REACHING 16.4% MODULE EFFICIENCY WITH BACK-CONTACTED MC-SI SOLAR CELLS

A.A. Mewe, M.W.P.E. Lamers, I.J. Bennett, M. Koppes, I.G. Romijn, A.W. Weeber
ECN Solar Energy, P.O. Box 1, NL-1755 ZG Petten, The Netherlands
Phone: +31 224 564323; Fax: +31 224 568214; email: mewe@ecn.nl

ABSTRACT: We obtained 17.6% cell efficiency on 160 µm and 17.1% on 120 µm thin multicrystalline silicon screen printed cells of 156 x 156 mm^2. These cells are the best from two batches of cells that have been produced using improved processing on ECN's industrial metal-wrap-through (MWT) cell concept. With these batches of cells, four 36-cells modules were made: two modules with 160 µm thin cells and two modules with 120 µm thin cells. The module manufacturing, which is based on a conducting substrate foil, succeeded with 100% yield in our module pilot line. The modules were independently measured by TÜV Rheinland and JRC-ESTI, and resulted in a new certified world record module efficiency of 16.4% on an aperture area of 8904 cm^2.
Keywords: multicrystalline silicon, metal-wrap-through, module integration

1 INTRODUCTION

An important milestone to achieve a competitive energy price in PV is to reduce the costs to 1 €/W_p for the complete module. Under these conditions grid parity may be reached in Southern Europe in 2015 provided the Balance-of-System costs will reduce simultaneously. Several cell concepts have been considered, all at a thickness of 120 µm. Within the EU funded integrated CrystalClear project six concepts were chosen for evaluation with respect to efficiency and costs. For these concepts it should be possible to reach 1 €/W_p module cost after upschaling to 500-1000 MW_p annual manufacturing [1].

At ECN, the cell research focused on the so-called MultistaR, which is an advanced metal-wrap-through (MWT) cell on multicrystalline material. As formulated in 2005, a cell efficiency of 17.0% would lead to the cost target [2].

The use of ECN's metal-wrap-through technology has a number of advantages over standard H-pattern cells: current gain due to reduced cell front metallization coverage, higher fill factor for larger cells due to the unit cell design, higher packing density in the module, less resistance losses in the module and less cell breakage during module manufacture as the cell is fully back-contacted.

Research on the MWT cell concepts has been going on for several years at ECN and has led to a successful cell concept [3], which is very close to industrialization and market introduction. Improvements with respect to all cell aspects had to be made to reach the 17% efficiency goal.

Module integration using the foil concept in our industrial scale pilot line is essential for the module performance. The improvements with respect to the module technology will be extensively discussed by Bennett et al. [4].

2 DEVELOPMENT OF THE MWT CELL CONCEPT

In all processing steps of the industrial MWT process, separate improvements have been implemented to reach the highest cell efficiency. The process flow of the industrial MWT cell is shown in Fig. 1. Except for the hole drilling, the hole metallization and isolation of the rear emitter contacts, the cell processing is the same as for conventional cell processing.

The cell improvements include optimizations on texturization [5], emitter formation, emitter contacting [6], SiN_x antireflection coating, MWT metallization [7], Al BSF formation and diode isolation. Some of the process improvements have already been published. The emitter, SiN_x coating, Al BSF and diode isolation will be explained in more detail in the next sections.

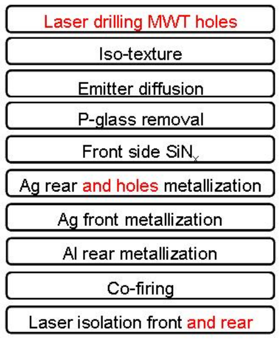

Figure 1: Process flow of the industrial MWT cell. The differences with standard industrial H-pattern cell processing are indicated in red.

2.1 Emitter formation and contacting

The different features of the emitter profile are very important parameters for the cell performance, determining surface passivation and contact resistance. A homogeneous 75 Ω/sq emitter, referred to as "improved emitter", has been formed using a $POCl_3$ tube furnace. According to SIMS analysis, the n^{++} region is shallower, but has a higher surface concentration, enabling a good contact to the emitter metallization.

Compared to a standard emitter, a considerable increase of J_{sc} and V_{oc} is observed without fill factor loss, as shown in Table I. The improved emitter leads to 0.5% absolute increase of cell efficiency in this experiment.

Table I: Cell characteristics of the improved emitter compared to the standard emitter.

