SINGLE-STEP LAMINATED FULL-SIZE PV MODULES MADE WITH BACK-CONTACTED MC-SI CELLS AND CONDUCTIVE ADHESIVES

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ABSTRACT: An alternative way for producing PV modules is presented. These modules are equipped with back-contacted cells connected to an interconnection foil by means of electrically conductive adhesives. The interconnection foil is a modification of standard back-sheet foil. The conductive adhesive is cured together with the EVA encapsulant, which implies a single-shot interconnection and lamination cycle. The savings in labor, reduction of machine equipment and a higher module efficiency lead to a reduction of the €/Wp price. Measurements show that modules can be produced with a higher power output when compared to modules using soldered standard cells. Outdoor test results show the viability of the concept.

1 INTRODUCTION

The continuous drive to reducing the cost level of PV modules leads to larger and thinner solar cells. Increasing the wafer area from 156 cm^2 to 225 cm^2 results in a 44% increase of the cell current. This current can be led away without significant fill-factor losses only if thick copper ribbon is used. However, it is foreseen that the first 400 cm^2 cells will be market introduced this year. This implies yet another 78% increase of cell current (relative to 225 cm2 cells). In that case two busbars will no longer be adequate. Furthermore, the ribbon thickness must increase significantly. The drawback of thick ribbon is that it is difficult to solder without introducing large stresses into the solar cell which leads to cell warping and possible breakage. The problem becomes even worse when the cell thickness decreases, and when PV industry has to comply with lead-free legislation. Affordable solder alternatives, e.g., Sn96.5Ag3.5 instead of Pb40Sn60, cause a temperature increase of at least 40ºC. This implies that even more thermo-mechanical stresses will be introduced into the thin and fragile cells.

ECN has introduced a new module concept, the Pin-Up Module (PUM), as a solution to these projected problems [1]. The current PUM cell is a back-contacted solar cell in which the interconnection to cell strings takes place during the lamination cycle, resulting in a single-shot interconnection and lamination cycle. The temperatures at which the connections are established are identical to the lamination temperature of approximately 150ºC. The interconnection between cells is no longer established by ribbon, but by an interconnection foil. The standard back sheet foil can be adapted for that purpose. An electrically conductive adhesive that is cured during the lamination cycle establishes the connection between the PUM cells and the interconnection foil.

In this paper we discuss the following subjects:

- the manufacturing of 225 cm^2 PUM cells with 15.7% efficiency,
- the manufacturing of the interconnection foil,
- the behaviour of conductive adhesives, and
- the test results of a manufactured full-size (36-cells) module.

2 PUM CELL MANUFACTURING

A PUM cell consists of a unit-cell design that is repeated over the total cell area. This means that increasing the size of the PUM cells does not lead to efficiency losses when compared to standard cells. Standard cells, using two busbars to collect the current, suffer from an increase of series resistance when the cell dimensions increase. For PUM cells, this is not the case because the unit-cell dimensions determine the series resistance. When connecting cells together, this advantage increases even more because PUM does not need thick ribbon for low series resistance. Thin and wide interconnection material can be used instead. The interconnection of cells does not affect the front-side coverage of the PUM cell, which is only 5.3%. Furthermore, PUM cells can be packed more densely in a module, because there is virtually no space needed between consecutive PUM cells. In our modules we keep a distance of only 1mm between the PUM cells. The combinational effect is that a 36-cells module consisting of 225 cm^2 cells could produce up to 10% more relative output power than an identical module using standard cells.

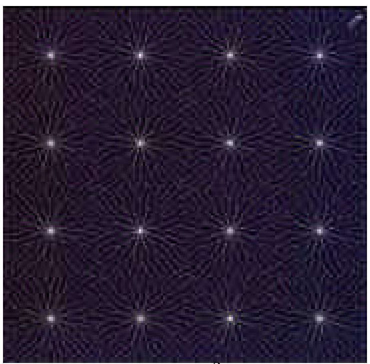

Figure 1: Photograph of a 225 cm^2 PUM cell.

3 PUM SOLAR CELL RESULTS

The processing of PUM cells is not very different from standard cell processing. As-cut wafers require an initial laser drilling of 16 holes (225 cm^2 cells). At ECN we run an in-line process that includes successively a combined saw-damage removal and texturization step with acidic acid, phosphorous emitter diffusion, SiN_x PECVD and finally the printing and firing steps of the front side and rear-side metallisation. After the phosphor diffusion, edge isolation is accompanied by an additional emitter isolation. This is required to remove the shunt paths at the rear of the PUM cell. Therefore, rings are laser scribed around each of the 16 holes on the rear side of the wafer.

