279 WATT METAL-WRAP-THROUGH MODULE USING INDUSTRIAL PROCESSES

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ABSTRACT: This paper describes results of metal wrap through (MWT) cells produced from n-type Czochralski silicon wafers, and modules produced from those cells. The use of n-type silicon as base material allows for high efficiencies: for front emitter contacted industrial cells, efficiencies up to 20% have been reported. MWT cells allow even higher cell efficiency due to reduced front metal coverage, and additionally full back-contacting of the MWT cells in a module results in reduced cell to module (CTM) fill factor losses.

MWT cells were produced by industrial process technologies. The efficiency of the MWT cells reproducibly exceeds the efficiency of front contact cells based on the same technology by about 0.2-0.3%, and routes for further improvement are analyzed.

60-cell modules were produced from both types of cells (MWT and H-pattern front emitter). In a direct module performance comparison, the MWT module, based on integrated backfoil, produced 3% higher power output than the comparable tabbed front emitter contact module. CTM current differences arise from the higher packing density, and in this experiment from a lower reflectance of the backfoil, in MWT modules. CTM FF differences are related to resistive losses in copper circuitry on the backfoil versus tabs. The CTM FF loss of the MWT module was reduced by 2.2%abs compared to the tabbed front emitter contact module.

Finally, simple process optimizations were tested to improve the n-type MWT cell and module efficiency. A module made using MWT cells of 19.6% average efficiency resulted in a power output of 279W. The cell and module results are analyzed and routes for improvements are discussed.

Keywords: metal wrap through; MWT; n-type silicon

1 INTRODUCTION

The majority of solar cell production is presently based on p-type crystalline silicon wafers using the very mature double-side contacted (with an H-pattern grid) technology. For further increase of PV competitiveness, high efficiency, ease of mass production, and low cost, preferably combined with lower use of resources and improved environmental footprint, are required.

Back-contacted solar cell concepts such as Interdigitated Back Contact (IBC), Emitter Wrap Through (EWT) and Metal Wrap Through (MWT), have been considered and developed for industrial application especially in the last decade. In contrast to traditional H-pattern cells, back-contacted cell designs allow reduction of shading loss on the front side resulting in an increase of the short-circuit current and overall efficiency of the cell. Also, back-contacted cell technologies present cost and efficiency advantages at module level. In parallel to the significant progression of back-contact cell technology, solar cell process development and research using n-type Si substrates and low-cost processing has taken place especially over the last 5 years. N-type silicon solar cells (an expression used widely to mean solar cells with an n-type base) represent an alternative to the traditional p-type silicon solar cells and can potentially fulfill the objectives of low cost and high efficiency with only modest changes to the current wafer and cell production processes [1,2,3]. Recently a high efficiency industrial n-type H-pattern technology has been developed through a collaboration between ECN, Yingli Solar and Amtech/Tempress, and has been taken into production by Yingli Solar under the brand name “Panda” cells [1]. In order to further increase cell and module efficiencies and decrease cost, we have combined the n-type doped crystalline silicon with back-contact MWT solar cell technology [4] and developed high-efficiency n-type MWT crystalline silicon solar cells (n-MWT).

In this paper results from a simple process designed for high-efficiency n-MWT solar cells [5] will be described. We designate the n-type H-pattern non-wrap-through cell with contact grids on front and rear, as "n-Pasha" (for n-type cell, Passivated on both sides and with H-pattern grids). A direct comparison between mono-crystalline n-Pasha and mono-crystalline n-MWT results, using neighbor wafers will be given. Focus is on the relative gains (due to Voc, Jsc) and losses (due to series resistance) of n-MWT compared to n-Pasha cells, to understand how to maximize the cell efficiency gain of n-MWT cells. We also describe results for n-MWT modules. In particular we focus on differences in cell-to-module (CTM) loss of fill factor and current of integrated-backfoil-based MWT compared to tabbed n-Pasha cells. Also here we analyze the losses and routes for improved efficiency. Finally, results from cell and module process improvements are discussed.