	J_{sc} [mA/cm^2]	V_{oc} [V]	FF [-]	η [%]
improved	34.0	0.615	0.780	16.3
standard	33.5	0.605	0.781	15.8

Improving the silver emitter contact contributes to an enhanced efficiency by low line and contact resistance and limited shadow loss. A new Ag paste was compared to the standard, and showed a gain of 1% relative in

$J_{sc}xV_{oc}$ and more than 0.5% absolute in FF [6].

2.2 SiN_x anti-reflection coating

Acting as an anti-reflection coating as well as providing bulk and surface passivation, an optimized SiN_x layer on the front side of the cell is of considerable importance. For the advanced MWT cells, the composition of the layer was tuned to get the optimum transmittance while keeping excellent passivation properties. In Fig. 2 the EQE ratio of our standard SiN_x and the optimum SiN_x layer is shown. It can be clearly seen that the gain is especially in the blue response, due to higher transmittance through the layer.

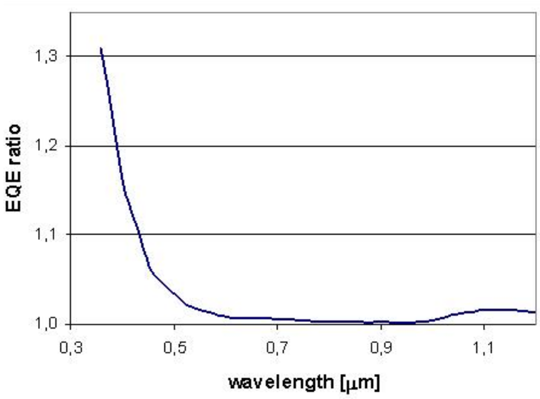

Figure 2: The EQE ratio of two encapsulated neighbouring cells with the optimal SiN_x coating and the standard coating.

2.3 Al BSF formation

The Al metallization on the rear side has the function of rear conductor, passivating layer through the BSF formation and contact to the silver pads that will be the interconnections to the module foil. Especially the BSF formation can be improved, both by the choice of the Al paste as well as tuning the firing in combination with the Ag contacting on the front.

In Fig. 3 the importance of a proper BSF formation is reflected in the resulting efficiency. The use of paste I results in an efficiency gain of 0.1% absolute compared to the standard paste II. As expected, the gain is mainly in $J_{sc}xV_{oc}$. In the IQE data we observed a clear enhancement of the red response, which is directly related to the BSF quality.

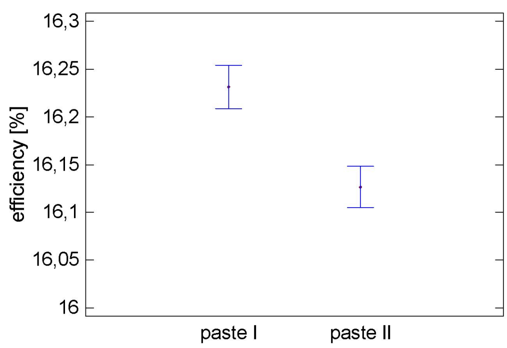

Figure 3: The use of Al paste I results in 0.1% higher efficiency than paste II, due to the BSF quality.

2.4 Diode isolation

Isolation of the diode in the MWT cell is normally performed using laser scribing. However, in H-pattern cell processing, laser isolation is sometimes replaced by wet-chemical isolation as it leads to better results.

For the advanced MWT cells, the standard laser processing was optimized and compared to wet-chemical isolation, as shown in Fig. 4. Clearly, optimizing the standard laser process leads to an enhanced fill factor. This may be explained by reduced laser damage as the optimized laser grooves are narrower, shallower and better defined. The wet-chemical isolation gives an even higher improvement, and leads to the best fill factor, which can be explained by a more homogeneous rear surface.

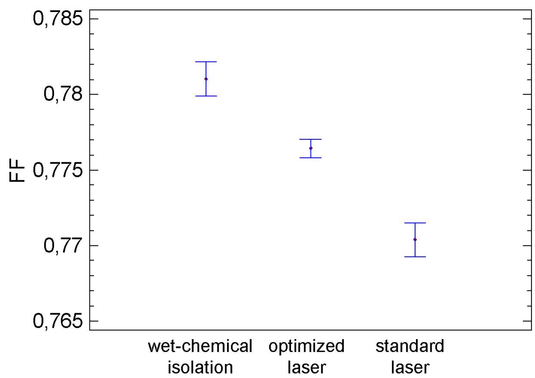

Figure 4: The use of different laser techniques and chemical isolation leads to different FF, due to differences in recombination. The best results have been obtained by wet-chemical isolation.

2.4 Integration of all improvements

All process improvements that are mentioned in the previous sections will lead to a large overall cell efficiency gain compared to the industrial MWT processing. An educated guess of the gain that can be obtained in the final processing of the advanced MWT cells is 1.6% absolute. The contributions of the individual process steps are listed in Table II.

