Ultra-Lightweight PV module design for Building Integrated Photovoltaics

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***Abstract* — Most of the existing solutions for Building Integrated PV (BIPV) are based on conventional crystalline-Silicon (c-Si) module architectures (glass-glass or glass-backsheet) exhibiting a relatively high weight (12-20 kg/m²). We are working on the development of robust and reliable lightweight solutions with a weight target of 6 kg/m². Using a composite sandwich architecture and high thermal conductivity materials, we show that it is possible to propose lightweight PV modules compliant with the IEC 61215 thermal cycling test. We further show that we are able to upscale the size of the devices from 2-cells up to 16-cell modules.**

***Index Terms* — BIPV, crystalline-silicon module, lightweight, reliability, composite sandwich structure.**

I. Introduction

Photovoltaic (PV) technology showed an impressive field deployment during the last decades, with estimations showing in 2016 a growth over 2015 of 30% of installed capacity, totaling a cumulative capacity of 295GW [1]. However, in several countries (e.g. Switzerland), the amount of land available for solar fields is extremely limited [2]. Consequently, integration of PV in buildings (Building integrated photovoltaics, BIPV) appears as a high potential solution [3]. Most of the BIPV products currently on the market are based on standard crystalline-Silicon (c-Si) modules architectures exhibiting the drawback of a high weight, due to the presence of one or several glass sheets [4], [5]. Table I shows standard module weights for c-Si photovoltaic modules. The high weight puts constraints on the building envelope and the supporting structure resulting in increased BOS (balance of system) costs and installation limitations in the case of building refurbishment.

The development of lightweight aesthetic PV elements is of high importance for large-scale deployment of BIPV, especially when renovating buildings.

TABLE I
Typical Module Weight for c-Si PV Modules

Module layup (c-Si technologies)	**Weight, w [kg/m²]**
Glass-Backsheet	12 – 16
Glass-Glass	14 – 17
Glass-Glass for BIPV	≥ 20
Proposed lightweight solution	5-7

In this study, we propose an ultra-lightweight PV module based on c-Si technology with a weight of ~6 kg/m². To reach this low weight, the module is built with a glass-free frontsheet and the backsheet is built using a composite sandwich structure, bringing the needed mechanical stiffness to the module [6]–[8]. Due to the use of different stacked materials with different thermal properties, the main challenge is to avoid early failure of the structure during a sub-set of IEC 61215-2:2016 qualification tests.

II. Materials and Methods

A. Ultra-Lightweight PV design, processing and testing

PV Module Design

Our ultra-lightweight PV module is based on the use of an innovative composite sandwich structure as a backsheet and a glass-free frontsheet (see Fig. 1). The composite sandwich materials include glass fiber reinforced polymer (GFRP) and a lightweight material with a honeycomb structure [9]. Two type of honeycomb materials are tested having a low or a high thermal conductivity.

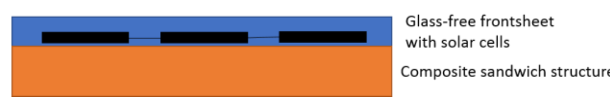

Fig. 1. Sketch of our ultra-lightweight PV module design developed for BIPV applications.

Ageing tests methods

Three replicas of 2-cells module were manufactured for each sample design defined in Table II. These modules were subjected to the Thermal Cycling (TC) test, performed according to IEC 61215-2:2016 (but with no current injection) [13]. The condition named *Reference* represent a condition manufactured with a commercially available sandwich structure.

TABLE II

SUMMARY OF MATERIALS AND PROCESSING CONDITIONS USED

Sample	Materials		Processing Conditions
	Adhesive	*Core*	*Process duration*
Reference	Thermoset liquid	Low conductivity	Short Proc + 24 h
Sample 1	Adhesive	Low conductivity	Short Proc
Sample 2	Adhesive	High conductivity	Short Proc
Sample 3	Adhesive	High conductivity	Long Proc

B. Differential scanning calorimetry (DSC)

DSC is a widely used technique in PV industry to access the degree of crosslinking of thermosetting adhesives [14]–[16]. In our case, we can use it to evaluate the quality of the sandwich after processing. The tests are performed in a Mettler Toledo DSC1 system operated in single-run mode. The samples consist of 1 mm-thick discs of 5-10mg. Thermograms are recorded under constant nitrogen flow from -20°C to 225°C at a heating rate of 10°C/min, held at 225°C for 1 min and then cooled down to -20°C at a cooling rate of 10°C/min. The enthalpy associated to the crosslinking reaction (ΔH_{cured}) is evaluated from the area of the exothermal peak between 110°C to 200°C. Knowing this parameter allows to calculate the crosslinking degree [17]:

$$X = \frac{\Delta H_{uncured} - \Delta H_{cured}}{\Delta H_{uncured}} \quad (1)$$

Where X is the degree of crosslinking and $\Delta H_{uncured}$ corresponds to the enthalpy peak of the uncured samples between 110 and 200°C.