2 MWT CONCEPT FOR N-TYPE MATERIAL

2.1 Benefits of combining MWT technology with n-type material

MWT technology presents several advantages over the standard H-pattern cell technology. Apart from the current gain due to reduced front-side metallization coverage, integration into a module is easier, as the cell is fully back-contacted. The mechanical stress induced on the cells by conductive adhesive based interconnection (used in our MWT modules) is low, and as a result, the breakage is reduced. Consequently, thinner and larger cells can be interconnected without yield loss. In addition, the packing density can be significantly increased. The front side metal grid benefits from a small unit cell pattern allowing large cells (cf. fig. 1). The cell interconnection can be optimized for low series resistance losses and significantly reduced efficiency loss from cell to module, since the constraints related to normal front-to-back tabbed interconnection (i.e., shading loss from the width of tab, and stress on the cell) are absent [4].

In addition to the efficiency enhancement due to MWT layout, efficiency can be increased using silicon base material with improved electrical properties. In that respect, n-type wafers generally allow (much) higher lifetimes than p-type wafers [6,7]. In contrast to boron-doped p-type material, boron-oxygen complexes are absent in n-type material. Therefore it will not suffer from lifetime degradation due to formation of a boron-oxygen related metastable defect upon illumination [8,9]. Also, n-type silicon has been proven to have a higher tolerance to common transition metal impurities [10,11,12]. In practice, lifetimes of several milliseconds are readily obtained in n-type Cz. The n-Pasha cells developed by ECN, Yingli Solar and Amtech (and daughter company Tempress) and brought into production by Yingli Solar, use the conventional non back-contact H-pattern cell structure [1]. In addition to benefiting from high base diffusion length, this cell design has other advantages, in particular, significantly improved rear side optical and electronic properties, compared to standard p-type cells. So far, best cell efficiency of 19.49% (independently confirmed by Fraunhofer ISE) in trial production [12] and 19.89% in production [13] have been reported.

MWT cell process technology in general remains close to conventional front contact cell processing, and the simplicity of the rear-side contact pattern of the MWT cells allows large tolerance regarding print alignment. The cell structure comprises a front side emitter and therefore will be less sensitive to material quality variations than back-contact back-junction cell designs. Also, integrated MWT cell and module technology has already proven itself for p-type technology. Therefore, we have designed a novel low-cost industrial process to make very high efficiency n-type back-contact modules.

2.2 Approach to cell process development

The n-type MWT process is very similar to the industrial process used for n-Pasha cells. Laser processing is used to form via-holes by which the front side metal grid is wrapped through the wafer. Like the n-Pasha cells, the cell structure comprises a boron emitter, a phosphorous Back Surface Field (BSF) and an open rear side metallisation suitable for thin wafers. Metal contacts are deposited by industrial screen-printing process with no further requirements regarding alignment compared to the screen-printing process used in the industrial n-Pasha process. The front and rear side metal grid patterns are based on a H-pattern lookalike grid design, combined with the unit cell concept [14]. We have chosen a H-pattern lookalike grid because it is well suited for a comparison of losses between n-MWT and n-Pasha cells. As module interconnection of n-MWT cells does not require tabs on the front of the cells, the front side busbars can be significantly slimmed down compared to conventional n-Pasha cells. As a result, total shading losses are reduced. Correspondingly, however, resistance in the busbars affects the total series resistance of the cell. Shading and resistance losses are balanced to increase power output of the n-MWT cells compared to the n-Pasha cells. The front and rear sides of the cells made according to this process sequence can be seen in Figure 1.