Table II: Cell efficiency gain upon integration of all optimized process steps.

Process step optimization	Absolute efficiency gain [%]
Texture	0.3
SiN_x AR coating	0.1
Emitter	0.6
Emitter contact	0.15
MWT metallization	0.15
Base contact and BSF	0.1
Diode isolation	0.2
Total	**1.6**

The silicon wafer material for the advanced MWT cells was supplied by Deutsche Solar (120 μm cells) and REC (160 μm cells). Each batch consisted of about 80 cells.

For the 160 μm thin cells, an average efficiency of 17.4% for all processed cells was obtained. The best cell reached an efficiency of 17.6%. The 120 μm thin cells showed much more spread in efficiency due to larger variation in material quality, while the best cell reached 17.1%.

With this result, the 17.0% cell efficiency goal on 120 μm thin material has been reached for individual cell processing. Larger batch processing on 160 μm thin material showed that we are able to reach significantly higher efficiency.

If we compare the efficiency gain of the optimized processes on the 160 μm thin cells with respect to the standard industrial MWT process carried out in 2006, we observe that the actual gain is 1.9% absolute. This is shown in Fig. 5 and indicated as "Industrial 2006" and "2009". The actual gain is almost the same as the predicted gain of Table II, which is 1.6% absolute. The difference between the predicted and observed gain can be explained by material differences.

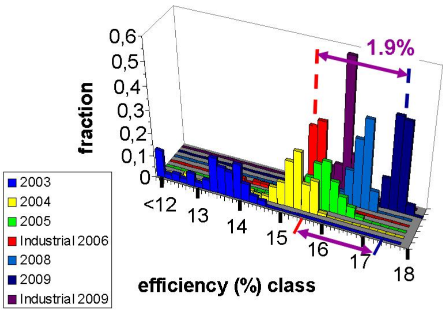

Figure 5: Efficiencies of MWT cells processed during the last years. All values have been calibrated to the solar spectrum as defined in IEC 60904-3 Ed. 2, April 2008 [8]. The median values of the "Industrial 2006" process and the "2009" process show a difference of 1.9% absolute.

3 MODULE INTEGRATION

3.1 Cell efficiency

In Fig. 6 and Table III the IV characteristics of the cells that were selected for the modules are shown.

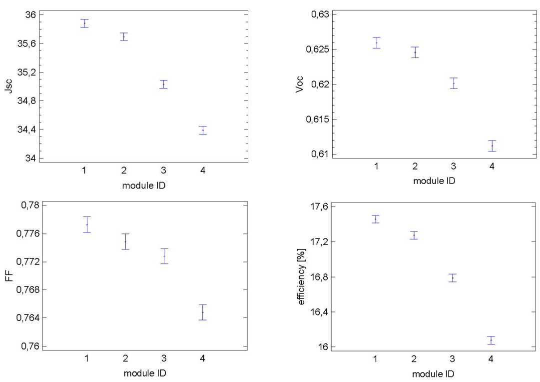

Figure 6: Average cell characteristics and their standard deviations of the advanced MWT cells used in the four modules. The module results are shown in Table IV.

The 160 μm thin cells were used for modules 1 and 2, while the 120 μm thin cells were used to manufacture modules 3 and 4. The 160 μm cells show higher J_{sc} and V_{oc}, which is reflected in the resulting efficiency. This difference is at least partially due to the material quality, as indicated by lifetime measurements on the material. The IV results of the cells in module 4 are slightly lower compared to the cells in module 3, due to ongoing process optimization on these cells.

Table III: Average and maximum efficiencies of the cells that were selected for the 36-cells modules.

module	cell thickness	wafer supplier	average cell η	max cell η
1	160 μm	REC	17.5%	**17.6%**
2	160 μm	REC	17.3%	
3	120 μm	DS	16.8%	**17.1%**
4	120 μm	DS	16.1%	

3.2 Module concept

The module concept used to integrate the back-contacted MWT cells into modules is a substrate foil concept. The conductive foil is patterned according to the positions of the emitter and base contacts of the cell. The lay-up of the module is illustrated in Fig. 7. Using the foil concept, a high packing density of cells in the module can be reached, and resistance losses are minimized.

For the integration of the cells into modules, several improvements have been made to the module materials. This is explained in more detail elsewhere [4].

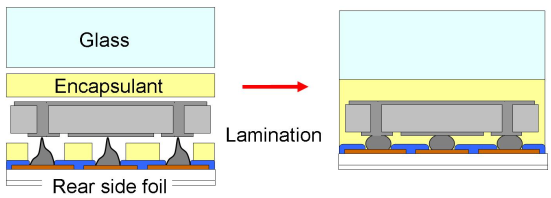

Figure 7: The copper layer is patterned to divide the layer into separated conducting paths for emitter and base polarity. The conductive adhesive provides the electrical connection between the foil and the cell.

