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HIGH EFFICIENCY N-TYPE METAL-WRAP-THROUGH CELLS AND MODULES USING INDUSTRIAL PROCESSES

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ABSTRACT: We report on our high efficiency n-type metal-wrap-through (MWT) cell and module technology. In this work, bifacial n-type MWT cells are produced by industrial processes in industrial full-scale and pilot-scale process equipment. The n-type cells benefit from high recombination lifetime in the wafer and bifaciality. When combined with MWT technology, high-power back-contact modules result, which can employ also very thin cells.
We will discuss optimization of the MWT contact layout and impact on paste consumption, showing how MWT technology, like multi-busbar technology, can support very low paste consumption while increasing efficiencies at the same time. We report a cell conversion efficiency of 21% (in-house measurement on a not conducting, but reflecting chuck), a significant gain compared to our earlier work.
Full-size modules (60 cells) have been made with power exceeding 300Wp and cell-to-module ratios of the different I-V parameters are discussed. Modules from cells with average efficiency of 20.9% are pending. This work shows that low-cost n-type bifacial cells are suitable for industrial high efficiency back-contact technology.

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

1 INTRODUCTION

High efficiency, ease of industrialization and reliability are the main drivers towards low-cost (€/Wp) Silicon PV. The International Technology Roadmap for PV from March 2014 expects the share of n-type solar cells and modules to become close to 40% in the next 10 years [1]. In accordance with this expected trend, the ECN's n-type Metal-Wrap-Through (n-MWT) technology is a relatively small step from the n-type front-and-rear contact and bifacial Pasha technology (developed by ECN and produced by Yingli under the brand name Panda cells [2]) to a high-efficiency rear-contact cell and module technology which offers significant cell and module performance gain in a cost-effective way [3]. With only modest changes to the n-Pasha production process, the n-MWT technology reproducibly increases the performance with up to 3% power gain at module level [3] and up to 5% module power gain are anticipated. A full size module made using n-MWT cells of 20.5% average efficiency resulted in a power output of 300.5 Wp. To place in perspective, with cell efficiency over 20.9%, a full area n-MWT module power between 305 and 310 W is expected.

ECN's MWT module technology is based on interconnection with an integrated conductive back-foil and allows to reduce cell-to-module power loss compared to a conventional tabbing technology, as used to interconnect the n-Pasha cells. Also, the module manufacturing based on integrated back-foil can be done with higher yield and reduced interconnection-process-related stress, allowing use of (much) thinner cells and therefore offering additional cost reduction possibilities. In this paper, the latest results of the n-MWT technology development will be shown. Besides an $0.15\%_{abs}$ efficiency gain obtained over n-Pasha in a direct comparison run between n-MWT and n-Pasha, a best cell efficiency of 21% was obtained on n-MWT in a recent run including process adjustments which will be discussed.

2 ECNs n-TYPE TECHNOLOGY PLATFORM

ECN's aim is to develop highly efficient, low-cost and reliable solar cells and module concepts that can easily be adopted in mainstream industrial production. Based on over 10 years of research, ECN has established a technology platform on n-type Cz material that encompasses three different cell-module concepts (Figure 1). The basis of the technology platform is the relatively simple n-Pasha cell, a bifacial solar cell with H-patterned metallization on both front and rear. In 2010, ECN, Tempress and Yingli Solar introduced this cell to the market as a novel bifacial cell concept called Panda while in 2013 Nexolon America selected this cell concept for their new production line, enabling the production of bifacial modules.

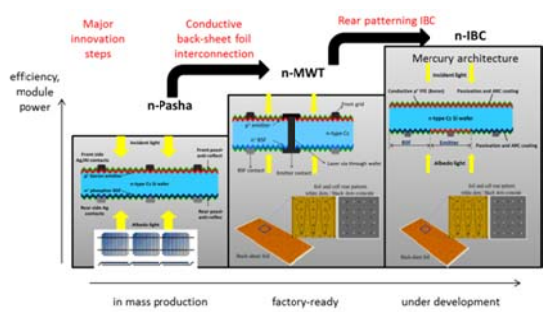

Figure 1: ECN's technology platform

The next step up in performance on the technology platform is the integrated back contact n-MWT cell and module that combines two of ECN's cell concepts already proven both in the lab and on a large scale in industry: 1) ECN's p-type MWT cell and module concept, based on foil interconnection and 2) the n-Pasha n-type cell concept, as described above. The n-MWT cell process yields a higher short circuit current and therefore a higher efficiency due to reduction of front side metallization coverage compared to n-Pasha H-pattern. The cell interconnection is based on a back contact interconnection foil with integrated Copper or Aluminum conductor layer. This module architecture enables higher module power due to optimization for low series resistance losses. It significantly reduces efficiency loss from cell to module, since the constraints related to normal front-to-back tabbed interconnection (i.e., shading loss and series resistance from the tab, and stress on the cell) are absent [4]. The n-MWT modules are ready to be produced on industrial scale. Yingli announced recently in a press release their trial production of n-MWT cells and modules [5].

