17.9% BACK-CONTACTED MC-SI CELLS RESULTING IN MODULE EFFICIENCY OF 17.0%

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ABSTRACT: We obtained 17.9% cell efficiency on 160 micron thin cells sized 156 x 156 mm^2 using ECN's Metal-Wrap-Through (MWT) concept. Several cell processing steps were optimized and this led to an increase of more than 2% absolute in cell efficiency compared with previously reported values [1]. With these high-efficiency cells a 36-cell module was manufactured in our industry scale module pilot line. The aperture area efficiency of this module was 17.0% (as independently confirmed by JRC-ESTI): a world record in his category in 2009 and early 2010 [2]. In this module the average cell efficiency was 17.8%; this shows a small difference between cell and module efficiency.
Keywords: multicrystalline silicon, metal-wrap-through, module integration.

1 INTRODUCTION

Currently, PV industry focuses on obtaining higher efficiencies, and simultaneously reducing material and production costs. This can be obtained wiht the integrated ECN metal-wrap-through (MWT) cell and module concept.

The use of ECN's MWT 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, less cell breakage during module manufacture as the cell is fully back-contacted, and the potential to use very thin cells.

The ECN-MWT cell and module concept has proven itself to be a high efficiency design. With this concept a module efficiency for mc-silicon of 17.0% was reached, which was the world record in 2009 and early 2010 in his category [2]. Even more, the ECN-MWT concept is a low-cost, industrially viable option: cost calculations show PV module direct manufacturing costs of about 1 €/Wp [3].

2 ECN-MWT CELL AND MODULE PROCESS FLOW

2.1 ECN-MWT cell process flow

The ECN-MWT cell consists of 16 unit cell structures (4x4). In the middle of the unit cell structure a laser hole is drilled through which the emitter metal contacts are wrapped, realizing all electrical contacts on the rear. More details can be found in [1,4,5]. In Figure 1 a photo of a MWT cell is shown.

The ECN-MWT design allows a very easy up scaling of the wafer size by a simple addition of more unit cell structures without increases in series resistance or shading losses. Industrial ECN-MWT cell processing, which is based on screen-printing, closely resembles conventional industrial H-pattern processing; the main differences are the laser drilling, metallization and isolation of the holes. This industrial cell process flow is given in Table I.

Figure 1: Photograph of a 243 cm^2 back-contacted MWT cell.

Table I: Industrial H-pattern and ECN-MWT solar cell processing on 243 cm^2 mc-Si wafers. The additional steps required to fabricate an ECN-MWT cell are highlighted in red.

Process sequence mc-Si cells
1. Laser drilling of holes
2. Texture
3. Emitter formation
4. Glass removal, Cleaning
5. Front side SiN_x:H deposition
6. Screen-printing of the Ag front side, Ag holes, Ag rear side and Al rear side metallization
7. Simultaneous firing
8. Laser isolation around the holes and edge

Cell manufacturing of the MWT cell starts with laser drilling of the holes. A subsequent wet-chemical texturing step is combined with the removal of saw and laser damage. The homogeneous emitter is formed using high-temperature phosphorus diffusion. Glass removal and cleaning is followed by deposition of the SiN_x:H anti-reflection and passivation coating on the front side of the wafer. Metallization of the front side, the holes and the rear side is done by screen-printing. The contacts are formed by a short high temperature step (peak firing). The final step is laser isolation of the edge and around the holes.

In previous work by ECN it was demonstrated that a significant gain in efficiency can be obtained using a MWT concept as compared to the conventional H-pattern one. For the ECN-MWT cell, the metallization front side coverage of 5.5% resulted in a 2-3% relative gain in J_{SC} as compared to an H-pattern cell which had a metallization coverage of 7.5% [1,4,5].

2.2 ECN-MWT module process flow

The ECN-MWT module manufacturing uses a interconnection foil on which the cells are placed. The electrical contacting of the cells with the foil is done using a conductive adhesive. This way of module fabrication of back-contacted solar cells combines a low series resistance with a high yield even for thin cells. The use of the conductive adhesive avoids any soldering stress or stress at the edges of the cells. As no tabs are needed in between the cells and no area is required for the string matrix, this method of module fabrication also allows a higher packing density. Even more, the use of the conducting foil allows more efficient current collection over the whole cell area as compared to conventional 2 mm tabs. Finally, module assembly can be done up to 8 times faster than conventional module assembly with H-pattern cells. It was demonstrated that a 2% relative gain in *FF* and a 1% relative gain in J_{SC} can be obtained at the module level [1,6] compared to conventional H-pattern module manufacturing using tabber-stringer. An illustrative image of a cell in the module, which shows the placement of the different components, is given in Figure 2.

