DEVELOPMENT AND CHARACTERISATION OF INDUSTRIAL BIFACIAL PV MODULES WITH ULTRA-THIN SCREEN-PRINTED SOLAR CELLS

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ABSTRACT: In recent years there has been a growing interest in bifacial cells and modules and several research groups have dedicated efforts to the development of these technologies. The motivation behind is the large energy production gain that can be achieved with these modules, which is in the range 5-20% depending on the bifaciality of the cells and the optimization of the system installation.
This paper summarizes the work-programme carried out at Isofotón to develop a suitable technology for the production of industrial bifacial PV modules with ultra-thin screen-printed bifacial cells. A full characterization of the prototypes fabricated in terms of energy yield and reliability is also reported.
Keywords: bifacial, module manufacturing, interconnection.

1 INTRODUCTION

In recent years there has been a growing interest in bifacial cells and modules and several research groups have dedicated efforts to the development of these technologies [1-3]. The motivation behind is the large energy production gain that can be achieved with these modules, which is in the range 5-20% depending on the bifaciality of the cells and the optimisation of the system installation.

A technology for the production of industrial bifacial PV modules with ultra-thin screen-printed bifacial cells has been developed at Isofotón. The bifacial solar cells have an internal structure with a phosphorus diffused emitter in their front side, and can present two different configurations: a local rear contact with or without a boron doped emitter. The B doping source is deposited by screen-printing and continuously diffused in a belt furnace. PECVD silicon nitride is used in both sides to create the AR coating.

This paper focuses on the module developments, related to the following production steps:

- Bifacial cell sorting
- Interconnection of ultra-thin bifacial cells (<150 µm)
- Lamination with transparent polymeric backsheet and in-laminate ultra-flat by-pass diodes.

Finally, the prototypes constructed have been characterized in terms of reliability and energy yield.

2 MODULE MANUFACTURING PROCESS

2.1 Bifacial cell sorting

The first step in the module manufacturing process is the sorting of the cells according to their electrical parameters. In standard solar simulators only the front side of the solar cell receives radiation. A bifacial cell, however, operates with radiation reaching both surfaces. A realistic measurement of a bifacial cell should in principle involve two lamps facing the front and back sides of the cell. This implies the modification of the standard cell sorting equipment.

Based on the structure of the bifacial cell, however, it is expected that the solar cell behaves linearly, ie the current measured with irradiance on both sides is equal to the current from the front only plus the current from the rear side only. This hypothesis was confirmed experimentally, by monitoring the outdoors IV curves of a bifacial module with solar radiation reaching both sides of the module (Bif) and by covering alternatively each side, with irradiance only on the front (MF) and only on the back-side (MB). As Fig. 1 shows, the module behaves linearly, which implies that the cell sorting can be done by measuring first the front side of the bifacial cell and then the rear.

A model of the bifacial cell and the interconnected circuit was developed using SPICE. Through a sensibility analysis on the module output power, it was shown that including the cell bifaciality (defined as the ratio of $I_{sc\text{-}back}$ / $I_{sc\text{-}front}$) in the sorting parameters set is sufficient for an accurate classification of the bifacial cells.

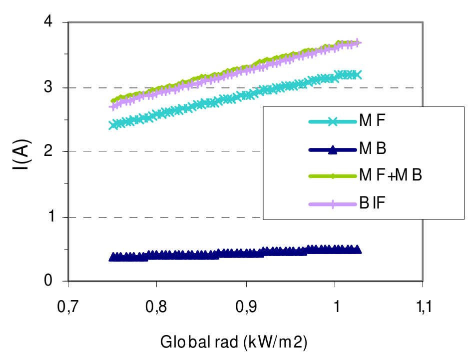

Figure 1: Short-circuit current of a bifacial module measured by covering the back-side (MF), covering the front-side (MB) and in bifacial configuration (BIF). The measured data show the linearity of the short-circuit current.

2.2 Cell interconnection

The bifacial solar cells under development are multicrystalline 125x125 mm and with thicknesses in the range 100-150 µm.

The cell interconnection was carried out using a snap-cure conductive adhesive which can lower the operating temperature down to 100ºC, with processing times comparable to soldering. This reduces drastically the stress over the cell, as the cell bow measurements illustrate. These measurements (shown in Fig. 2) are performed after attaching the interconnecting tabs only on one side of the cell, to avoid compensation of the bending forces on each side of the cell. The cells with glued tabs present always a lower bow than the soldered cells, as summarized in Table I. This effect is especially important for the thinnest cells.

Table I: One-side bow reduction of cells with glued ribbons with respect to cells with SnPbAg soldered ribbons.

Wafer thickness (µm)	Bow reduction (%)
105-115	74%
180-190	63%
210-220	37%
250-260	34%

a) b)

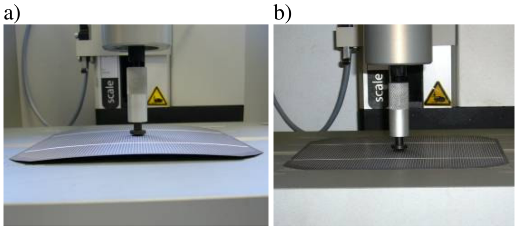

Figure 2: 110µm thick solar cells interconnected a) by SnPbAg soldering and b) with conductive adhesive.