Over the last year we focused on improving the emitter process to increase the cell efficiency and to improve the shunt resistance. A series of 157 PUM cells were processed on silicon material with a thickness of 330µm. This material is from the same supplier and from comparable quality when compared to the material used for the production of PUM cells in 2003 [2].

The fill factor is practically independent of shunt resistance when Rsh>7Ω for 225 cm^2 cells. In 2003, only 34% of the PUM cells had a shunt resistance beyond. This has significantly improved to 87% of the 2004 group of PUM cells. It was found that the doping in the laser drilled holes was hindered because the phosphorous acid had difficulties to flow into the holes. Therefore, the emitter metallisation can easily be fired all the way through the emitter into the base region. This obviously leads to shunting. This problem was reduced by manually injecting phosphorous acid into the holes just before feeding the wafers into the diffusion belt oven. POCl3 emitter diffusion might not show this problem because the POCl3 gass will penetrate more easily into the holes.

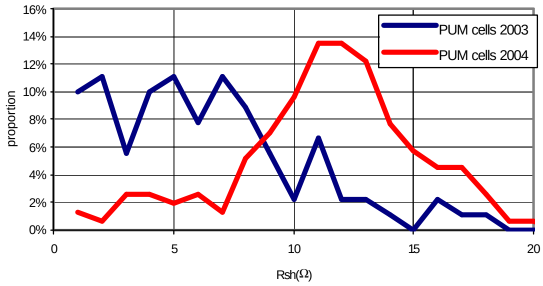

Figure 2: Shunt resistance distribution of 225 cm^2 PUM cells with 330µm thickness (bin size 1Ω).

The average cell efficiencies are in the order of 15.2% which is an improvement of 1.6% absolute when compared to results presented last year [2]. The top cell efficiency improved by 1.2%. Improvements are entirely attributed to improvements of the emitter processing.

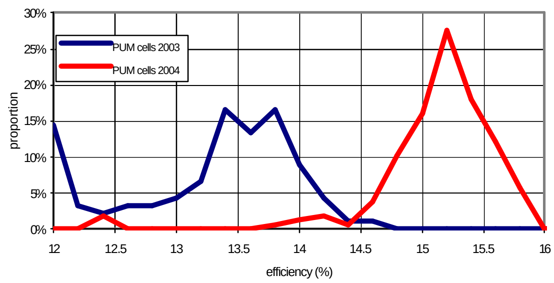

Figure 3: Efficiency distribution of 225 cm^2 PUM cells in 2003 and 2004 (bin size 0.2%).

Table 1: Comparison of average (best 36) cell and top cell results for 330µm PUM cells in 2003 and 2004.

	Jsc (mA/cm^2)	V_{oc} (mV)	FF (%)	eta (%)
best 36 2004	33.5	613	75.6	15.5
best 36 2003	31.3	597	73.7	13.8
top cell 2004	34.0	618	76.6	15.7
top cell 2003	32.1	603	74.9	14.5

4 INTERCONNECTION FOIL

The interconnection foil is made of the same materials present in standard back-sheet foils. However, the order of layers has been changed into PVF-PET-aluminium because we will use the aluminium as an interconnection layer. This requires the aluminium to be the top layer, which can then be patterned by etching. Such techniques are widely applied in the electronics industry.

Figure 4: Interconnection foil design for 36 cells 225 cm^2 PUM module. The foil dimensions are 145x65 cm^2.

The foil pattern is shown in Figure 4. The foil pattern has been optimised for minimum electrical resistance. The design of the foil and the rear side of the PUM cell are mutually dependent. The PUM cell must have connection spots in such a way that a single cell design can be placed anywhere on the foil, while still resulting in a series connection. At the corner sections of the foil (top and bottom), the foil design must be such that the foil patterning goes around the corner without needing to rotate the PUM cells. A rear side design PUM cell design that meets these requirements is shown in Figure 5.

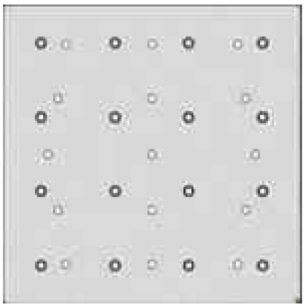

Figure 5: Photograph of the rear side of a 225 cm^2 PUM cell.

The patterned foil cannot be used directly to interconnect PUM cells because the aluminium will be oxidised. This hinders the formation of a good electrical connection. Therefore, the aluminium requires post-treatment to create an anti-corrosion layer in a comparable way as is done in the electronics PCB industry.