Apart from being a cost-effective high-efficiency PV technology, the n-MWT technology is the logical step in the roadmap from n-Pasha to n-type IBC (interdigitated back contact) technology. In an IBC cell, the p-n-junction and all metallization is moved to the rear. Recently ECN has presented n-type IBC Mercury cells [6, 7], that employ a relatively conductive Front Floating Emitter to avoid electrical shading issues present in conventional FSF (Front Surface Field) IBC cells, resulting in relaxed demands on the geometrical resolution in the processing. This allows manufacturing of highly efficient solar cells from a process similar to the n-pasha and n-MWT cell processes. The IBC Mercury design can be combined with ECN's back-contact module technology similar to the n-MWT cells. The Mercury cell is currently under development at ECN, and will also be presented in this conference [8].

3 APPROACH TO n-MWT CELL PROCESS DEVELOPMENT

The n-type MWT process is similar to the industrial process used for ECN's n-Pasha and Yingli Solar's Panda cells (Pasha= bifacial cell design with passivated front and rear side and with H-pattern contact grids). This makes it easy to directly compare the two concepts. Like the n-Pasha cells, the n-MWT cell structure comprises a front-side boron emitter, a phosphorous Back Surface Field (BSF) and an open rear side metallization 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 layout [9]. 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 2 (15 via-holes layout).

Figure 2: Image of an n-type MWT silicon solar cells (239cm^2) with a H-pattern based unit cell design and 15 vias: front side (left picture) and rear side (right picture)

3.1 Efficiency gain of MWT over front-and-rear-contact cells

N-type MWT and n-type Pasha solar cells were prepared from adjacent n-type Cz wafers (239 cm², 200 µm thickness, around 1.7 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 pastes 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 with comparable J_0 and metallization parameters, to illustrate the relative changes associated with MWT design. R_{se} obtained from fit to two-diode model. J_{sc} corrected for spectral mismatch. N-type Pasha and n-type MWT measurement chucks have a reflective surface to simulate the operation in a module with white back sheet.

	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF (%)	η (%)	R_{se} (mΩ)
Av. on 12 cells					
n-Pasha	38.90	652	78.4	19.89	4.9
n-MWT	39.95	652	76.8	20.04	5.7
Best efficiencies					
n-Pasha	38.97	653	78.5	19.98	4.8
n-MWT	40.01	653	77.0	20.10	5.6

The J_{sc} gain of 2.6% for the n-MWT cells is related to the reduced front metal shading losses thanks to the narrower front busbars. Because the n-Pasha process used non-contacting front busbar paste [2], no V_{oc} gain of the n-MWT cells from the reduction of busbar area (reduced metal recombination) is achieved. In this experiment the cell efficiency benefit of the MWT structure is therefore about 0.15%abs, compared to about 0.25%$_{abs}$ previously reported. The major 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

Source of R_{series} in MWT cell	R_{series}	FF loss
Metal via resistance	0.2 mΩ	0.3% abs.
Front side busbars	0.7 mΩ	1.1% abs.
Increase of I_{sc}		0.1% abs.
Total	0.9 mΩ	1.5% abs.

3.2 Improving MWT efficiency through the number of contact points and process optimization

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. However, this may also increase recombination, and therefore, cause V_{oc} loss [3]. More importantly, increasing the number of vias allows to reach similar or better benefits of paste reduction as in multi-busbar cells because less and thinner fingers can be used. For example, 5 rows of vias provide the same opportunity for paste reduction (and FF gain) as a solar cell with 5 busbars.

Further gain is possible by using other metallization grid patterns than the rectangular H-pattern grid. For the rear, contact pads can be added without increasing the number of vias, almost without effect on recombination, again resulting in reduction of metallization paste and resistive losses. We estimate that increasing the number of vias and contact points by approx. a factor of 2 should enable reductions of paste consumption also by approx. 50%, even in combination with an increase of cell efficiency.

We have analyzed the efficiency change of an n-MWT cell as a function of the type of front-side pattern (H-pattern as shown in figure 2 or ECN's "Star"-pattern from which a unit cell is shown in figure 3), the number of holes and the front metallization properties. The results of the calculation are presented in table 3. The absolute efficiency change includes the effect of the number of contact points and metallization coverage on the V_{oc}, I_{sc} and pseudo-FF.

