# Development Towards 20% Efficient N-type Si MWT Solar Cells For Low-Cost Industrial Production

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Compared to traditional H-pattern cells, back-contact Metal Wrap Through (MWT) cells allow higher efficiency at cell level thanks to the front metallisation coverage, and higher efficiency at module level thanks to the reduced interconnection resistance losses. We have developed, in collaboration between ECN and Yingli Solar, n-type mono-crystalline MWT solar cell technology leading to efficiencies up to 19.7% (in-house measurements) on large area wafers (239 cm²). In this article, we demonstrate that efficiency of MWT cells reproducibly exceeds the front contact H-pattern cells based on the equivalent technology by about 0.25% absolute. Based on a loss analysis, we present solutions which open the possibility for further efficiency increase. We also describe module results where approximately 3% power increase has been obtained on MWT module over the corresponding H-pattern tabbed module (273 Wp for MWT versus 265 Wp for H-pattern module). Options to reduce cost and improve efficiency at module level are also discussed.

## 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. However, for a successful and large scale introduction of silicon PV on the market, competitiveness with other energy sources has to be improved. Consequently, high efficiency and ease of mass production, preferably combined with lower use of resources and improved environmental footprint, will be the main drivers to make Silicon PV a low-cost (cost/Wp) technology able to contribute to the rise of renewable energies.

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 (or absence) 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. These will be reviewed in the first section of this paper. 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 become active in 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 fulfil the objectives of low cost and high efficiency with only modest changes to the current wafer and cell production processes [1,2,3]. The use of n-type material has several advantages over the use of p-type which will also be described in the first section of this paper. Recently a high efficiency industrial n-type H-pattern technology has become available through ECN, Yingli Solar and Amtech Tempress collaboration and has been taken into production by Yingli Solar under the brand name "Panda" cells [1]. In this paper, we will 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 all sides and with H-pattern grids). In order to further increase cell and module efficiencies and decrease cost, we have combined the strength of the n-type doped crystalline silicon with our back-contact MWT solar cell technology [4] and developed high-efficiency n-type MWT crystalline silicon solar cells (n-MWT) in collaboration with Yingli Solar.

In this paper, after a brief description of the benefits of n-type crystalline silicon material and ECN's MWT cell and module technology, results from a simple process designed for high-efficiency n-MWT solar cells [5] will be described, as well as a direct comparison between mono-crystalline n-PasHa and mono-crystalline n-MWT technologies, using neighbour wafers. Focus of the analysis will be 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 loss of fill factor with respect to the loss in modules with tabbed n-PasHa cells. The FF losses are related to resistive losses in the copper circuitry on the back-foil for MWT versus the tabs for the conventional design. Also here we analyse the losses and routes for efficiency and cost improvements of the n-MWT modules.

## ECN's MWT concept adapted to n-type crystalline silicon material

### Benefits of the alliance between ECN's MWT technology and n-type material

MWT technology presents several advantages over the standard H-pattern cell technology. First there is the already mentioned current gain due to reduced front-side metallization coverage. In addition, and more importantly, integration in the 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 technology) is much less, 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 which contributes to a higher module efficiency. The front side metal grid benefits from a small unit cell pattern designed to reduce fill factor loss when up-scaled to larger cells (cf. fig. 1). Furthermore, the cell interconnection can be easily optimized for low series resistance losses and significantly reduce 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. For p-type mc-Si, it was demonstrated that a 2% relative gain in FF and a 1% relative gain in Jsc can be obtained at the module level compared to conventional H-pattern module manufacturing using tabber-stringer [4].

