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WORLD FIRST 17% EFFICIENT MULTI-CRYSTALLINE SILICON MODULE

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ABSTRACT

The overall demand in reducing the cost of electricity from solar energy has driven the cost of solar modules down. ECN developed an innovative module technology to enable this cost reduction requirement. The back-contact solar module concept caters specifically for high-efficiency solar cell types. It combines advanced module manufacturing design and process with emphasis on manufacturability and performance to provide an effective route toward the reduction of cost-performance ratio of crystalline silicon module. This paper discusses the recent achievement in the delivery of the world's first 17% efficient multi-crystalline silicon module by utilizing the back-contact module concept, and the corresponding optimizations that resulted in this number.

Keywords: metallization-wrap through, back-contact, high efficiency module

INTRODUCTION

For electricity generation through solar energy to be commercially attractive, it has to reach a point at which photovoltaic electricity is equal to or cheaper than conventional grid power. This grid parity can be achieved by reducing the manufacturing costs, by increasing conversion efficiencies and/or by improving the lifetime of solar modules.

One way of driving down the cost of modules is by reducing the cost of materials used. Approximately two-third of the cost of crystalline silicon modules comes from the solar cells. This portion in turns consists one-third of the silicon material cost. Therefore, an obvious approach to reduce cost is to use less silicon and thus thinner wafer in the manufacturing of the solar cells. Thinner wafers are more fragile and require different approach in cell and module processing to minimize losses due to breakage and stresses during fabrication. In addition to less silicon usage, the selection of materials used in the module construction can further decrease the overall cost of solar panels. However, any changes require extensive material testing and recertification to ensure that the new module design still fulfill the product warranty; at present PV modules are typically sold with 20 year warranty or beyond.

The second module cost reduction approach is to employ cells with greater output performance in the module construction. This calls increasing the cell efficiencies and/or minimizing the output loss experienced when cells are assembled into modules. The existing multi-crystalline silicon solar cells have metal structures on both sides to form electrical terminals to drain the current off. The cells are subsequently interconnected into strings by metal ribbons to be assembled into modules. By changing the way the current collection paths are formed on cell and module levels, it is possible to increase cell output while maintaining a minimal cell-to-module conversion loss.

ECN developed a Back-Contact module technology to assemble Metallization-Wrap Through (MWT) solar cells into modules (Figure 1) [1][2][3].

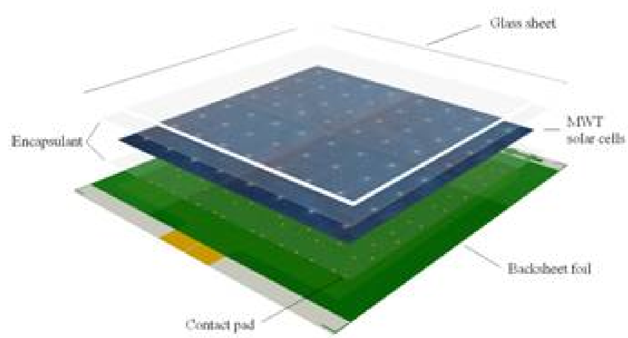

Figure 1 Schematic overview of ECN Back-Contact Solar module concept used with Metallization-Wrap Through solar cells.

Figure 2 Eurotron back-contact module assembly pilot line at ECN module technology laboratory.

The module assembly line was developed in collaboration with Eurotron BV (Figure 2). In the back-contact modules, the current generated by the solar cells is drained through 16 holes to the back of the cells. The front-side metallization pattern has been optimized to minimize shading and resistance losses; while the rear-side consists of a matrix of front and rear-side contacts. The front-side metal coverage is optimized for current collection and is typically 2% less in comparison to conventional H-pattern cells. Furthermore, resistive losses due to front-side metallization are also smaller in comparison with conventional solar cells because the effective finger length is smaller.

In back-contact modules, tabs are replaced by a conductive foil. The foil is similar to a standard Tedlar-PET-Tedlar back-sheet foil with an inner layer of a metal sheet. The metal sheet is patterned to match the contact points on the rear of the MWT cell. With the utilization of the conductive foil, busbars are no longer necessary and the metal layer can be designed much wider to accommodate more current flow. The absence of tabs in additions allows the cells to be placed closer together, increasing the packing density of the modules to ~99%. The cells are interconnected to the foils with a conductive adhesive. The lower processing temperature of the adhesive, as compared to soldering, results in a lower residual stress after cooling to room temperature. This gives a low-stress interconnection cured at of low temperature making it suitable for very thin cells. Conductive adhesives also have the advantage over traditional solders of being lead-free.

These advantages combine to minimize the loss from cell-to-module, leading to a relative increase of 4-5% in output power when compared to modules made with H-pattern cells based on the same cell processing. Several side-by-side comparisons on neighboring wafers, cells and modules have been performed [4][5] where it is consistently shown that back-contact modules produce 2% more output current and module fill factors are 3% higher than modules fabricated with H-pattern cells.