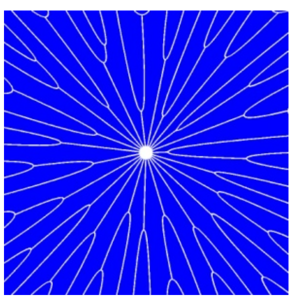

Figure 3: Schematic of a star-pattern unit cell

Table 3: Absolute efficiency change of an n-MWT cell calculated for different front side pattern (H-pattern or Star-pattern), different number of via-holes (up-to 25). Assumed front metallization properties: W_{line} = 56 µm, R_{line} = 0.23 Ω/cm.

Front pattern type	Number of holes	Metallization area (%)	Calculated absolute efficiency change
5x5 Star-pattern	25	3.6	+0.40%
4x4 Star-pattern	16	3.6	+0.37%
5x5 H-pattern	25	4.3	+0.10%
4x4 H-pattern (reference)	16	4.6	0.00%

From this study, the best efficiencies will be reached using the Star-pattern. Compared to the currently used H-pattern with 16 holes the Star-pattern with 25 holes will allow to improve the efficiency by around 0.4% absolute while reducing paste consumption (metallization area) by about 20%. The H-pattern design involves a busbar to connect the fingers to the via-holes. Increasing the number of holes will therefore reduce the busbar length and the distance to the via-holes for the charge collected in this busbar, as well as the current collected per unit cell. Consequently, an efficiency gain of around 0.1% will be obtained by increasing the number of holes from 16 to 25, again in combination with a reduction of paste consumption (however, more modest than in the case of the Star pattern).The efficiency gain calculated for the Star-pattern grid is negligible when going from 16 to 25 holes.

Similar efficiency benefits and larger paste reductions can be obtained by using more contact points on the rear of the cell, giving rise to the estimated feasibility of a factor 2 reduction of paste consumption mentioned above.

To maximise the efficiency gain even further, new n-MWT patterns with 36 vias (6 rows with each 6 vias) were designed and tested. The simplest new n-MWT design is based on 6 thin busbars connecting the rows of 6 vias. The rear pattern also consists of thin busbars, connecting 7x7 (-4, because of semisquare wafer format) base contact points (figures 4-A and 4-B). Alternatively, different front side patterns can be designed for improved aesthetics. Two examples were tested: the so called "star" pattern and a "circle" pattern (figures 4-C and 4-D). All three 6x6 front side configurations were combined with the rear side metal pattern shown in figure 4-B and compared against the old 4x4 pattern in a cell experiment consisting of 4 groups. All cells were processed in parallel from adjacent n-type Cz wafers (239 cm², 200 µm thickness, around 3.8 Ωcm resistivity). Process steps and process parameters applied were identical for all groups apart from the front metallisation design as visible in figure 4.

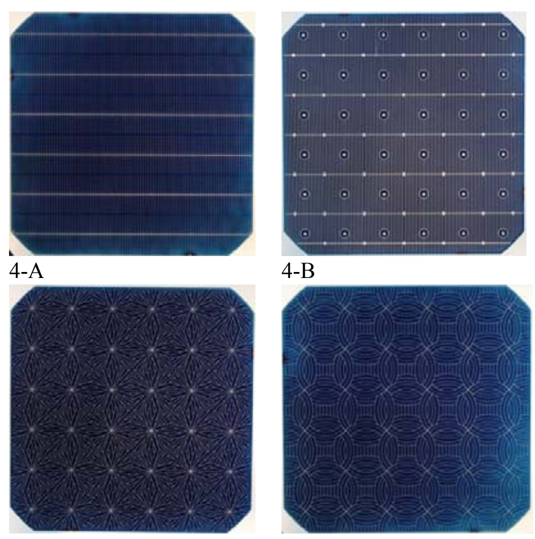

Figure 4: A) Front side 'new' nMWT: 6x6 vias with thin busbars. Metal fraction ~ 3.1% of total cell area **B)** Rear side 'new' n-MWT: 6x6 emitter contacts and (7x7)-4 base contacts (corners are excluded due to the semisquare wafer **C)** Star pattern, metal fraction ~ 4.7% of total cell area **D)** Circle pattern, metal fraction ~ 4.4% of total cell area

The I_{sc}, V_{oc}, FF and efficiency data of the 4 groups are shown in figure 5. I_{sc} and V_{oc} were both found to depend mainly on the metal fraction. The increased number of vias did not seem to have a negative effect on the passivation (V_{oc}) at this stage. The 4x4 n-MWT pattern has the largest metal fraction of around 5% including the busbars, resulting in the lowest currents. The "new" n-MWT pattern with busbars and 36 vias has the smallest metal fraction of only 3.1%, which resulted in cells with a high current of average 9.63 A, and average V_{oc} of 654 mV. Due to different metal printing method, the "star" and "circle" front print resulted in wider lines. Therefore, contrary to calculations presented in table 3, the metal fraction of these two designs is higher than the metal fraction of the "new" n-MWT pattern with busbars leading to lower I_{sc} and V_{oc} .