In addition to the efficiency enhancement due to MWT layout, efficiency can be increased using silicon base material with improved electrical properties. One of the most important characteristics of wafers for solar cells is the minority carrier diffusion length which is directly dependent on the minority carrier recombination lifetime and will have a significant impact on the cell efficiency. Consequently, minority carrier diffusion length and lifetime should preferably be as high as possible. In that respect, n-type wafers are a good candidate as they generally allow (much) higher lifetimes than p-type wafers after gettering and passivation [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 or in general upon minority carrier injection [8,9]. Also, n-type silicon has been proven to have a higher tolerance to common transition metal impurities, such as those present in silicon produced from quartz and carbon [10,11,12]. Thanks to this feature, n-type material could have a higher tolerance for lower-quality feedstock. In practice, lifetimes of several milliseconds are readily obtained in n-type Cz which makes it a base material of choice for high efficiency cells such as back-contact cells, or back-junction back-contact cells which require even longer minority carrier diffusion length. ECN, Yingli Solar and Amtech (and daughter company Tempress) brought into production one year ago ECN's high-efficiency industrial cell process developed for n-type wafers, using the conventional non back-contact H-pattern cell structure to production (n-PasHa cells [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.

For many years, the companies Sanyo and Sunpower have produced high efficiency solar cells and modules from n-type material. Both manufacturers apply advanced technologies and use high-quality mono-crystalline base material. SunPower is manufacturing fully back-contacted cells (Interdigitated Back-Contacted, IBC) and Sanyo is producing so-called HIT (Heterojunction with Intrinsic Thin-layer) cells. The MWT technology presents certain advantages over these high efficiency cell structures. For example, both of the above mentioned cell structures, in addition to the complexity of the cell processing, require very high quality of silicon material as well as surface passivation, and the IBC cells require high alignment accuracy of the metal contacts on the back side. In contrast, the MWT cell process technology remains close to conventional cell processing and the simplicity of the rear-side contact pattern of the MWT cells allows large tolerance regarding prints alignment. Also, the cell structure comprises a front side emitter and therefore will be less sensitive to material quality variations.

As mentioned previously, our integrated MWT cell and module technology, originally designed for p-type silicon material, has already proven itself, and significant efficiency gain over conventional non back-contact H-pattern cell and module level has been demonstrated. By merging these two successful technologies, even higher cell efficiency and module power output than the n-PasHa or p-type MWT can be attained. Thus, we have designed a novel low-cost industrial process to make very high efficiency n-type back-contact modules.

## Cell processing approach

In order to keep future production costs as low as possible, the n-type MWT process, also co-developed by ECN with Yingli solar, 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. The passivation process of the highly-doped boron emitter uses industrial equipment and provides excellent passivation quality on industrial emitters. 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 electrical contact is formed during a co-firing step through the passivation layers. The front and rear side metal grid patterns are based on a H-pattern lookalike grid design combined with the ECN unit cells concept developed to reduce series resistance in MWT cells when up-scaled to larger wafers [14]. We have chosen this design because it is well suited for a comparison of losses between n-MWT and n-PasHa cells. As module interconnection of our n-MWT cells does not involve a tab soldering process, our front side busbars can be significantly slimmed down compared to conventional n-PasHa cells. As a result, total shading losses related to metallisation are reduced leading to a significant current gain. Correspondingly, however, resistance in the busbars is larger, which affects the total series resistance of the cell. Through an optimised design of the busbars geometry, it is possible to balance shading and resistance losses to increase power output of the n-MWT cells compared to the n-PasHa cells (see section 3).

The rear side metallization of our n-MWT cells also has an open structure which enhances the rear-side reflection and improves the internal quantum efficiency in the long wavelength range. As a consequence, current and voltage are enhanced compared to cell structures comprising a full aluminium back surface field. Also, at module level, an open rear side metallisation can increase the annual energy yield by employing bifacial modules. The front and rear sides of the cells made according to this process sequence can be seen in Figure 1.