2.3 Module lamination with ultra-flat by-pass diodes

In a bifacial module it is convenient to avoid the use of a standard junction box, as this would imply one cell less in the module to avoid undesirable shadowing effects. This in turn would increase the area per Wp in the module. One way to circumvent this problem is the use of by-pass diodes of small size, that can be laminated on the edge of the module.

A Schottky 10A diode, with only 1mm thickness and less than 5mm width, was selected as ideal candidate for this application. Module samples were laminated with these by-pass diodes, using EVA and a transparent polymeric backsheet of excellent transmittance, based on ETFE.

3 MODULE RELIABILITY

The bypass-diode thermal test described in IEC61215 2nd ed. was conducted in order to assess the thermal behaviour and long-term reliability. For a test current of 6A the calculated junction temperature of the diode was 96ºC, well below the maximum value rated by the manufacturer, and considered to be safe for the module encapsulation material.

The test current was then increased up to 10A during a period of one hour. After this the diode was still operational and there was no damage observed in the module lamination materials. The maximum temperature recorded on the module surface with an infrared camera was 165ºC, as shown in Fig. 3. From this value the calculated diode junction temperature was still below that specified by the manufacturer. These results indicate the suitability of this type of ultra-flat by-pass diodes for PV module manufacturing.

a) b)

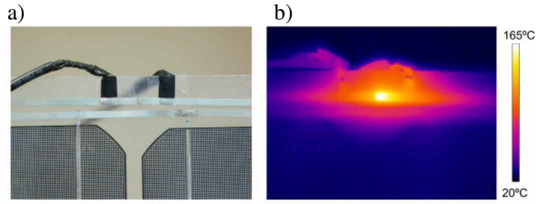

Figure 3: Visual and infrared images of in-laminate by-pass diode, after forcing a current of 10 A through the diode for a period of 1 hour.

The other new component in the module, the ETFE film, was also submitted to reliability testing. It was introduced in a UV chamber for a period of 600h, equivalent to 30kWh/m2 of UV radiation received. As shown in Fig. 4 the transmission curves measured before and after the test are almost identical. There was also no variation in the measurements after 1000h of damp-heat exposure at 85ºC and 85% relative humidity.

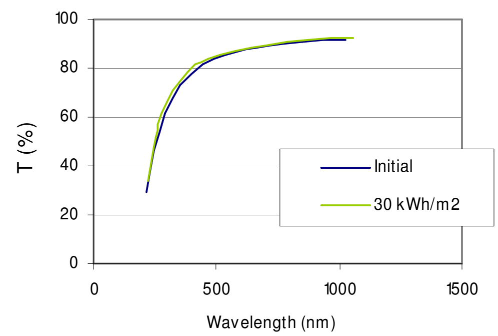

Figure 4: Transmission of ETFE backsheet before and after receiving 30kWh/m2 of UV radiation. The variations are within the measurement tolerances.

In order to test the reliability of the conductive adhesives used for the cell interconnection, several module prototypes were built with 200µm monofacial cells. The samples were submitted to accelerated degradation tests. They were initially placed in a damp-heat chamber at 85ºC with 85% relative humidity for 1200 hours, and subsequently exposed to thermal cycles of 6 hours between -40ºC and 85ºC, up to a total of 400 cycles.

Table II: Module parameters of a module prototype built with conductive adhesives and a reference module, after 1200 hours of damp-heat (DH) exposure and 200/400 thermal cycles (TC).

	CA			Reference		
	FF (%)	P (W)	ΔP (%)	FF (%)	P (W)	ΔP (%)
Initial	74,8%	80,5	0,0%	74,8%	79,5	0,0%
1200 DH	74,8%	79,4	-1,3%	74,6%	77,6	-2,4%
200 TC	72,1%	78,2	-2,8%			
400 TC	71,6%	75,6	-6,2%	73,4%	76,6	-3,7%

The module interconnected with CA satisfied the requirements of IEC61215 with a power decay under 5% for 200TC. It had however a slightly larger decay for the

400TC. This could be related to the dispensing and curing process of the adhesive which was not fully optimized at the time of manufacturing these samples. Recent testing on new samples produced in Ref. [4] have shown successful results up to 500TC.

4 OUTDOORS MONITORING

Several bifacial module prototypes were installed in an outdoor monitoring station in order to i) analyse the operating temperature of the bifacial modules compared to the monofacial, ii) optimize of the albedo conditions to maximize the output power, and iii) compare the energy yield of bifacial and monofacial modules.

4.1 Temperature monitoring of mono- and bifacial modules

It is often stated that bifacial cells operate at a lower temperature than monofacial cells with aluminium back-surface field, due to the lower infrared absorption on the open-grid rear metallization. To investigate this fact, a module was constructed with 2 strings of monofacial cells and 2 strings of bifacial cells. They were laminated in the same package to avoid temperature differences due to the materials. Internal PT100 sensors of small size were laminated on the back of 2 reference cells. The system was placed outdoors and the temperature monitored.