As expected the FF of the 6x6 vias busbar pattern is clearly better than for the 4x4 vias busbar pattern, but the highest FFs are obtained for the 6x6 "Star" pattern that is specially modelled and designed to limit resistance losses. However, its higher FF is not sufficient to compensate for the I_{sc} and V_{oc} loss due to wider front-side metallization resulting in a lower efficiency compared to the "busbar" pattern. The highest efficiency of 20.3% average is therefore obtained for the 6x6 vias busbar pattern because of its superior J_{sc} and V_{oc}, Corresponding to around 0.6%$_{abs}$ average efficiency gain over the former 4x4 n-MWT pattern.

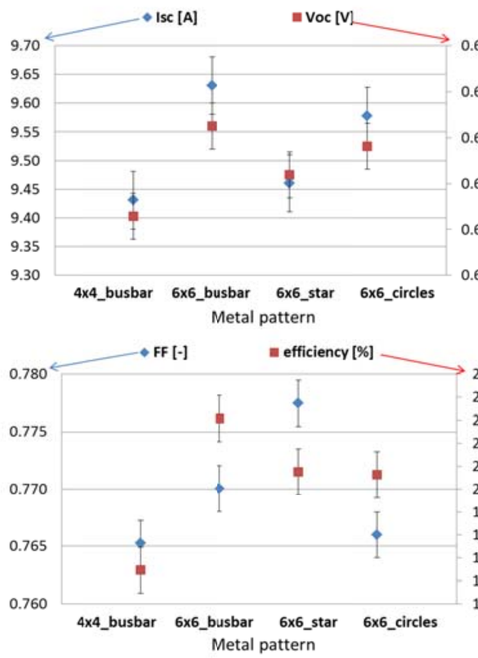

Figure 5: I_{sc}, V_{oc} (top graph) and FF, Efficiency (bottom graph) of n-MWT cells with different amount of vias (16 and 36) and different front metal patterns.

In two following runs, a batch of 60 cells and a second batch of 150 cells was processed using the "new" n-MWT pattern with busbars and 36 vias (figure 4-A & 4-B). Also, recent process improvements developped on n-Pasha cells [10] were integrated to the n-MWT cell process. I/V data are presented in table 4.

Table 4: I/V characteristics of n-type MWT cells. n-MWT measurement chuck has a reflective surface to simulate the operation in a module with white back sheet. J_{sc} corrected for spectral mismatch.

	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF (%)	η (%)
Average of 1st batch of 60 n-MWT cells	39.8	651	79.3	20.5
Average of 134 n-MWT cells	40.0	654	79.3	20.8
Best efficiency n-MWT	40.3	656	79.4	21.0

From this second run a best cell efficiency of 21% (spectral mismatch corrected) and average efficiency of 20.8% over more than 134 cells were reached with a very narrow efficiency distribution (shown in figure 6) indicating a very stable process.

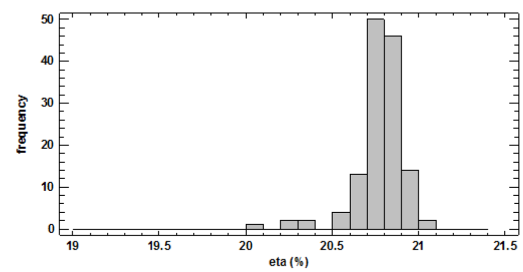

Figure 6: Efficiency distribution of 134 n-MWT cells fabricated with the optimized 6x6 via pattern and including recent n-Pasha improvements (before spectral mismatch correction).

4 n-MWT MODULE POWER

We have previously extensively reported on n-MWT module performance compared to n-Pasha module performance, and in particular comparative cell-to-module losses [3]. Compared to the front to rear side tabbed interconnection used for the n-Pasha cells, the rear-side foil interconnection of the MWT module allows to reduce the module series resistance by using more interconnect metal (more cross-sectional area) and thereby reduce the cell to module FF loss. An n-MWT module outperforms the corresponding n-Pasha tabbed module with a CTM FF loss which can be below 0.8% absolute, more than 3 times lower than the FF loss for n-Pasha as shown in table 5.