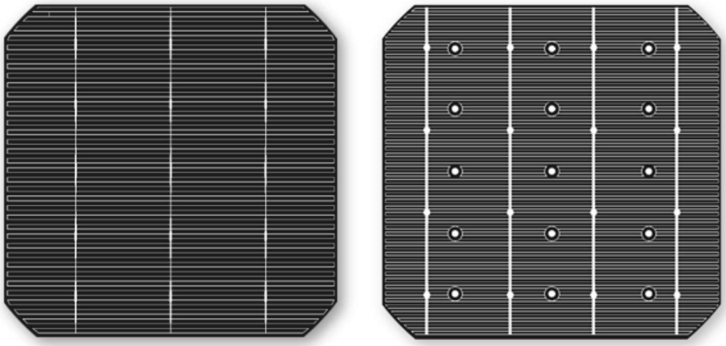

Figure 1. Image of n-type MWT silicon solar cells with a H-pattern based unit cell design: front side (left picture) and rear side (right picture).

## N-type MWT versus n-type n-PasHa solar cells – direct performance comparison

### Experimental conditions and results

The n-type MWT and n-type PasHa solar cells were prepared from 200 µm thick and neighbouring n-type Cz wafers (239 cm², around 5 Ωcm resistivity). The n-PasHa cells were processed using our high efficiency industrial process [1]. The n-MWT cells were processed according to the process described above. Both groups were processed in parallel in the ECN pilot line 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. Extra steps specific to the n-MWT process, such as LASER hole drilling or metal via paste printing, were also carried out in the ECN pilot line.

I/V measurements of n-MWT and n-PasHa cells were performed using two measurement methods. The first measurement method uses a flash light source and consequently induces capacitive transient effects in the cell leading to an underestimation of the FF. For both cell types, this measurement setup incorporates a contacting method comparable to the module interconnection procedure. n-PasHa cells are contacted in a similar way as the tab interconnection method using rows of multiple voltage and current probes which contact the front and rear side busbars. N-MWT cells are contacted in a similar way as the foil interconnection method, using only one current and voltage probe contact per emitter or base collection pad located on the rear side of the cells. Resistance losses in the interconnection tabs for H-pattern and in the interconnection foil for MWT, which are significantly lower in the foil than in tabs, are not included in this measurement. This means that on module level the efficiency difference will be larger (in favour of MWT).

The second measurement method uses a continuous light source (class AAA solar simulator) which does not induce any capacitive transient effect. Also, the chucks on which the cells are mounted have temperature control, and their reflectance is well-defined when using this I/V measurement system. On the other hand, in this case the contacting method of n-PasHa cells is not representative for the module interconnection procedure, because the rear-side grid is contacted on its full area by the conductive surface of the measurement chuck. In consequence, the FF of n-PasHa cells is (slightly) overestimated by this measurement system. The n-MWT measurement chuck being identical in both measurement setups, the contacting method of n-MWT cells remains representative for the module interconnection method, also using the second measurement system.

To improve accuracy of the comparison between n-MWT and n-PasHa cells regarding current and voltage, these two cell types were evaluated based on the IV data acquired by the second measurement system. These I/V data are presented in table I. A cell calibrated by ESTI (European Solar Test Installation) was used as a reference. Combining the uncertainties of the reference cell, calibration procedures and spectral mismatch correction, the measured short circuit current is given with an accuracy of ±2% relative. For a fair comparison, the FF overestimate for the n-PasHa cells, due to the full-area contact of the rear side grid, was evaluated. By comparing FF deviations of n-MWT and n-PasHa between the two measurement methods and using the support of modelling, this FF overestimate was estimated at approx. 0.2% absolute.

**TABLE I.** I/V characteristics of n-type PasHa cells and n-type MWT cells measured at ECN (continuous light source measurement system), with comparable $J_o$ and metallization parameters, to illustrate the gains associated with MWT design. ESTI calibrated cell was used as a reference. Rse obtained from a fit to the two-diode model. Jsc's were corrected for spectral mismatch.
*FF overestimated by approx. 0.2% absolute.