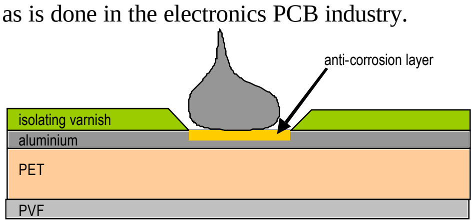

Figure 6: Overview of the layers in a back-sheet foil, and how it is modified into an interconnection foil.

The processing steps for the interconnection foil using aluminium are then as follows: First, etch resist is printed on the aluminium. Next, the aluminium is etched away to realise the interconnection pattern. Then, the etch resist is removed and a layer of isolating varnish is printed over the complete foil except for the interconnection spots. This is identical to the anti-solder mask. Next, the interconnection spots are plated with the anti-corrosion layer. The isolation varnish then has the function of masking the foil.

The isolation varnish has additional functions. First, short-circuiting will be prevented between the foil (emitter contact) and the aluminium rear side of the PUM cell (base region). Second, it acts as a UV blocker for the PET layer. Some parts of the PET layer are not covered by PUM cells and become sensitive to UV exposure.

5 CONDUCTIVE ADHESIVES

The selection of a conductive adhesive is not only determined by the electrical and mechanical properties after curing, but also depends on the curing characteristics [3].

The demand for extremely high electrical conductance limits the choice of adhesives to silver-filled epoxies. The amount of silver in the conductive adhesives generally amounts to 70-75% of its weight. This corresponds to approximately 25-30% of its volume. Typical resistivities $\rho_{adhesive}$ of less than 1mΩ-cm are reported by the adhesive manufacturers. For PUM cells, the resistance R_c per contact depends on the contact diameter d_c and the EVA thickness d_{EVA}, according to:

$$R_c = \rho_{adhesive} \cdot \frac{d_{EVA}}{\frac{1}{4}\pi d_c^2}$$

For a contact area of 3mm in diameter and EVA thickness of 200µm, contact resistances R_c can easily be kept below 1mΩ.

The mechanical strength of the conductive adhesives is usually specified in shear strength, and is a function of the size and materials involved during test. Typical strengths as reported by the adhesive manufacturers are in the order of 10MPa. We carried out FEM analysis on a 4x9 PV module by looking at the shear stresses working on an adhesive interconnection spot.

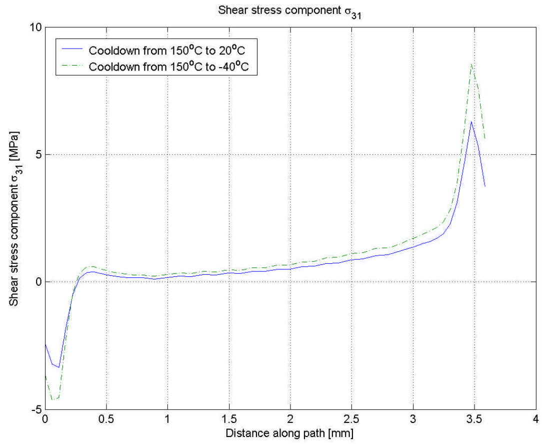

Figure 7: Shear stress FEM analysis on an adhesive interconnection spot in a 4x9 module.

Figure 7 shows the simulation results for a spot size of 3.6mm in diameter, and a height of 200µm. It appears that the stresses are hardly dependent on the location of the connection spot in the module. The stresses are determined by the local material conditions, i.e., the differences in thermal expansion coefficient between the interconnection foil, EVA, adhesive and solar cell. In this simulation, the expected shear stresses come close to what the adhesives can handle. This may result in tearing of the adhesive from the interconnection foil or from the solar cell contact areas. Increasing the EVA thickness reduces the shear stress problem.

The adhesives achieve their full strength only after complete curing. The curing process causes shrinkage of the epoxy compound which causes the silver particles to touch. Then, the adhesive becomes isotropically conductive. To select the proper adhesive, we tried to match the curing behaviour with the temperature profile during lamination. The mechanical strength of the adhesive, while curing, is determined by DMA (dynamical mechanical analysis) testing as a function of the measured temperature profile.

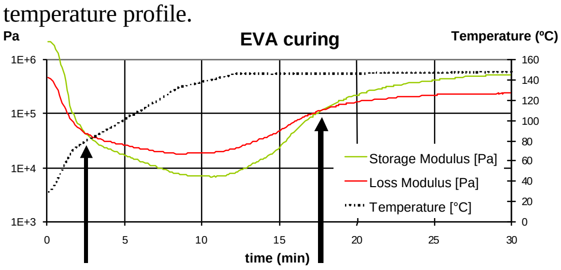

Figure 8: DMA test of EVA under lamination-cycle temperature conditions. The arrows indicate solid-to-fluid and fluid-to-solid transitions.