C. Four-point bending tests

The resistance of the composite sandwich structure under bending load is investigated by means of four-points bending tests [18], [19]. This test allows us to identity three main parameters: i) bending stiffness, D (resistance of the beam against load), ii) Yield Load, P_y (limit of the elastic region) and the typical failure mode under load (input about the weakest interface and/or component of the structure) [20]. The test is performed on a Walter+Bai AG EC80-MS mechanical testing instrument in displacement control at a rate of 20μm/s, as represented in Fig. 2.

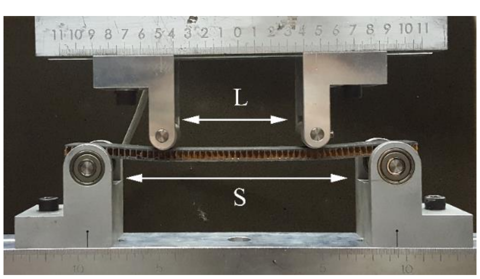

Fig. 2. Setup used to perform four-point bending tests. *S* represents the outer load span and *L* the inner load line.

We used an outer load span (S) of 190 mm and an inner load line (L) of 47.5mm. A linear variable displacement transducer (LVDT) is used to measure the load point displacement and the applied load is measure with a 10kN load cell. Coupons of 25mm width and 220mm length are prepared according to conditions presented in Table II. From this test, we obtain load point displacement (δ) versus load (P). For well-bonded cores, the in-plane shear stiffness is sufficiently large so that the overall displacement is only dominated by the bending momentum, leading to Equation 2. The sandwich beam stiffness D can thus be determined from the slope of the bending curve in the elastic regime [20].

$$D = \frac{PL^3}{48\delta} \quad (2)$$

III. RESULTS AND DISCUSSION

The 2-cells modules (see Table II) are analyzed after 70 and 200 cycles of the TC test, as shown in Fig. 3. After 200 cycles, we obtain a power loss of -1.2%, -2.4% and -1.3% for the *Reference*, *Sample 1* and *Sample 3*, respectively. Thus, according to IEC 61215-2:2016's pass/fail requirements (power drop limited to -5%), all these samples passed successfully the 200 cycles.

From the visual inspection of the 2-cells modules, we see that *Sample 1* and *Sample 2* are delaminated, suggesting that the manufacturing process did not enable a proper crosslinking. In order to evaluate the quality of the sandwich we perform DSC to quantify the degree of crosslinking.

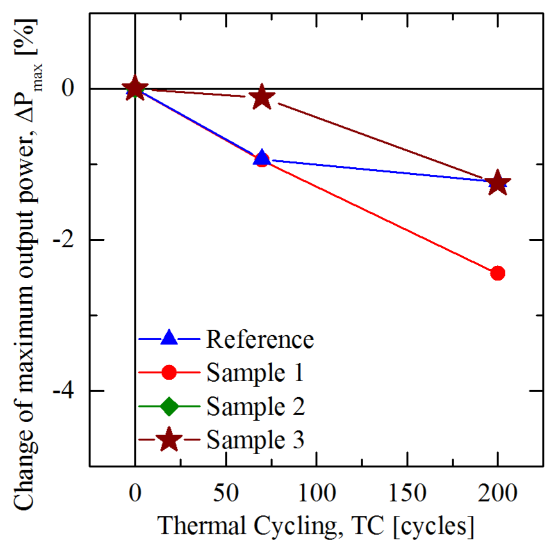

Fig. 3. Results from TC from 2-cells mini-module. Electrical properties are analyzed after 70 and 200 cycles. *Sample 2* failed after few cycles so its electrical performance could not be measured.