| | **Jsc (mA/cm$^2$)** | **Voc (mV)** | **FF (%)** | **η (%)** | **Rse (mΩ)** |
|---|---|---|---|---|---|
| **Av. on 4 cells** | | | | | |
| PasHa | 38.40 | 638 | 79.10* | 19.38 | 4.5 |
| MWT | 39.50 | 644 | 77.10 | 19.61 | 5.8 |
| **Best efficiencies** | | | | | |
| PasHa | 38.50 | 638 | 79.20* | 19.45 | 4.4 |
| MWT | 39.62 | 644 | 77.20 | 19.70 | 5.7 |

The average current density (Jsc) measured on the n-MWT cells approaches 40 mA/cm$^2$ and outperforms the Jsc measured on the n-PasHa cells by around 1.1 mA/cm$^2$ (i.e. a 2.8% relative gain). Also, the n-MWT cells show an average open-circuit voltage (Voc) gain of 6 mV (≈1% relative) compared to the n-PasHa cells. On the other hand, from this I/V measurement, series resistance (Rseries) of the n-MWT cell is higher than Rseries of n-PasHa cells by 1.3 mΩ. Correspondingly, the average fill factor (FF) of the n-MWT cells is 2% absolute lower than the FF of n-PasHa cells. Even if the FF remains so far limiting, a resulting efficiency gain of 0.25% absolute is measured on the back-contacted cells opposed to the H-pattern cell.

The additional Rseries and FF loss measured for the MWT cell will be analysed and discussed in the next section, using FF values of n-PasHa cells corrected by 0.2% for the reason described earlier. In consequence, the Rseries and FF loss analysis of n-MWT presented in the next section refers to an Rseries higher by 1.2 mΩ, and to a FF lower by 1.8% absolute compared to n-PasHa cells. Note that by applying this FF correction, the efficiency gain of MWT over n-PasHa cells becomes 0.3% absolute.

## Results analysis and discussion

The analysis of fill factor losses observed for the n-MWT cells is based on the evaluation of additional series resistances generated by the metal vias used to carry the charges extracted by the front side emitter grid to the rear side, and the difference in front metallization grid design. Contributions to series resistance and FF losses are summarized in the table II.

Resistance of each metal via is quantified by a 4 point probe measurement technique. The total series resistance losses induced by all metal vias of the n-MWT cells are approximately 0.2 mΩ. This contribution to the overall series resistance losses of the n-MWT cells corresponds to a 0.3% absolute FF loss.

The second contributor to the lower FF measured on n-MWT cells is the higher resistance induced by the narrower front side busbars. Figure 2 shows the series resistance, the metal coverage induced losses, and the resulting total power losses relative to H-pattern, plotted versus the MWT busbar width. As the front side busbar width of MWT decreases, the losses in series resistance are rapidly compensated by the gain in current. Based on these trends, the n-MWT front side busbars width was chosen to minimize power losses and was fixed at 30% of the front side busbars width of n-PasHa cells. At this optimum, the series resistance losses are evaluated at 0.6 mΩ resulting in an absolute FF loss of 0.9%.