Table 5: 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%

A 60-cells n-MWT module was fabricated using the first batch of cells processed with the 6x6 vias and also including some of the recent process improvements developed on n-Pasha. I/V data of this batch of n-MWT cells are presented in the first row in Table 4.

This is the first time ever that a full 60 cells module has been made from n-MWT cells with the new 6x6 pattern. A module power of 300 Wp was reached.

Cell data, corresponding maximum module power and calculated cell-to-module ratios are shown in table 6. The n-MWT module I-V parameters were measured at ECN using a class A multi-flash tester (16-flash measurement). The module shows a gain in I_{sc} of 3% as compared to the cells and a loss in FF of 2%.

Table 6: 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)

	Isc [A]	Voc [V]	FF [%]	η [%]	Pmax [W]
n-MWT cells	9.66	0.651	79.3	20.5	298.9
n-MWT module	9.92	38.85	78.0		**300.5**
CtM	1.03	1.01	0.98		1.01

A new 60-cells n-MWT module will be assembled in the coming month with the best 60 n-MWT cells processed using the "new" n-MWT pattern discussed in the previous section (20.9% average efficiency). Assuming similar cell to module ratio's, we can expect a module power of well above 305 Wp.

5 PROCESSING OF 140 µm THIN n-MWT CELLS

In addition to an improved cell-to-module power ratio, the ECN's MWT module technology exerts less stress during interconnection allowing use of thinner cells and therefore offering a significant cost reduction opportunity. Therefore we compared cells from 140 µm and 200 µm n-type Cz wafers thickness with similar electrical properties (bulk lifetime and diffusion length) and processed in parallel. Average I/V data are presented in Table 7. These cells was fabricated according to a process at an intermiediate phase of improvements. Also the former 4x4 n-MWT busbar front-side grid pattern was used for this test. Therefore, this process being less optimal than it is today, the average cell efficiency presented in Table 7 is lower than the one presented in section 3, Table 4.

Table 7: I/V characteristics of n-type MWT cells processed from 200 µm and 140 µm thin wafer.

	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF (%)	η (%)
Av. on 12 cells				
n-MWT–200µm	40.0	652	76.8	20.0
n-MWT–140µm	39.6	651	76.5	19.7

No increase in breakage rate was observed during the processing of these thin n-MWT cells at ECN. Comparable V_{oc} and FF show that there is no significant shift between bulk and surface recombination. A ≈1% relative lower J_{sc} for the thin n-MWT cells is probably due to reduced light trapping. This effect is illustrated by the higher reflectance at the long wavelengths as shown in Figure 7. This also correlates with the lower IQE of the thin n-MWT cell for wavelengths of 1000nm and longer (due to the rear internal reflection being less than 100%). These results are consistent with PC1D modelling of our cells. However, we note that fluctuations of 1% in J_{sc} between cells from nominally good material quality can occur anyway, even for standard thickness wafers. Therefore it is difficult to draw firm conclusions on the effect of wafer thickness on J_{sc} at this moment.

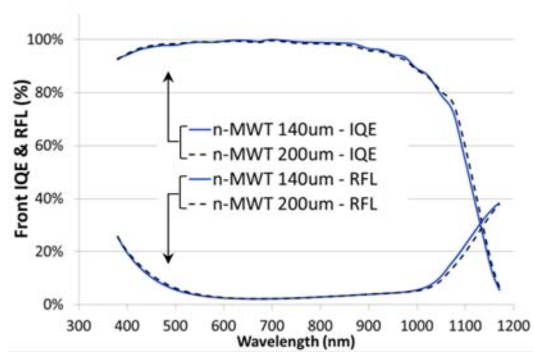

Figure 7: Internal quantum efficiency and Reflectance measured from the front side of n-MWT cells processed from 200 µm and 140 µm wafer thickness.

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 300.5 Wp from cells of 20.5% average efficiency. With current density (J_{sc}) above 40 mA/cm^2 and open circuit voltages above 655 mV, the large area 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 recent direct comparison experiment, an efficiency gain of 0.15% absolute for MWT was achieved with a best MWT cell efficiency of 20.5%. Further optimisation of the cell contacting layout and cell processing resulted in a significant performance boost from which a best cell efficiency of 21.0% was reached providing in a same time opportunity for paste and therefore cost reduction. Also, the narrow efficiency distribution on a large batch of cells proves the good stability of the process.

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. Interconnection of a batch of cells with average efficiency of 20.5% resulted in a module power above 300 Wp. Module power gain above 305 Wp is expected to be reached by interconnected the 60 best n-MWT cells with an average efficency of 20.9% manufactured in the last run. This work is currently being conducted.

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