A. Analysis of composite sandwich structure quality

Fig. 4 shows the results obtained from the DSC measurements for not processed and processed adhesive (*Sample 1*, *2* and *3* with respective processing as shown in Table II). *Sample 1*, processed with a low conductive core, shows a higher degree of crosslinking on the adhesive close to the heating plate than the adhesive far from the heating plate (72% and 1% degree of crosslinking, respectively). The fact that we are using a low conductive core does not allow a good heat transfer through the sandwich, affecting strongly its final quality. These values explain why delamination is observed during TC. The cycles in temperature induce thermal stresses in our modules, consequently, since the quality of our adhesive is very low, the composite sandwich structure will not behave as structural component, but instead, allow our frontsheet to expand when temperature rises and contract when temperature decreases.

By substituting the low conductivity core by a high conductivity core (*Sample 2*) we observe a very small increase of the degree of crosslinking on the top skin but a big decrease on the crosslinking on the bottom skin. The use of a high conductive core allows a good heat transfer from the bottom to the top, so good that most of the heat is lost in the laminator body.

Keeping the high conductivity core but increasing the full processing time, we can increase the stiffness of the sandwich adhesive. For *Sample* 3, the DSC done in both adhesive layers show their high degree of crosslinking and no delamination is observed during TC any more.

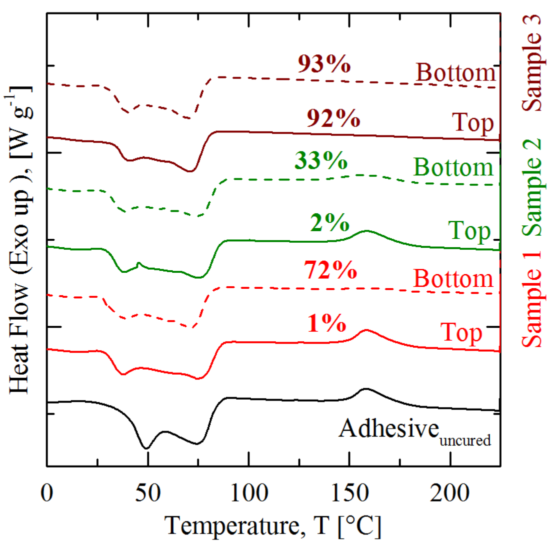

Fig. 4. DSC measurements obtained for an uncured adhesive (no processing), Sample 1, 2 and 3 (top and bottoms refers to close, respectively far from the heating plate).

B. Sandwich bending stiffness

The mechanical properties, bending stiffness and yield load obtained for the different composite sandwich structures are represented in Fig. 5. We can see that the *Reference* condition shows very good results: its bending stiffness is 14.9 N.m^2 and the yield load of about 356.8 N. Its excellent mechanical properties make this sandwich ideal for applications where high stiffness is needed. However, from the manufacturing point of view, this adhesive does not suit the requirements within PV industry, due to the too long manufacturing process. *Sample 1* shows a bending stiffness very low (8.5 N.m^2) and a typical failure mode of skin debond. This failure mode is typical on sandwiches where adhesive does not have enough stiffness and thus cannot transfer the stress properly. *Sample 2* presents even lower bending stiffness and lower yield load due to the very low crosslinking degree as explained in the previous section. From all samples, *Sample 3* is the best candidate, where higher values for bending stiffness are obtained. We found that a bending stiffness of 9.6 N.m^2 is enough to pass the TC test without delamination nor bending of the composite sandwich structure. From all these results, we decide to upscale the solution of *Sample 3*.

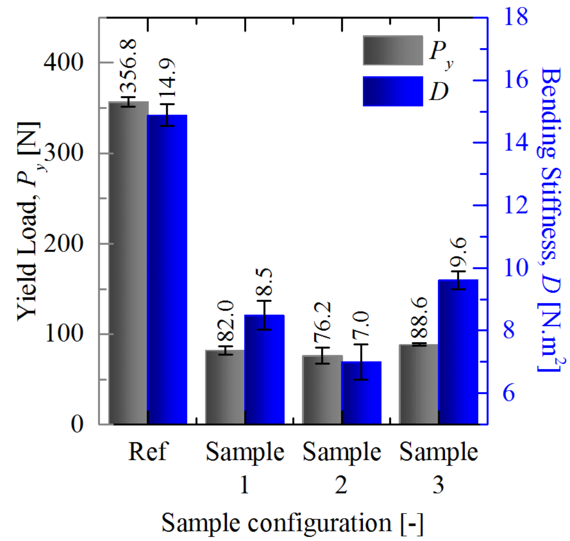

Fig. 5. Bending stiffness of all samples obtained from four-point bending tests.