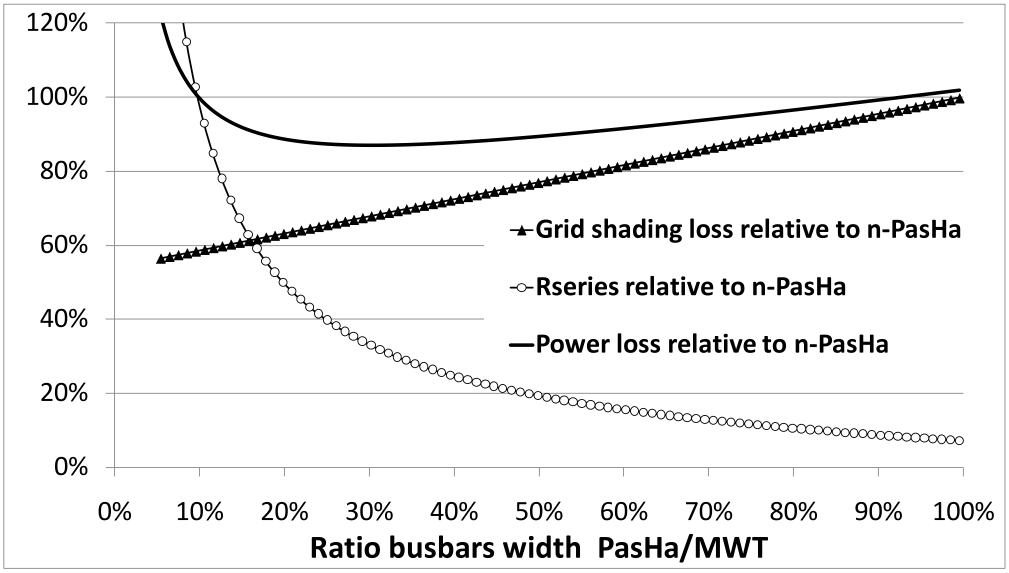

Figure 2: Calculated grid shading loss, series resistance, and resulting power loss of n-MWT cells relative to n-PasHa cells.

In addition to the Rseries induced by the thin front side busbars of n-MWT, extra Rseries losses were identified in the front side grid fingers. Despite an identical nominal opening designed in the screen, the front side finger width printed on the n-MWT cells was 10 µm narrower than the front side grid fingers printed on the n-PasHa cells, most likely due to the small changes of the paste rheology during the printing process. The number of fingers being identical for both type of cells, the narrower fingers printed on n-MWT cells increase line resistance loss as well as contact resistance loss. From analytical modelling, these Rseries losses are evaluated at 0.2 mΩ corresponding to an absolute FF loss of around 0.3%.

Finally, the increase of short circuit current measured on n-MWT cells will induce an increase in Power loss and consequently FF loss. A current increase of 2.8% will result in approximately 0.1% absolute FF loss.

**TABLE II.** Calculated contributions to series resistance and FF losses of the n-MWT cells compared to the n-PasHa cells.

| Source of Rseries in MWT cell | Rseries loss | FF loss |
|---|---|---|
| Metal vias 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 Isc | | 0.10% abs. |
| **Total** | **1 mΩ** | **1.6% abs.** |

From these modelling results, approximately 1.6% of the observed 1.8% additional FF losses present in the n-MWT cells, compared to n-PasHa cells, can be well evaluated and explained. A remaining 0.2% absolute FF loss has not been clearly accounted for in the loss analysis, but this discrepancy is so small that it is likely related to measurement and modelling uncertainties.

## Solutions to reduce series resistance of n-MWT cells for an efficiency boost

As described in the previous section of this paper, more than half of the contribution to series resistance in the n-MWT cells is due to the resistive losses in the front side busbars. As shown in figure 2, the reduction of the n-MWT front side busbars width by 30% relative to the n-PasHa front busbars results in a resistive loss increase of 35% relative to n-PasHa leading to a FF loss of 0.9% absolute for the n-MWT cells.

The first option which presents itself to reduce this FF loss is to reduce the front-side busbars sheet resistance of the MWT cells by improving their design and the conductivity of the metal paste. These two parameters must be tuned together as the optimum busbar design will also depend on the metal paste conductivity. Optimisation of the busbar design will also influence shading loss (linked to the metal coverage) and Voc loss (linked to the metal contact-related recombination). Figure 3 illustrates the relative power loss as a function of the relative front busbar sheet resistance reduction as well as the resulting cell efficiency for n-MWT cells. From this calculation, a realistic busbar sheet resistance reduction of 50%rel. results in a total losses reduction of approximately 4%rel. leading to an absolute efficiency gain of 0.1%.

