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High efficiency n-type metal wrap through cells and modules

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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 upto nearly 20% have been reported. MWT cells allow even higher cell efficiency, and additionally full back-contacting of the MWT cells in a module results in reduced cell to module (CTM) losses.
MWT cells were produced by industrial process technologies. The efficiency of the MWT cells reproducibly exceeds the front contact cells based on the same technology by about 0.2-0.3%, and routes for further improvement are analysed.
60-cell modules were produced from both types of cells. The MWT module, based on integrated backfoil, produced 3% higher power output than the comparable tabbed front emitter contact module. In particular differences in CTM loss of current and fill factor will be presented. CTM current differences arise from the higher packing density, and 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 2.2%$_{abs}$ lower than for the tabbed front emitter contact module. Also here the losses are analysed and routes for improvement discussed.

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

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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 which 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 and reduced cost of n-MWT modules.

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.

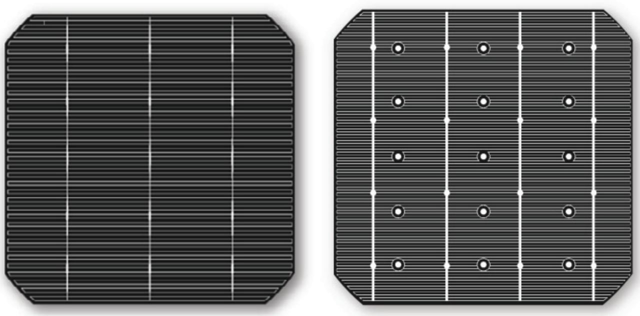

Fig. 1. Image of n-type MWT silicon solar cells with a H-pattern based unit cell design: front side (left picture) and rear side (right picture)

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, 5 Ωcm resistivity, bulk lifetime of 1ms as specified by the material supplier). 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.)

	Jsc (mA/cm2)	**Voc (mV)**	**FF (%)**	**η (%)**	**Rse (mΩ)**
Av. on 4 cells					
PasHa	38.4	638	79.1*	19.38	4.5
MWT	39.5	644	77.1	19.61	5.8
Best efficiencies					
PasHa	38.5	638	79.2*	19.45	4.4
MWT	39.6	644	77.2	19.70	5.7

As mentioned previously, in contrast to n-PasHa cells, the front side grid busbars of the n-MWT cells can be much narrower. Also, n-MWT and n-PasHa cells include the same number of front side fingers but the n-MWT fingers are 10µm narrower most likely due to the small changes of the paste rheology during the printing process. These front side grid pattern differences between n-MWT and n-PasHa cells lead to a 2.5% absolute reduction in front side metal coverage for n-MWT. As a result, shading loss and metal contact related recombination will considerably decrease leading to an important current and voltage gain for the n-MWT cells of 2.8% and 1%, respectively. While the voltage gain is only due to the reduced front recombination [15-17], the current gain will arise from the reduction of shading loss as well as from the voltage gain. From experimental results [18], it has been demonstrated that approximately 0.6% current increase is obtained for every 1.0% increase in voltage.

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 (Fig. 2). However, this may also increase recombination, and therefore, cause Voc loss (mixed dashes 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 optimization, cell efficiency above 20% is possible.

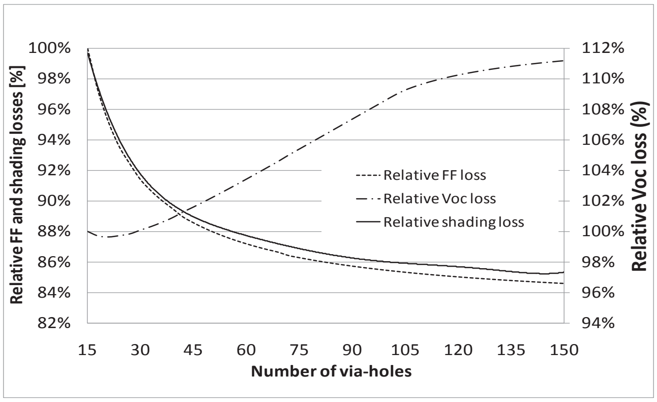

Fig. 2. Calculated relative FF, shading and Voc loss as a function of the number of via-holes for n-MWT cells

4. N-type MWT versus n-type PasHa modules – direct performance comparison

n-MWT and n-PasHa cells were processed in parallel and were encapsulated in 60-cell modules. 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 [19]. 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, according to the international standard IEC60904-9, with an estimated measurement accuracy of ±4% and a measurement reproducibility within 1%. An ESTI calibrated module was used as a reference. 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 module power and FF loss from cell to module (multi-flash class A, IEC60904-9 measurement, ESTI reference module)

	Pmax (W)	Absolute cell-to-module FF loss
n-MWT module	273	0.8%
n-Pasha module	265	3%

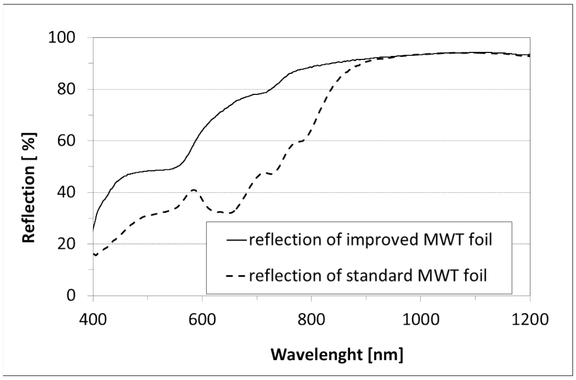

Fig. 3. Reflection measured in air of standard MWT integrated back-foil (used in experiment of Table 3) and a preliminary improved back-foil

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 I_{sc} 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 I_{sc}. The CTM I_{sc} gain can be further optimized by adjusting the spacing between the MWT cells.

5. Conclusion

We have developed a manufacturing process for metal-wrap-through silicon solar cells on n-type mono-crystalline Czochralski (Cz) silicon wafers, leading to efficiencies up to 19.70% on large area wafers (239 cm², 5 Ωcm). With current density (J_{sc}) approaching 40 mA/cm2 and open circuit voltages of 644 mV, n-MWT solar cells outperform n-PasHa solar cells (non back-contact n-type bifacial H-pattern cells) 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. By optimization of metal grid designs, paste properties and contacting layout, efficiencies above 20% are within reach.

Further performance enhancement at module level is obtained thanks to the ECN MWT module manufacturing technology based on integrated conducting back-foil. In a first full size module (60 cells) experiment, in a comparison to an equivalent n-PasHa tabbed module, a power increase of approximately 3% for the n-MWT module was obtained. This module power gain can also be increased further, for example by optimizing the back-sheet reflectivity or the cell packing density. All together, these results indicate the potential of the n-type MWT technology to become a breakthrough for low cost, high power solar energy generation.

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