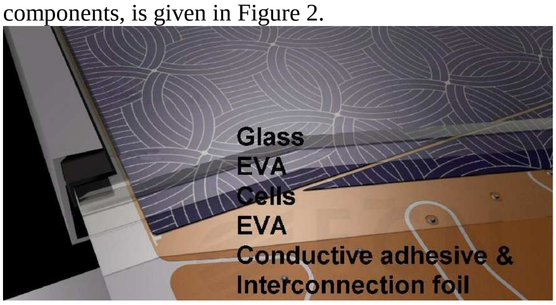

Figure 2: Illustrative image of the MWT module, showing the placement of the different components.

Module manufacturing is performed in our automated pilot line, a photo of the pilot line is shown in Figure 3.

Figure 3. The MWT automated pilot line at ECN.

The module process flow is giving in Table II. Process steps 1 to 6 can each be performed within one minute for a 60-cell module.

The module build begins with the placement of a patterned conductive foil to a carrier plate using vacuum. After the printing of the conductive adhesive on the foil, the rear side encapsulant is perforated at the positions where the conductive adhesive is printed to allow contact with the cells and is placed on the foil. Subsequently, a pick-and-place robot places the cells on the foil such that the contacts on the cell make contact with the conductive adhesive. As a last step before lamination the sheet of encapsulant and glass is placed on the front side of the cells. During lamination the cells are encapsulated by the encapsulant and the conductive adhesive is cured, which secures the electric contact between the cells and the foil. The module is finalized by the placement of the junction box and frame. More details on the ECN-MWT module manufacturing is given in [7].

Table II: Industrial ECN-MWT solar module processing.

Process sequence ECN-MWT module
1. Placement interconnection foil
2. Screen printing conductive adhesive
3. Puncturing rear side sheet of encapsulant and placement on foil
4. Pick and place of MWT cells
5. Placement of front side sheet of encapsulant
6. Placement of glass
7. Lamination
8. Finishing module assembly (placement junction box and frame)

3 EVOLUTION OF MWT CELL PROCESS FLOW

To show the progress made with MWT the efficiency distribution on mc-Si cells from the last 7 years is depicted in Figure 4.

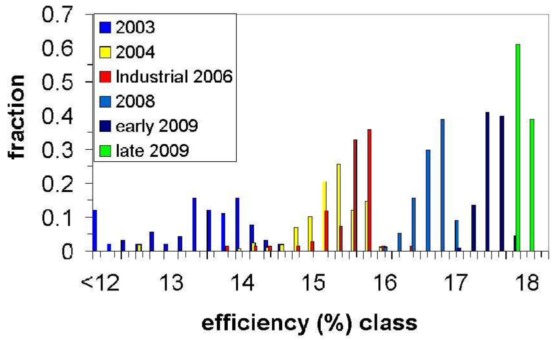

Figure 4: ECN-MWT efficiency throughout the years. When required, efficiencies are recalculated to the new spectrum as defined by Green [8].

The first ECN-MWT mc-Si cells were presented in 2000 with efficiencies of 12.5% [9]. At that time the wafer size was 156 cm^2 and the wafers were 330 µm thick and the anti-reflection coating of the cell was still with TiO_2 as SiN_x was just making its entry in the PV world. The first ECN-MWT modules were made using pins to contact the front side of the wafer. The first focus for improvement lay on aspects specific for the MWT cell, like the metallization pattern [10]. In the following years the focus lay on improving the connection between the MWT cell and module: the use of pins, soldering and conductive adhesives were compared. It was found that the conductive adhesive would be the industrially most viable option, regarding contact resistance and stress, but also regarding costs, durability, stability and synergy with the cell processing [11,12]. In the mean time several cell process steps on H-pattern were improved in the years 2000-2003, for example the TiO_2 coating was permanently replaced by a passivating SiN_x-coating. Also the cell size was increased to the standard of 225 cm^2, though cell thickness remained at 330 µm. MWT module processing was further optimized as not only the interconnection, but also the interconnection foil was improved [4]. In 2003 MWT cell efficiencies up to 14.5% were reached though the spread in efficiency was still large. In 2004 the emitter process was improved for MWT cells leading to efficiencies up to 15.7% and with a smaller spread in efficiency [5]. Improvements of the emitter process led to a significant increase in the shunt resistance, which led to higher V_{OC}, J_{SC} and *FF*. In 2006 the industrial MWT cell and module process flow was introduced [1]. With this flow efficiencies of on average 15.5% were obtained on cells which were 240 µm thick. A first comparison between H-pattern and MWT modules was published which showed an efficiency increase of 0.7% absolute for MWT.