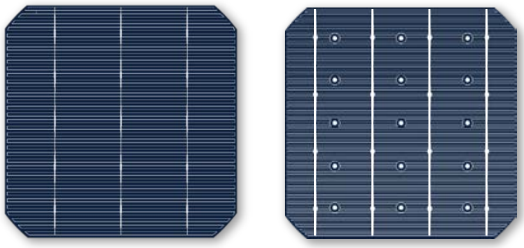

Figure. 1. Image of n-type MWT silicon solar cells with a H-pattern based unit cell design: front side (left picture) and rear side (right picture).

3 DETAILED COMPARISON OF N-TYPE MWT AND N-TYPE PASHA SOLAR CELLS

3.1 Experimental results and analysis

n-type MWT and n-type Pasha solar cells were prepared from 200 µm thick and neighboring n-type Cz wafers (239 cm², around 5 Ωcm resistivity). Both groups were processed in parallel and received identical texture (random pyramids formed by alkaline etching), emitter and BSF profiles, passivation, SiNx anti-reflective coating (ARC), metal paste for emitter and BSF contacts and firing. I/V data are presented in Table 1.

Table 1. I/V characteristics of n-type Pasha cells and n-type MWT cells (continuous light source), with comparable Jo and metallization parameters, to illustrate the gains associated with MWT design. ESTI calibrated reference cell (2% Isc uncertainty). Rse obtained from fit to two-diode model. Jsc corrected for spectral mismatch. (* indicates FF overestimated by approx. 0.2% absolute, due to shorting of the n-Pasha rear grid on the electrically conductive measurement chuck.)

	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF (%)	η (%)	R_{se} (mΩ)
Av. on 4 cells					
Pasha	38.4	638	79.1*	19.38	4.5^3
MWT	39.5	644	77.1	19.61	5.8
Best efficiencies					
Pasha	38.50	638	79.2*	19.45	4.4
MWT	39.62	644	77.2	19.70	5.7

The Voc gain of 1% for the n-MWT cells is related to the reduced metal contact area to the emitter [15-17]. This reduced front recombination also results in some (relatively small) Isc gain.

Even though the FF is reduced, a resulting efficiency gain of 0.25% absolute is measured on the back-contacted cells compared to the H-pattern cell. Contributions to series resistance and FF losses are summarized in Table 2.

Table 2. Calculated contributions to series resistance and FF losses of the n-MWT cells compared to the n-Pasha cells. Contribution by 'front side fingers' is due to unintended difference in print resolution between n-Pasha and n-MWT.

Source of R_{series} in MWT cell	R_{series}	FF loss
Metal via resistance	0.20 mΩ	0.30% abs.
Front side busbars	0.60 mΩ	0.90% abs.
Front side fingers	0.20 mΩ	0.30% abs.
Increase of I_{sc}		0.10% abs.
Total	**1.0 mΩ**	**1.6% abs.**

From the results in Table 2, approximately 1.6% of the observed 1.8% additional FF losses present in the n-MWT cells, compared to n-Pasha cells, can be explained. The discrepancy between model and experiment is small compared to measurement and modeling uncertainties.

3.2 Solutions to reduce series resistance of n-MWT cells and increase efficiency

Several options exist to reduce the FF loss of n-MWT cells relative to n-Pasha cells. A straightforward option is increasing the number of vias [5]. As illustrated in Figure 2, when the number of via-holes increases, FF and Jsc increase thanks to the reduction of resistive and shading losses (dashed black and solid blue lines). However, this may also increase recombination, and therefore, cause Voc loss (dotted blue line in Fig. 2). From modeling we expect a maximum efficiency increase of around 0.23% absolute compared to the current number of vias. Together with other grid optimisation, cell efficiency above 20% is possible.

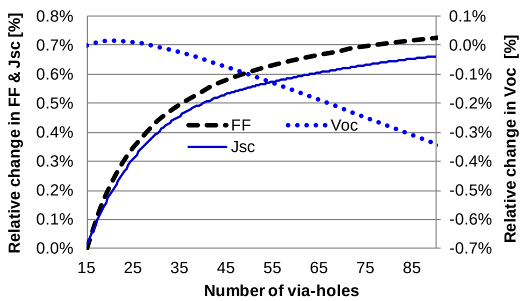

Figure. 2. Calculated relative FF, shading and Voc changes as a function of the number of via-holes for n-MWT cells.