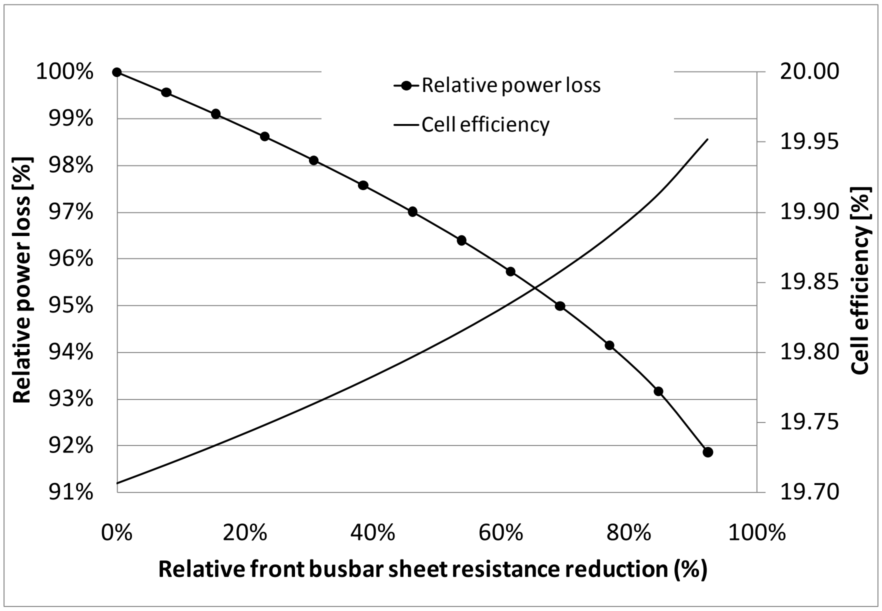

Figure 3: Calculated relative power loss and cell efficiency variation as a function of the relative front-side busbar sheet resistance reduction for n-type MWT cells.

FF loss of MWT cells can be mostly reduced by increasing the number of via-holes, meaning increasing the number of contacts to the front side metal grid.

As illustrated in Figure 4, when the number of via-holes increases, FF loss decreases thanks to the reduction of resistive losses in the front busbars (short dashes). Also, the width of the busbars can be further reduced leading to a significant reduction of the shading loss (solid line). On the other hand, the addition of via-holes will result in an augmentation of the contact points area on the rear-side leading to an increase of metal contact-related recombination. Therefore, the Voc loss tends to increase together with the increase of number of via-holes (mixed dashes). However, as shown from the dashed curve plotted in figure 5, if the number of via-holes does not exceed approximately 65 (around 4 times the current number of via-holes used), the Voc loss is compensated by the FF and shading loss reduction resulting in a maximum efficiency gain of around 0.23% absolute over the present cell design.

The two possibilities exposed above to improve efficiency of n-MWT cells can be applied simultaneously. Efficiency variation of n-MWT cells with optimized front busbar sheet resistance is plotted in figure 6 (solid line) as a function of the number of via-holes. As busbar sheet resistance is minimized, around 15 via-holes less are required to reach the optimum cell efficiency compared to n-MWT cells with standard front busbar sheet resistance. The reduction of front busbar sheet resistance together with the optimisation of the number of via-holes allow to reach a potential cell efficiency above 20%.

