junction cells, monofacial BSF or cells with dielectric passivation [5]. Recently we have developed PERT type front emitter bifacial solar cells with industrially feasible process steps. The main advantages of our process are that i) it is applicable to thin wafers as the rear is not fully metallised, ii) the bifacial structure enables an increased power output and iii) it is applicable to p-type as well as - with slight modification - to n-type silicon substrates. The main difference from the standard screen printing process is the application of a boron (B) diffusion in an open tube furnace in combination with an open AgAl-contact, instead of a full rear side metallisation with an Al-paste for contact and BSF formation. The structures of the bifacial devices resulting from our process are depicted in Figure 1.

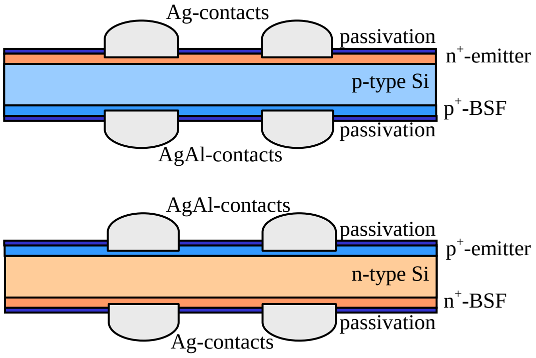

Figure 1: Bifacial front junction solar cells with opposite substrate doping.

Details on the process of p-type solar cells are given in [2,3] and on n-type process in [4]. The best results for both substrate polarities are summarised in Table I, which depicts the solar cells parameters under front illumination only. An efficiency of 16.1% was reached on a p-type mc SoG-Si substrate and 17.1% on an n-type Cz-Si substrate.

Table I: Best solar cell results for p- and n-type bifacial solar cells on (125 mm)^2 substrates.

type	substrate	FF [%]	J_{sc} [mA/cm^2]	V_{oc} [mV]	η [%]
p	multi c-Si	75.6	34.3	620	16.1 [2,3]
n	mono c-Si	76.0	36.3	620	17.1 [4]

3 INNOVATIVE CELL INTERCONNECTION

The solar cells described above

In addition to the fact that the solar cells described above can be fabricated on the two substrates of different polarity using the same processing sequence (leaving the solar cell manufacturer higher flexibility in the choice of the material) they can also be combined to simplify module fabrication. Figure 2 shows the idea of our innovative concept for cell interconnection, which is pending patent by the International Solar Energy Research Center ISC Konstanz.

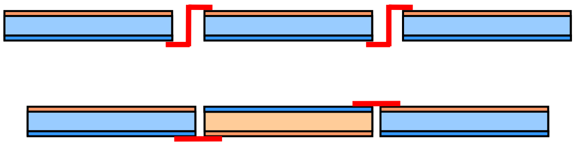

Figure 2: Interconnection of p-type solar cells in a standard module (top) and innovative alternate interconnection of p- and n-type solar cells in a pn-module (bottom).

Standard module fabrication is based on the interconnection of the opposite sides of neighbouring cells. Using alternating p- and n-type devices is a simple trick that allows direct interconnection of equivalent sides (front-to-front and back-to-back) of neighbouring cells. This concept is illustrated in the bottom part of Figure 2. With this technology it is possible to pick and place the cells on conducting paths (similar to rear contact cells) without a pre-stringing procedure, where in some cases a flip of the cell is still necessary. As the trend continues towards thinner substrates, our technology could lead to a lower breakage of cells during module fabrication. In summary, our interconnection method has the following advantages:

i) simpler interconnection procedure
ii) closer assembly of cells, if needed (e.g. for aesthetic reasons)
iii) higher yield during module fabrication.

In addition to these advantages the module, using the bifacial cells, has an increased power output as compared to standard monofacial modules as will be shown in the following.

4 PN-MODULE PROTOTYPES AND RESULTS

In order to prove the principle of our concept, three modules were produced at three different module manufacturers.

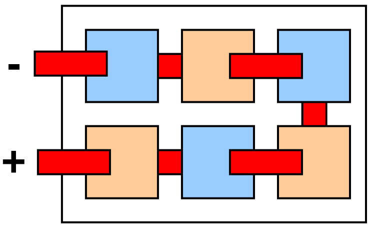

Figure 3: Scheme of alternate interconnection of p- and n-type solar cells in a 2x3 pn-module.