The average MWT cells efficiency demonstrated with ECN cell process established in 2006 was 15.5% [1]. In 2009, optimization works were carried out at the cell and module level to further boost the cell and module outputs. The aim of this paper is to explain the achievement obtained at the end of 2009 - an increase of more than 2% absolute efficiency from 2006 was achieved, delivering cells with average efficiency of 17.8% and the world's first multi-crystalline silicon module with an aperture area efficiency of 17.0%.

APPROACH

In this work, 160µm multi-crystalline p-type silicon wafers were used to fabricate the MWT solar cells. The wafers material was optimized to deliver high-quality wafers. They were supplied by REC Wafer.

The MWT cells were fabricated by ECN and they incorporated a number of improvements in the texturization, emitter formation and metallization processes [6]. The steps are as follows and the expected individual step and overall efficiency gains are presented in Table 1:

1. Laser was used to drill 16 holes in the wafers.
2. An improved texture process removed the saw damage. This improved iso-texturing with HF/HNO_3 resulted in low reflectance.
3. An advanced diffusion with $POCl_3$ phosphorus source formed an improved emitter profile.
4. Wet chemical clean process developed by ECN removed the phosphorous glass layer (PSG) formed during diffusion.
5. Anti-reflection coating was deposited with PECVD tool as passivation layer. In this process, hydrogen was incorporated to give an excellent surface passivation. The composition of the SiNx:H was optimized to obtain both good light in-coupling and optimized passivation quality.
6. Screen printing was used to apply silver in the holes, at the rear, and at the front. An optimized front side metallization pattern was according to the design of the Sunweb® pattern of Solland Solar BV. In addition, further gain was obtained by proper selection of the silver and aluminum pastes for the emitter and base to ensure good contactability and back-surface field passivation in the case of the aluminum paste.
7. Optimized wet-chemical etching was used for junction isolation to obtain some gain in cell efficiency.

Process Step	*Absolute gain in eff.* (%)
Improved texture, lower reflection	0.30
Improved SiNx:H anti-reflection coating	0.10
Improved emitter contact	0.15
Improved front metallization pattern	0.30
Improved emitter	0.50
Improved conductivity in holes	0.15
Improved p-type contact	0.10
Improved isolation	0.20
Overall improvement	**1.80**

Table 1 Overview of efficiency gains due to improvements in the industrial ECN MWT process flow as defined in 2006.

As shown in Table 1, the integration of all the improvements in the process steps as described in the previous paragraphs lead to an absolute increase of 1.80% absolute in efficiency as compared to ECN's MWT processes established in 2006.

The 36 best cells were selected and used to manufacture a 36-cell module in a 4x9 lay-out configuration on the Eurotron module assembly pilot line at ECN. The process flow of the back-contact module assembly is illustrated in Figure 3. After lamination, the performance of the finished module was measured on a class-A flash tester at ECN and this measurement was independently confirmed at JRC-ESTI.

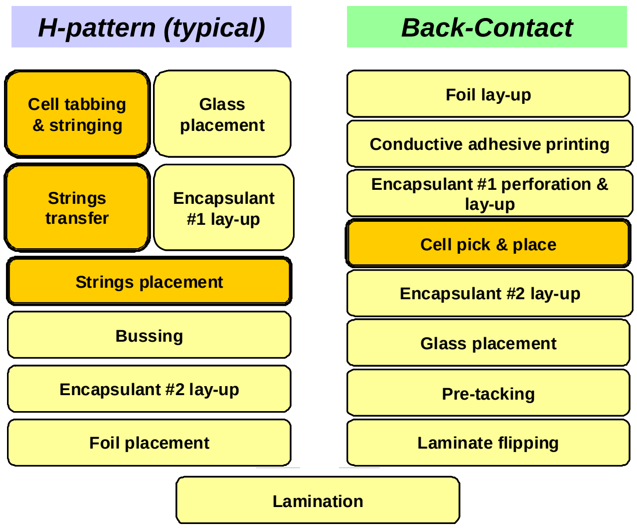

Figure 3 Back-contact versus typical H-pattern solar module assembly process flow.

Several improvements were carried out on the module level to increase the output of the module in two areas – the reduction of loss due to interconnection of cells and the improvement in light capture.

The conductive adhesive material and dimension were optimized for low contact resistance to minimize cell-to-module interconnection loss. The composition of the adhesive was tuned to match the curing profile of the encapsulation material of the module. This allowed the adhesive curing to be carried out during the lamination process.

To enhance light capture in the module, improvements were done on the back-sheet foil and the glass sheet. The back-sheet foils were optimized to allow more light to be reflected between the cells. The glass sheet was coated with an anti-reflective layer called KhepriCoat and was provided by DSM BV. The optical property of the layer was tuned to match the spectral response of the fabricated MWT cells.