Following the definition of the industrial process flow, all aspects of the MWT cell were again optimized, the locations of these optimizations are shown in Figure 5. The separate cell efficiency improvements are given in Table III and in more detail explained in [13-15]. These optimizations include the introduction of a new 'plug' paste to improve the metallization of the holes [16], replacement of the laser isolation with chemical isolation and improved emitter formation. With these optimizations, except the front side metallization pattern, MWT cell efficiencies up to 17.6% were obtained on 160 µm thin cells size 243cm^2. With these cells a world record module efficiency of 16.4% on mc-Si material was obtained in 2009. Also cells as thin as 120 µm sized 243cm^2 were made with efficiencies up to 17.1% [13].

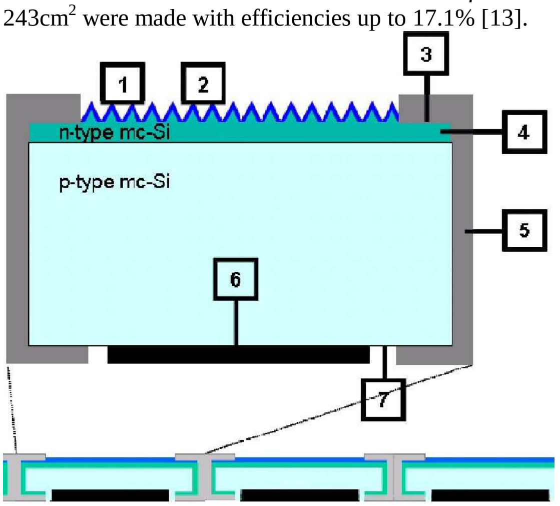

Figure 5: Locations of different optimizations in the ECN-MWT concept. Explanation of numbers is given in Table III.

Table III: When separate gains in efficiency are added, an absolute increase in efficiency of 1.8% can be expected relative to the industrial process flow as defined in 2006.

Nr.	Process step	Absolute gain in efficiency (%)
1	Improve texture, lower reflection	0.3
2	Improve SiN_x:H antireflection coating	0.1
3a	Improve emitter contact	0.15
3b	Improve front side metallization pattern	0.3
4	Improve emitter	0.5
5	Improve conductivity in holes	0.15
6	Improve p-type contact	0.1
7	Improve isolation	0.2
	Total	**1.8**

To gain even higher efficiencies the front side metallization pattern was optimized on the developed cell processing. A new pattern for the ECN-MWT cells was made with a relative reduction of 20% of the front side metallization coverage, while at the same time current collection was optimised. The application of this pattern resulted in an increase of 0.3% absolute in efficiency.

Integration of all optimized steps

Integration of all the optimized process steps, indicated by steps 1-7 in Figure 5 and Table III, should lead to an increase of about 1.8% absolute as compared to the MWT process flow as defined in 2006. The average ECN-MWT cell efficiency in 2006 was 15.5%, therefore average cell efficiencies of 17.3% were to be expected.

Integration of the found optimizations led to an average cell efficiency of 17.6% over 81 cells. This is an improvement of 2.1% absolute since 2006. The best cell has an efficiency of 17.9%. The cell efficiencies are shown in Figure 6. The wafer material was p-type mc-Si provided by REC Wafer, sized 156x156 mm^2 with a base resistivity of 1-1.5 Ω cm; the cell thickness was 160 µm. The wafer material was optimized by lowering the dislocation density. This material optimization and a possible positively mutual reinforcement of the multiple improvements could explain the discrepancy between the calculated 1.8% and the obtained 2.1% efficiency increase.