4 N-TYPE MWT VERSUS N-TYPE PASHA MODULES – DIRECT PERFORMANCE COMPARISON

The ECN module manufacturing technology used to interconnect the n-MWT cells is based on an interconnection foil with integrated Cu conductor layer, on which the cells are electrically contacted using a conductive adhesive. Compared to the front to rear side tabbed interconnection used for the n-Pasha cells, a rear-side foil interconnection allows to reduce the module series resistance by using more metal (more cross sectional area) and thereby reduce the FF loss after cell encapsulation.

n-MWT and n-Pasha module I-V parameters were measured at ECN using a class A multiflash tester (8-flash measurement). Average cell efficiency, maximum power and absolute FF loss from cell to module (CTM) are presented in Table 3. The n-MWT module outperforms the corresponding n-Pasha tabbed module with a power gain of 8 Wp and a CTM FF loss of only 0.8% which is more than 3 times lower than the FF loss for n-Pasha.

Table 3. n-type MWT and n-type Pasha average cell efficiency, corresponding module power and FF loss from cell to module (multi-flash class A, IEC60904-9 measurement, ESTI reference module).

	Average cell η	P_{max} (W)	cell-to-module FF loss
n-MWT module	18.9%	273	0.8%
n-Pasha module	18.6%	265	3%

The reflectivity of the back-foils used for the n-MWT module is much lower than the standard TPT back-foil used for the n-Pasha tabbed module. Therefore, significant gain (on the order of 1%) in Isc is possible for n-MWT modules by employing high reflectance back-foils. Fig. 3 illustrates a first step towards a back-foil with improved reflectance, which should result in about 0.5% gain in Isc. The CTM Isc gain can be further optimized by adjusting the spacing between the MWT cells.

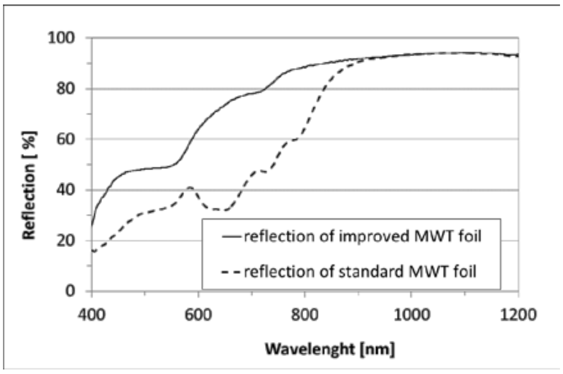

Fig. 3. Reflection measured in air of standard MWT integrated back-foil (used in experiment of Table 3) and a preliminary improved back-foil.

5 LATEST N-MWT CELL AND MODULE RESULTS

In addition to metallization grid design optimization, process improvements originally demonstrated on n-Pasha cell [15] were tested on the n-MWT solar cells. A batch of 60 n-MWT cells were prepared from 200 µm thick n-type Cz wafers (239 cm²). Standard metal paste for emitter and BSF contacts and firing process were used. I/V data are presented in Table 4.

Table 4. I/V characteristics of n-type MWT cells (continuous light source). ISE-certified reference cell (2% Isc uncertainty). Rse obtained from fit to two-diode model.