RESULTS

Figure 4 shows the External Quantum Efficiency (EQE) measurement on neighboring cells in test modules encapsulated using glass with and without KhepriCoat. The top chart illustrates the EQE of each test module type over the wavelength range of 380–1200nm. Included also in this chart is the AM1.5G spectrum. The bottom chart shows the differences in the EQE spectrum for the two samples, multiplied by the power density of the AM1.5G solar spectrum as reference. It can be seen that the KhepriCoat coating improves the EQE over the wavelength range of 380–975nm, while some loss was observed at wavelengths above 975nm. Further calculations were carried out by taking into account the lower light power density at higher wavelengths to determine the true gain in EQE. This results in an increase of 1.28% between 380 and 975nm and a decrease of 0.18% between 975 and 1200nm when using the coated glass, giving an overall EQE gain of 1.10%. The short-circuit current output was also measured (Table 2) on the test modules. A relative increase of 0.73% was observed for the module with KhepriCoat-coated glass as compared to the modules with standard glass. The nearly 0.4% difference between EQE and J_{SC} gain may be explained by measurement uncertainties and spectral mismatch of the solar simulator with the AM1.5G solar spectrum.

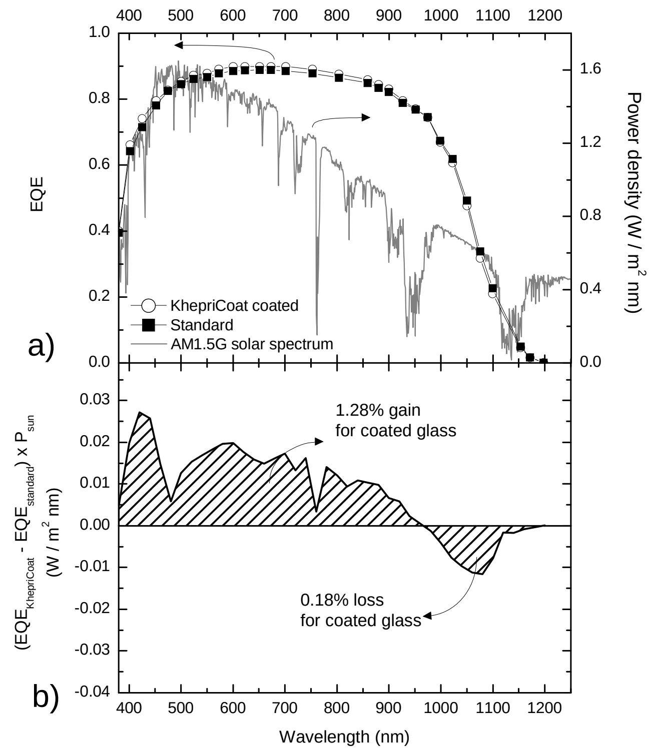

Figure 4 (a) External Quantum Efficiency spectra (left axis) and, (b) the difference in EQE spectrum of test modules with standard solar glass and KhepriCoat anti-reflection coated solar glass.

Sample	*J_{SC} (mA/cm^2)*
Module with standard glass	34.24
Module with KhepriCoat-coated glass	34.49
Observed relative gain	*0.73%*

Table 2 Short-circuit current of test modules with standard versus KhepriCoat-coated glass.

This analysis shows the benefit of using anti-reflection coated glass on module performance and that there is room for further improvement to the coating for better light capture.

A batch of 80 wafers was processed into MWT solar cells. The average cell efficiency was 17.6%. The best performing cell has an efficiency of 17.9%. Of all these cells, 36 best-performing cells, with an average efficiency of 17.8%, were selected to be assembled into one back-contact solar module. The aperture area of this module was 8885cm^2. The aperture area efficiency of 17.0% was measured. This was independently verified by JRC-ESTI.

	I_{SC} (A)	V_{OC} (V)	*FF* (%)	*Eff.* (%)
Premium cell	8.86	0.632	77.8	17.9
Average 36 cells before encapsulation	8.85	0.631	77.4	17.8
Module (aperture area = 8885 cm^2)	8.86	22.67	75.0	**17.0**

Table 3 Overview of premium cell and module efficiencies.

Figure 4 Picture of the finished multi-crystalline silicon MWT module with 17% aperture area efficiency.

CONCLUSIONS

We obtained an aperture-area (8885cm^2) module efficiency of 17.0% using 36 multi-crystalline silicon MWT cells. The full-size module was assembled with 36 large (156×156 mm^2) and thin (160µm) solar cells. The average cell efficiency for this module was 17.8%, giving a 3% relative difference between cell and module. The result was achieved using a combination of MWT cell and the corresponding back-contact module technology developed at ECN and by the incorporation of improvements in the processes and materials at both the cell and module level.

ACKNOWLEDGMENT

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