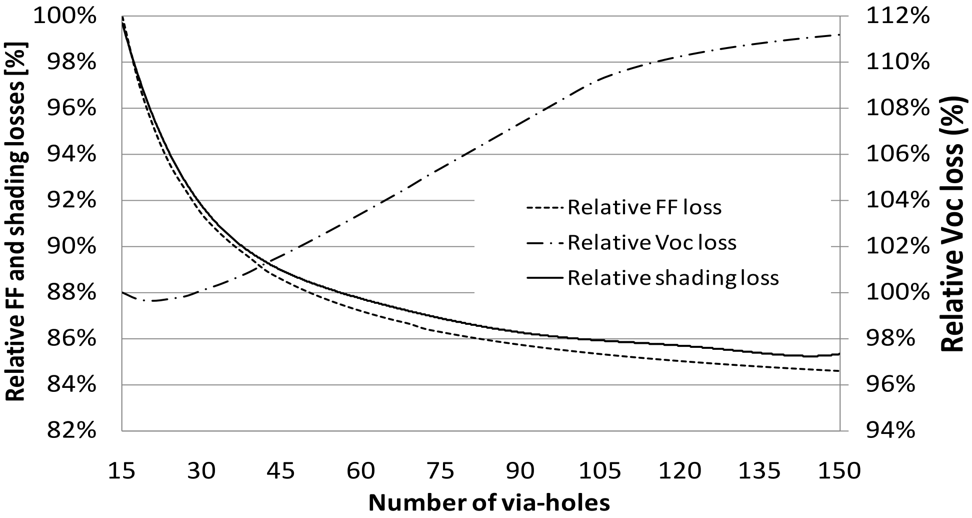

Figure 4: Calculated relative FF, shading and Voc loss as a function of the number of via-holes for n-MWT cells.

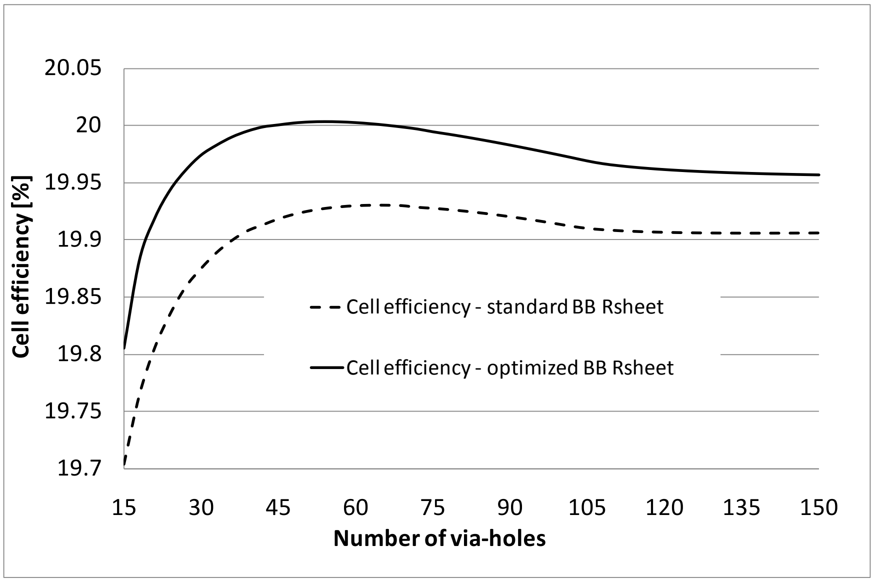

Figure 5: Cell efficiency variation versus the number of via-holes for n-MWT cell with standard and optimized busbar sheet resistance. The experimental cells contained 15 via-holes.

### A significant short circuit current and open circuit voltage gain for MWT.

Short circuit current, built up by the generation and collection of light-generated carries, will be directly dependent on the metal coverage which induces shading loss on the light-receiving side of the cell. As mentioned previously, in contrast to n-PasHa cells, the busbars included in the front side grid of the n-MWT cells can be much thinner leading to an important shading loss reduction and current gain. Also, n-MWT and n-PasHa cells include the same number of front side fingers but the n-MWT fingers are 10µm narrower. These front side grid pattern differences between n-MWT and n-PasHa cells lead to a 34% relative (2.5% absolute) reduction in front side metal coverage for n-MWT. The current gain is as expected about 2.8% relative.

Open-circuit voltage of a solar cell depends on the saturation current (Io) and the light-generated current (Isc) as described by equation 1. The saturation current Io, dependent on recombination in the solar cell, may vary by orders of magnitude and, as a result, is the key parameter which governs the Voc. In consequence, open-circuit voltage can be considered as a measure of the amount of recombination in the device.

$$Voc = \frac{nkT}{q} \ln\left(\frac{\mathrm{Isc}}{\mathrm{Io}} + 1\right)$$

Equation 1: Open circuit voltage as a function of: n=ideality factor; k=Boltzmann constant; T=temperature; q=electron charge; Io=Saturation current; Isc= short circuit current

Bulk and surface passivation quality of the n-MWT and n-PasHa cells being similar, the additional recombination, inducing a Voc drop of 1% relative for the n-PasHa cells, would be related to the extra metal contact area to the emitter consisting exclusively of the busbar area. In an analysis similar to that described by Benick et al. [15], equation 1 shows that an increase of 1% relative in Voc, observed in this experiment for n-MWT, is roughly consistent with a 34% relative front metal contact area reduction. Such impact of busbar- related recombination on the Voc is also described by, for example, G. Laudisio [16] and by A. Schneider [17].