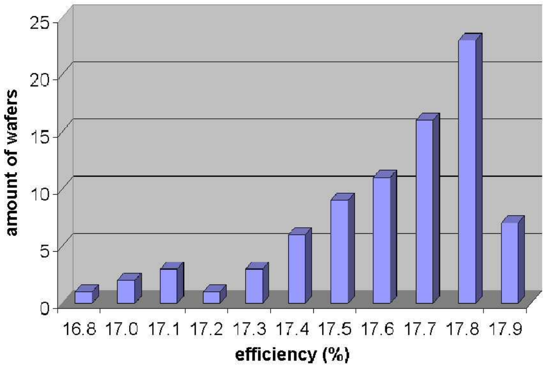

Figure 6: Cell efficiencies of MWT cells on REC material.

4 17% MWT-MODULE

From the 81 processed cells, 36 cells were selected and integrated in a 9x4 ECN-MWT module. The module efficiency of 17.0% was independently confirmed by JRC-ESTI. Cell and module efficiencies are given in Table IV. The module aperture area was 0.8885 m^2. Multiple MWT modules were manufactured at ECN with 100% yield, also when thinner cells were fabricated [13]. A photo of a MWT module is shown in Figure 7.

Table IV: Cell and module efficiencies. Cell efficiencies are measured with a class A solar simulator at ECN, module efficiency is independently measured by JRC-ESTI.

	Area (cm^2)	J_{SC} (mA/cm^2)	V_{OC} (V)	*FF* (-)	Efficiency (%)
Best cell	243	36.41	0.632	0.778	17.9
Average 36 cells before encapsulation	243	36.37	0.631	0.774	17.8
Average 36 cells after encapsulation	243	36.94	0.630	0.750	17.2
Module (aperture area)	**8885**	**36.41**	**22.67**	**0.750**	**17.0**

Figure 7: Photograph of a 60-cells mc-Si ECN-MWT module.

The light trapping parameters of the cell are optimized for use under glass, by optimization of the texture and SiN_x coating, allowing a higher J_{SC} in the module. Additionally, a special Khepricoat anti-reflcetion coating provided by DSM was applied on the glass improving the light trapping even further, this increased J_{SC} with 1.6% absolute. As the packing ratio is not 100% in the module a very small loss of 1.4% in J_{SC} was found due to the packing ratio of close to 99%. Consequently, the J_{SC} of the cells before encapsulation is comparable to the J_{SC} of the finished module. A small loss of only 2.5% absolute in *FF* was found due to the low resistance losses in the module components. The spectral response of a MWT cell and the module are given in Figure 8. It can be seen that the spectral responses are very similar, as is expected from the processing and the similar J_{SC}.

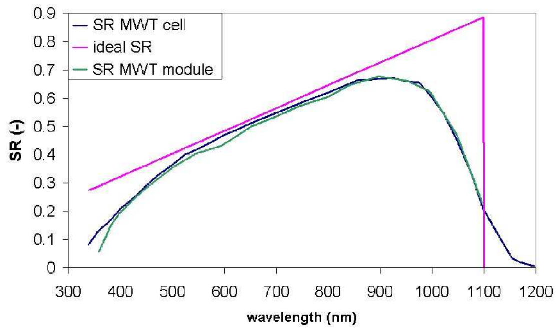

Figure 8: Spectral response (SR) of a MWT cell and the MWT module. Also given is the ideal spectral response (QE=1).

Main losses in the MWT cell are related to recombination in the emitter and the non-optimal reflection and passivation of the rear side. Recombination in the emitter and absorption in the SiN_x:H reduce the response below 550 nm, while the non-optimal reflection and passivation reduces the response for wavelengths above 900 nm. Recent work to improve the latter is presented in [17].

6 CONCLUSIONS

Improvements on all steps in the cell processing resulted in an efficiency increase of more than 2% absolute since 2006. The average efficiency of more than 80 mc-Si MWT cells, sized 243 cm^2, is 17.6% with a top efficiency of 17.9%.

Using 36 of these cells with an average efficiency of 17.8% a high module efficiency of 17.0% was obtained, which was the world record in 2009 and early 2010 in his category. Also various modules were made, also using thinner cells, with 100% yield.

In the future, further improvements can be made in the MWT process flow by improving the front and rear side reflection and reducing the emitter and rear side recombination.

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