Figure 3 depicts the geometry of a 2 cell x 3 cell pn-module with three p-type and three n-type bifacial solar cells which was used in all three cases. The six cells are connected in an alternating way (p-n-p-n-p-n) in series from rear to rear and front to front.

We want to emphasise that the purpose of this article is not the comparison of module technologies as the cells used for module fabrications were different and some of them suffered from poor fill factor. The module fabrication at different places served to prove the principle of our concept only.

4.1. First multi c-Si solar cell module at Soltech

The first bifacial (glass/glass) pn-module prototype was fabricated at Soltech, Belgium and is depicted in Figure 4 in comparison with a “standard” p-type module fabricated at the same place with same materials.

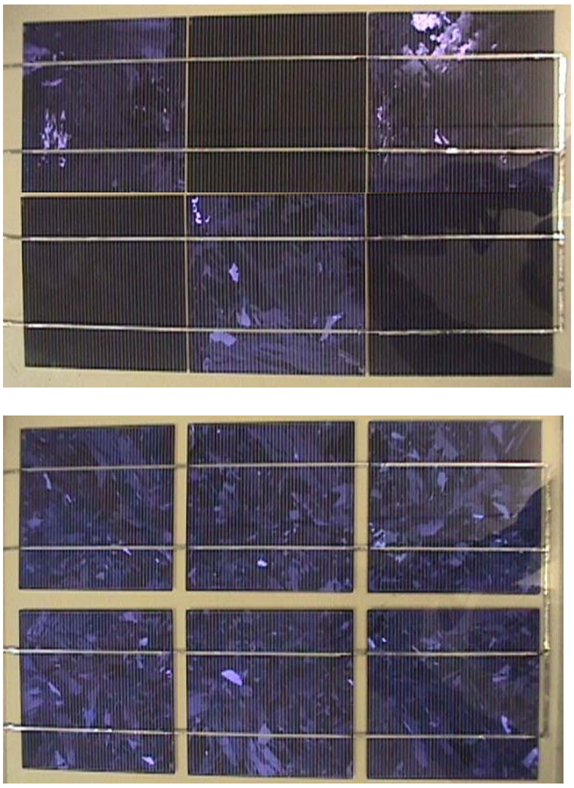

Figure 4: First bifacial (glass/glass) pn-module prototype with six (120 mm)^2 mc-Si solar cells interconnected in series (top) in comparison with a “standard” p-type module (bottom).

It is clearly visible that the cells can be assembled closer together in case of the innovative pn-type module.

Table II shows parameters for both modules (pn: yellow, standard: green) under front and rear illumination in case of the bifacial pn-module.

Table II: Parameters of the modules from Figure 4 under front (f) and rear (r) illumination.

	I_{sc} [A]	V_{oc} [V]	I_{mpp} [A]	V_{mpp} [V]	P_{mpp} [W]	η_{cell} [%]	FF [%]
f	4.5	3.6	4.2	2.8	11.7	13.5	71.5
r	2.6	3.5	2.3	3.0	6.7	7.9	73.4
f	4.7	3.7	4.5	3.0	13.4	14.2	77.1

The module parameters shown in Table II prove not only the principle of the pn-module but also show very similar current and voltage values as the “standard” module. The only difference can be observed in the fill factor (FF). On the one hand, the substrate resistivity of the cells assembled in the standard p-type module is very low (0.5 Ωcm) leading to an exceptionally high FF of 77%. On the otherhand, the main drawback of our solar cells is the low FF due to the low conductivity of AgAl paste [2,3,4]. A module made only with n-type cells led to a similar low FF of 71% [7] due to the high series resistance of the cells. This means that if the cell properties can be improved, the FF of the pn-module may then be in the range of the standard module.

In order to show the additional advantage of our glass/glass module, outdoor measurements were conducted looking at the benefit of the bifacial character. Figure 5 depicts the geometry of the measuring assembly.