From Figure 8 it can be seen that EVA changes from solid to a fluid at 80ºC, which is marked by an arrow at 2.5 minutes. The temperature profile is shown with the dashed line (right-hand axis). The EVA cross-linking starts when the temperature goes beyond 130ºC (10 minutes). At around 18 minutes, the EVA becomes solid again. The lamination is considered to be completed after 30 minutes as the EVA has completed it reaction.

Figure 9 shows the DMA test on a commercial available conductive adhesive. These results are representative for silver-filled epoxies. The adhesive achieves reactivity (beginning of cross-linking) after 5 minutes, and can considered to be completely cured 12-13 minutes after the starting point of the lamination cycle.

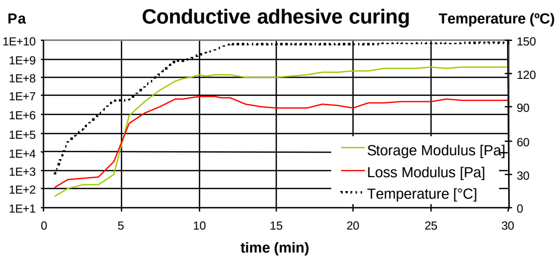

Figure 9: DMA analysis results on commercial available adhesive.

Unfortunately, these results do not fit well in the lamination cycle. This is shown in Figure 10, which depicts the timing of the different activities during the lamination cycle. It takes 5 minutes to evacuate the air from the laminator. Subsequently, the membrane is lowered to press the module materials together. For good mechanical contact, both EVA and adhesive should be in a fluid and non-reactive phase, as indicated in the figure. However, the epoxy-based adhesives cure too fast (Figure 9) which results in bad connections. Consequently, each adhesive dot becomes visible as a protuberance in the interconnection foil.

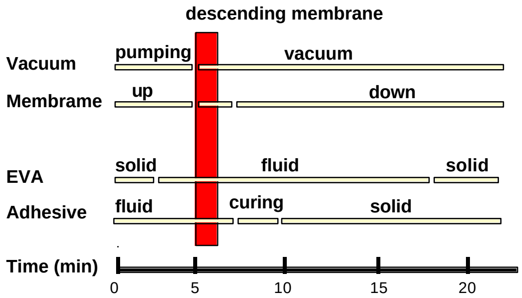

Figure 10: Lamination processing sequence versus time.

A solution to this problem is to increase the evacuating speed although it is limited to the EVA to become fluid. There is an additional risk of breaking the solar cells because the glass temperature requires time to fully warm up. Therefore, the best solution is to use adhesives that contain reaction inhibitors. Such adhesives can be custom made.

6 PUM MODULE FIELD TESTING

At the time of manufacturing 36-cell PUM modules, customised adhesives were not available yet. We found a work-around by using a thick silicone sheet in between the glass plate and laminator to slow down the temperature profile in the EVA and adhesive. This causes a delay to the melting of the EVA and to the point of reactivity of the adhesive. The interconnection foil of such manufactured modules were visually flat, and the corresponding modules worked properly.

Two tests were conducted to the PUM modules: an outdoor test, and a successive temperature cycling test. From earlier work [4], we expected the temperature cycling to be much more critical than damp-heat testing. After lamination, the PUM module produced 116.1Wp. The module was successively placed one month outside during august 2003. Then, the performance was improved to 118.6Wp, which may have been caused by additional curing of the adhesive. The module was subjected to a 200 cycle test from -40 to +85ºC. This caused the module to degrade to 100.8Wp. The extrapolated series resistance of the module increased from 4.8 to 14.8mΩ per cell, while other parameters (Jsc, Voc, Rsh) were not affected at all. Closer analysis of the glued interconnections revealed that the interconnections were mechanically overstressed at -40ºC. The large differences between thermal expansion coefficients of aluminium, PET, silicon, adhesive and EVA causes the adhesive to peel off from the interconnection foil. It appeared that the surface of the anti-corrosion layer was too smooth. Furthermore, the adapted curing profile impeded the mechanical strength of the bond. Both problems are solvable. Therefore, we expect to obtain better results from adhesives using reaction inhibitors.

7 CONCLUSIONS

A novel method for contacting and laminating back-contacted solar cells has been presented. The functions of tabbing and stringing are replaced by an interconnection foil that acts as the back-sheet foil at the same time. The back-contacted solar cells are electrically connected to this interconnection foil by using conductive adhesives. The curing profile of the adhesive must be tuned to the lamination cycle. If tuned properly, the mechanical strength of the adhesive is large enough to handle the mechanical stresses seen at the interconnection joints during temperature cycling.

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