The use of conductive adhesive as interconnection technology allows one-step interconnection and lamination of the module [9]. As it is a low-stress interconnection technique, very thin and fragile cells can be built into a module without cell breakage.

The cells are positioned onto the foil by a pick-and-place technique, which comprises all handling of the cells. A picture of the pick-and-place robot in action is shown in Fig. 8.

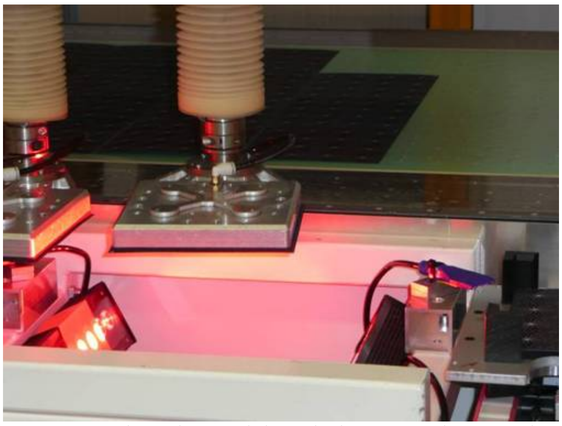

Figure 8: The robot's pick-and-place arms in operation to position the MWT cells onto the foil. This comprises the only handling of cells during the module build.

3.3 World record module

Four 36-cells modules were manufactured in our automated module pilot line; two modules with 160 μm thin cells and two modules with 120 μm thin cells. All four modules have been made with 100% mechanical yield.

All four modules were measured at TÜV Rheinland. Only the two best modules were also measured at JRC-ESTI, where they have the ability to measure the spectral response of a full-size module for spectral mismatch correction. This resulted in a new world record module of 16.4% on an aperture area of 8904 cm^2. For this module, the 160 µm thin cells were used. The measurements at TÜV Rheinland are also considered reliable, as the performance of the two best modules is identical to the JRC-ESTI data.

In Table IV, the measured module performance is quantified.

Table IV: Measured cell efficiencies at ECN and module performance at JRC-ESTI and at TÜV Rheinland, conform the solar spectrum as defined in IEC 60904-3 Ed. 2, April 2008 [8].

institute	ID (cell thickness)	cell η	encapsula-ted cell η	aperture area η
JRC-ESTI	**1 (160 µm)**	**17.5%**	**16.63%**	**16.44%**
TÜV	1 (160 µm)	17.5%	16.63%	16.43%
JRC-ESTI	**2 (160 µm)**	**17.3%**	**16.60%**	**16.37%**
TÜV	2 (160 µm)	17.3%	16.56%	16.36%
TÜV	3 (120 µm)	16.8%	16.23%	16.04%
TÜV	4 (120 µm)	16.1%	15.74%	15.55%

These results show the efficient module manufacture: low losses from cell to encapsulated cell due to efficient interconnection and low losses from encapsulated cell to module efficiency due to high packing density of the cells onto the foil and absence of bussing at the edges of the module. In Fig. 9 a picture of the full-size world record module is shown.

Figure 9: The world record module, with 16.4% efficiency on an aperture area of 8904 cm^2.

The results for the modules with 160 µm thin cells are slightly better than for the modules with 120 µm thin cells, which is due to the lower cell efficiency.

4 CONCLUSIONS

4.1 Cell performance

A maximum cell efficiency of 17.6% was reached on 160 µm thin advanced MWT cells by improving the process steps of the industrial MWT concept. The process stability was proven by the high cell efficiency average of 17.4% of the complete cell batch.

We reached the 17.0% effciency goal on 120 µm thin material for individual cells, with a maximum of 17.1%. The average cell efficiency of 16.8% for the best module is just slightly lower.

4.2 World record module

Four modules were manufactured with the advanced MWT cells in our module pilot line, all with 100% mechanical yield. The best module, made with 160 µm thin cells, showed a module efficiency of 16.4% on an aperture area of 8904 cm^2, as independently measured and certified by JRC-ESTI. This result is almost 1% absolute higher than the previous world record [10].

5 ACKNOWLEDGEMENTS

This work was financially supported by the FP6 European Crystal Clear project (EC contract SES6-CT-2003-502583). REC and Deutsche Solar are acknowledged for supplying the wafer material. Solland Solar Cells BV is acknowledged for use of the front side metallization pattern of their Sunweb cells.

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