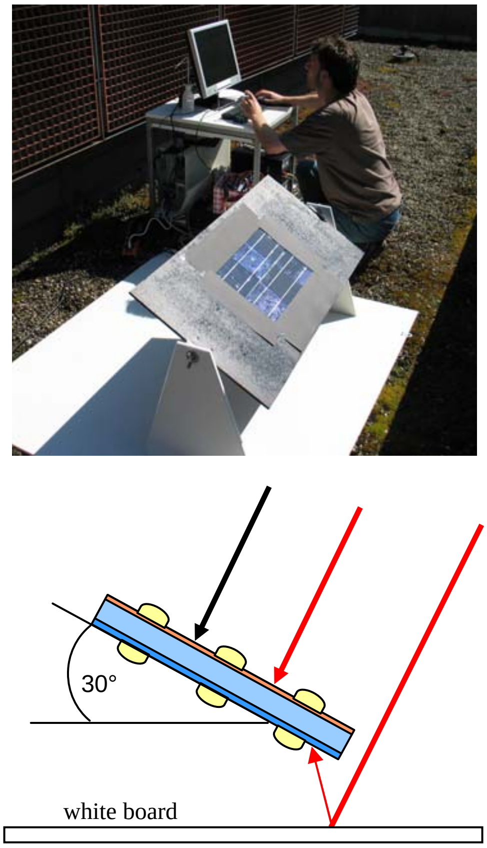

Figure 5: Photograph (top) and schematic picture (bottom) of the measuring assembly.

The mini module was embedded in a large black rack with an area of 1×0.5 m^2 simulating a larger module and its shadowing of the ground. This set-up was placed on a white board, shifted by 30° and oriented to the south. Measurements were performed during one day in August from 9am to 6:30pm in bifacial and monofacial (covered rear side) arrangement. Figure 6 summarises the results of these measurements.

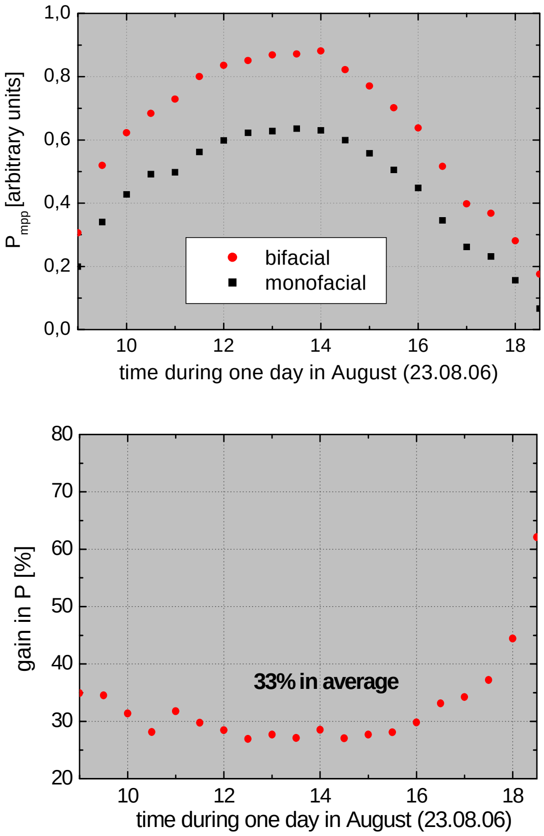

Figure 6: Power output of the module in bifacial and monofacial arrangement as a function of time during one sunny day in August (top) and the resulting gain in power (bottom) measured in Konstanz (southern Germany).

The upper picture of Figure 6 shows the power output of the module in bifacial and monofacial arrangement as a function of time during one sunny day in August and the resulting gain in power measured at the roof of UKON´s PV laboratory. The difference is clearly visible resulting in a >30% gain in efficiency averaged over the entire day.

4.2. Mono c-Si solar cell module fabricated at Isofotón

An additional module was manufactured at Isofotón using bifacial p- and n-type Cz-Si solar cells. The module is depicted below.

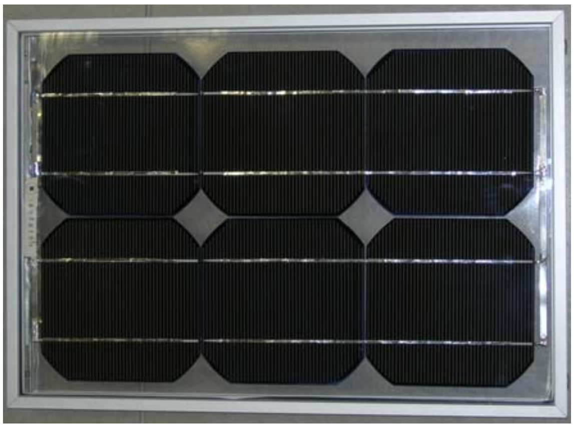

Figure 7: Bifacial pn-module prototype with six 148 cm^2 Cz-Si solar cells interconnected in series.