As shown in Fig. 5 no significant temperature difference between the two types of cells was appreciated. This is in agreement with the results of Ref. [5], where a thorough analysis shows that under atmospheric pressure, convection is the dominant heat transport mechanism and the effects of emission and absorption are negligible.

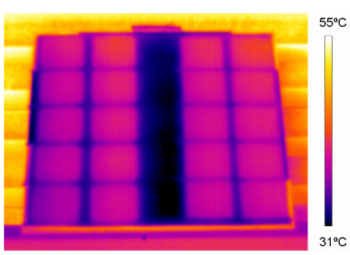

Figure 5: IR imaging of monofacial (left) and bifacial (right) modules showing no significant difference in the operating temperature.

4.2 Albedo optimization

A simple system was set up for the bifacial modules installation to optimize the radiation at the rear without including expensive optical equipment. A highly reflective white surface was placed on the ground and the wall behind the modules.

The distance to the wall was varied to optimize the amount of light able to reach the cavity and be reflected on the back of the module. For a very short distance little light can enter the cavity, whereas for long distances the reflected light does no longer reach the module rear side. There is therefore an optimum distance of the vertical wall for which the albedo is optimized. For the module prototype measured this optimum distance is 25 cm, as shown in Fig. 6. This is an example of how the albedo can be optimized in a simple way for a particular field installation, leading to a direct benefit on the electricity production of the bifacial modules.

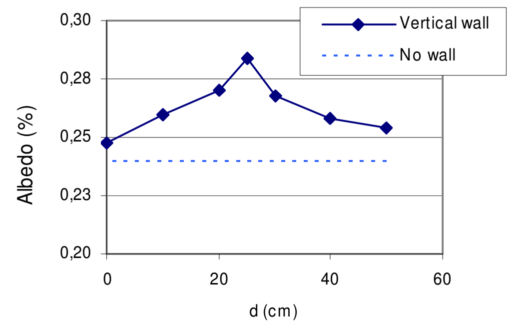

Figure 6: Example of albedo optimization by including a white vertical wall behind the module at varying distances. It is observed that for 25cm distance the albedo is increased by 20% with respect to the system with only a white ground and no vertical wall.

4.3 Energy yield measurements of mono- and bifacial modules

A bifacial module prototype was measured outdoors during a period of 4 weeks, taking the IV curve at intervals of 5 minutes. The total kWh produced was recorded and compared to a monofacial module of similar size, monitored during the same period of time. The results are shown in Table III. An increase of 13,96% in energy yield efficiency is observed for the bifacial module with respect to the monofacial, which is consistent with what was expected, for a module with a bifaciality of 60% and an average albedo of 25%. It is observed that for periods with a higher percentage of diffused to global radiation, the ratio kWh/kWp is further increased in the bifacial module with respect to the monofacial, due to the larger albedo factor.

Table III: Energy yield results of a bifacial module prototype compared to a standard monofacial module of similar size, measured during a period of 4 weeks in Málaga at an inclination of 45º facing south.

	Average daily kWh/kWp		
Week	Bifacial	Monofacial	Gain
1	5,99	5,20	15,20%
2	6,35	5,57	13,91%
3	5,34	4,77	11,79%
4	5,24	4,56	14,93%
Total	5,73	5,03	13,96%

4 SUMMARY

An industrial bifacial module with ultra-thin Si solar cells has been designed. The bifacial cells were demonstrated to behave linearly in the front and rear short circuit currents, which made possible a simple cell sorting procedure for minimization of mismatch losses.

The interconnection of the ultra-thin cells (<150µm) has been realised using a low-temperature conductive adhesive, which has shown very promising results in the reliability tests and bow reduction measurements.

To avoid the use of a junction box a by-pass diode of small size was included in the module design. The thermal behaviour of the diode was tested with success under stringent conditions.

Finally, several module prototypes were measured outdoors and compared to monofacial modules. It was shown that with a simple albedo optimization the kWh/kWp ratios can be significantly increased. For the prototypes tested the gain in this ratio is increased by 14% with respect to the monofacial modules.

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REFERENCES

[1] A. Kränzl, R. Kopecek, B. Terheiden and P. Fath, "Bifacial solar cells on multi-crystalline silicon", 15th International PVSEC, Shanghai 2005.

[2] F. Recart, G. Bueno, V. Rodríguez, I. Freire, L. Perez, R. Lago-Aurrekoetxea, "Large area thin BSF solar cells with simultaneously diffused boron and phosphorus screen printed emitters", 31st IEEE PVSC, Orlando 2005.

[3] J.C. Jimeno *et al*, "Low cost using ultra-thin bifacial cells", 22nd EUPVSEC Milan 2007.

[4] I. J. Bennett, P. C. de Jong *et al*, "Low-stress interconnection of solar cells", 22nd EUPVSEC Milan 2007.

[5] A. Hubner, A. Aberle, R. Hezel, "Temperature behavior of monofacial and bifacial silicon solar cells", 26th IEEE Photovoltaic Specialists Conference, 1997.