	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF (%)	η (%)	R_{se} (mΩ)
Av. on 60 cells	38.9	644	78.2	19.6	4.9
Best efficiency	39.1	646	78.5	19.8	4.7

Compared to cell efficiencies presented in section 3, FF of the n-MWT cells is improved by 1% absolute and a peak efficiency of 19.8% was obtained. However, current and voltage measured for this batch are lower than expected. In this experiment, no parallel group of n-Pasha cells was processed. Therefore, Internal quantum efficiency (IQE) of these n-MWT cells were compared to IQE of n-Pasha cells of similar efficiency (19.8%) but manufactured from a different Cz ingot and using somewhat different processing parameters. Average front-side IQE's plots, presented in figure 4, show a lower response of the n-MWT cells in the long wavelength compared to the n-Pasha cells. Preliminary analysis, supported by modeling, indicates this decrease of IQE to be a consequence of a lower rear-side passivation quality, resulting in a decrease in current and voltage. We expect to improve the rear side response, and consequently efficiency, of the n-MWT cells by matching more closely the processing parameters of the n-Pasha cells of figure 4.

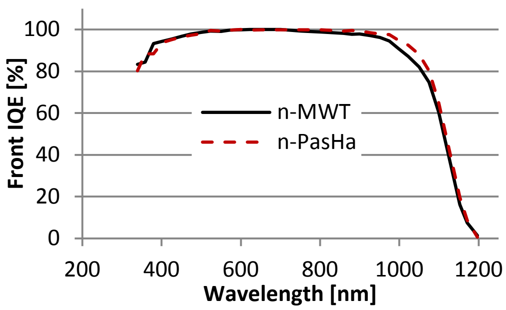

Fig. 4. Internal quantum efficiency measured from the front side of n-MWT and n-Pasha cells

Interconnection of the 60 n-MWT cells was done using the ECN module manufacturing technology as described in section 4. For this n-MWT module, back sheet with improved reflectivity was used. The n-MWT module I-V parameters were measured at ECN using a class A multiflash tester (16-flash measurement). Average cell efficiency, maximum power and absolute FF loss from cell to module are presented in Table 5.

Table 5. n-type MWT average cell efficiency, corresponding module power and FF loss from cell to module (multi-flash class A, IEC60904-9 measurement, ESTI reference module).

	Average cell η	P_{max} **(W)**	**cell-to-module FF loss**
n-MWT module	19.6%	279	1.3%

Despite an improved maximum power, this n-MWT module shows a slightly higher CTM FF loss compared to the n-MWT module presented in section 4 which is possibly due to the use of a different conductive adhesive. Also, the module Isc turned out to be lower than expected from results on earlier modules, probably because of Impp mismatch of a few n-MWT cells. With better Impp matching and the CTM FF-loss of Table 3, module power above 285Wp should be possible.

6 CONCLUSION

We have developed a manufacturing process for metal-wrap-through silicon solar cells and module on n-type mono-crystalline Czochralski (Cz) silicon wafers, leading to a module power, so far, of 279Wp from cells of 19.6% average efficiency. With current density (J_{sc}) approaching 40 mA/cm^2 and open circuit voltages of 644 mV, the large area (239 cm^2) n-MWT solar cells outperform n-Pasha solar cells (bifacial n-type H-pattern cells with contact grids on front and rear) manufactured with a comparable process. In a direct comparison experiment, an efficiency gain of 0.3% absolute for MWT was achieved. Loss evaluation assisted by analytical modeling demonstrates a clear potential for series resistance and fill factor improvements. From an initial optimization of metal grid designs, a FF increase of 1% absolute was achieved and a best efficiency of 19.8%. Additional optimization of paste properties and contacting layout as well as application of the optimum process parameters will allow the n-MWT cells to reach efficiency above 20%.

Performance enhancement at module level is obtained thanks to the ECN MWT module manufacturing technology based on integrated back-foil (conductive interconnect patterns integrated on the backfoil). In a full size module (60 cells) comparison experiment between MWT and equivalent n-Pasha tabbed modules, a power increase of approximately 3% for the n-MWT module was obtained. A later batch of cells with improved efficiencies (19.6% average) resulted in a module power close to 280Wp. This module power gain can be increased further by better Impp matching and further optimization of the back-sheet reflectivity or the cell packing density, and of course by further cell efficiency increase.

7 ACKNOWLEDGMENTS

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