IV. Upscaling: From Mini- To Medium-Area Modules

In the previous sections, we showed that a high conductivity core and a longer manufacturing process are needed to develop a lightweight module that has good mechanical properties, without bending nor delamination. We upscale this solution to a medium-area module (16-cells) and we test it under TC according to IEC 61215-2:2016 [13] (with current injection). We produced a set of three samples for this test with the size of 810 mm x 810mm. Before introducing the modules in TC we performed an electrical characterization (IV test), the wet leakage current test and the electroluminescence (EL) to analyze the initial state of the solar cells. Visual inspection (VIS) is also performed. Fig. 7 represents module power loss and fill factor loss during TC. We observed a power loss of -2.4% and a loss in fill factor of about -2.2%. These degradation rates are below the -5% pass/fail criteria present at the IEC qualification tests. Moreover, from Electroluminescence (EL) images and VIS we observe that no major change appears after the test (Fig. 7).

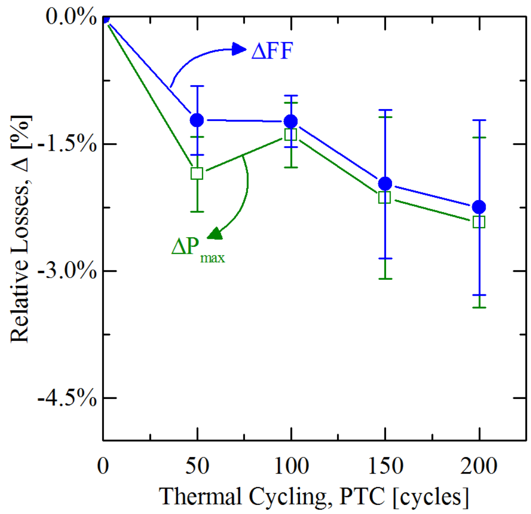

Fig. 6. Relative power and FF losses after TC with current injection of medium-area modules. Electrical properties are analyzed after 50, 100, 150 and 200 cycles.

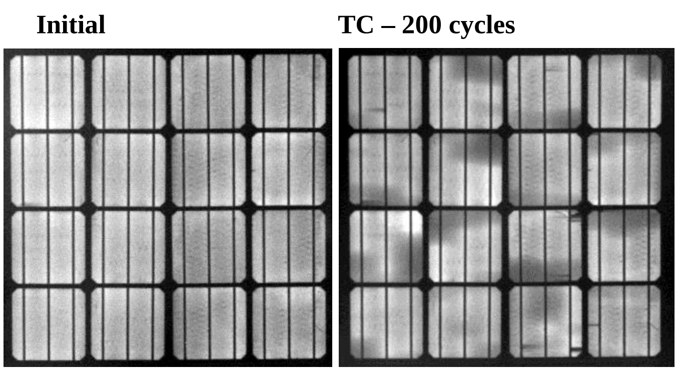

Fig. 7. EL images of one module tested under TC before and after 200 cycles.

The wet leakage test performed with our medium-area modules show that the insulation of our modules under wet operation conditions is very good, showing an insulation resistance higher than the pass/fail criterion of 40MΩ·m^2. The modules are being subjected to TC testing for an extended number of cycles.

With the aim of designing a BIPV product able to pass IEC certification, we are subjecting our test devices to a set of additional tests such as Damp-Heat, Hail, Mechanical Load tests within other tests. The feedback from these tests are then used to optimize the design and manufacturing process of our devices.

VI. Conclusion

In this study, we propose a lightweight PV module with a weight of 6 kg/m^2 for BIPV (and other) applications. The module is based on a composite backsheet and a glass-free frontsheet. We show that due to the sandwich architecture and the presence of a honeycomb-structured core, the manufacture process and the core thermal conductivity must be adjusted to enable high quality sandwich adhesive after processing. This solution is currently being up-scaled from 2-cells modules to 16-cells modules. The preliminary results obtained after thermal cycling (with power injection) are promising with only -2.4% power loss after 200 cycles and no sign of delamination nor bending. Other modules are currently being tested under different ageing tests to evaluate the influence of humidity, load or hail.

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