The parameters from flash-tester measurements are summarised in Table III and the power output from outdoor measurements at Málaga (Spain) are depicted in Figure 8.

Table III: Parameters of module from Figure 7 under front (f) and rear (r) illumination.

	I_{sc} [A]	V_{oc} [V]	I_{mpp} [A]	V_{mpp} [V]	P_{mpp} [W]	η_{cell} [%]	*FF* [%]
f	5.1	3.7	4.6	2.7	12.3	13.9	66.2
r	2.8	3.6	2.5	3.0	7.3	8.1	73.1

Similar as for the mc-Si module we see very good module parameters with the exception of the fill factors which are limited by the cell performance. The gain in power is averaged to about 15%.

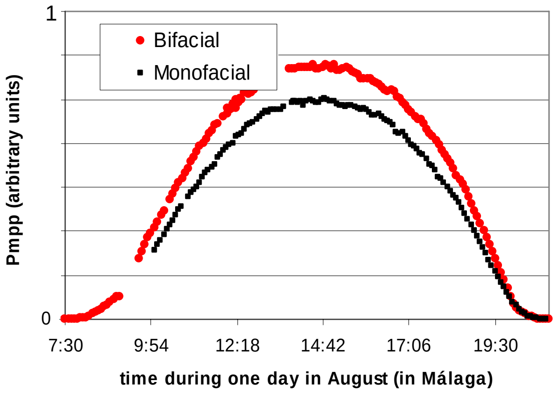

Figure 8: Power output of the Isofotón module in bifacial and monofacial arrangement as a function of time during one sunny day in August (in Málaga, Spain).

4.3. Mono c-Si solar cell module produced at Day4 Energy

The last module was processed with a very new technology at Day4 Energy [8]. The module with 6 cells without busbars is shown in Figure 9.

Figure 9: Bifacial pn-module prototype with six 148 cm^2 Cz-Si solar cells interconnected in series by Day4 technology [8].

As for the Isofotón module the parameters from flash-tester measurements are summarised in Table IV and the power output from outdoor measurements at Konstanz (southern Germany) are depicted in Figure 10.

Table IV: Parameters of module from Figure 9 under front (f) and rear (r) illumination.

	I_{sc} [A]	V_{oc} [V]	I_{mpp} [A]	V_{mpp} [V]	P_{mpp} [W]	η_{cell} [%]	*FF* [%]
f	4.9	3.6	4.5	2.9	13.1	14.8	73.3
r	3.1	3.6	2.2	3.1	6.7	7.5	61.1

A solar cell efficiency of 14.8% was reached in this module which is very close to that of the solar cells itself. The power propagation of mono- and bifacial arrangements is very similar to that of the previously discussed modules.

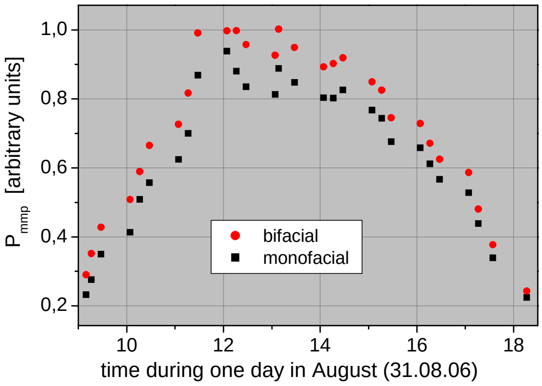

Figure 10: Power output of the Day4 module in bifacial and monofacial arrangement as a function of time during one sunny day in August (in Konstanz, Germany).

5 CONCLUSION

We have introduced an innovative concept for solar cell interconnection for simplified module fabrication and have proved the principle with different prototypes fabricated at three different module manufacturers. All modules show an excellent performance (showing a cell efficiency in module of 14.8%) except for relatively low fill factors due to the higher series resistance of solar cells used in these experiments. The increase of the fill factor e.g. by using alternative pastes is one of the foci of our further cell development [3,4]. Our concept should play an important role in future module fabrication as it has several advantages compared to standard module interconnection methods such as easier assembling, more compact packing of solar cells and higher yield during module manufacturing. In addition, the bifacial character of the glass/glass modules allows a higher power output: up to 30% depending on the installation and the surroundings of the module.

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