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

### Module assembly conditions and results

N-MWT and n-PasHa cells were processed in parallel and were encapsulated in 60-cell modules. As mentioned in the first section of this paper, the ECN module manufacturing technology used to interconnect the n-MWT cells presents several advantages such as the use of an interconnection foil on which the cells are electrically contacted via a conductive adhesive. Compared to a front and rear side tab interconnection technology used to interconnect 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. Figure 6 illustrates the absolute FF loss, calculated from the resistive losses in the metal foil, as a function of the copper foil thickness. The n-MWT cells were typically interconnected with a copper foil of 35µm thickness from which a FF loss below 1%abs. is expected.

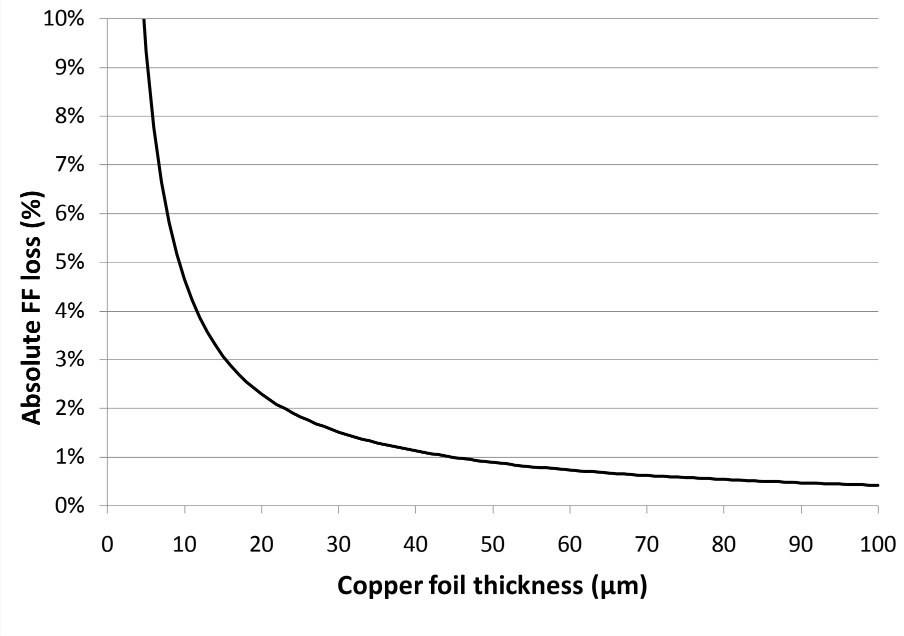

Figure 6: Calculated cell-to-module FF loss for an MWT module based on ECN's interconnection technology versus the copper foil thickness

N-MWT and n-Pasha module I-V curves were measured at ECN using a class A multiflash tester, according to the international standard IEC60904-9. An ESTI calibrated module was used as a reference. Maximum power and absolute FF loss from cell to module are presented in table III.

**TABLE III.** n-type MWT and n-type Pasha module power and FF loss from cell to module.

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

The n-MWT module outperforms the corresponding n-PasHa tabbed module with a maximum power gain of 8 watt and a cell-to-module FF-loss of only 0.8% which is more than 3 times lower than the FF loss for n-PasHa.

The reflectivity of the back-foils used for the n-MWT module is much lower than the standard TPT back-foil used for n-PasHa tabbed module. Therefore, significant gain (on the order of 1%) in Jsc is possible for n-MWT modules by employing high reflectance back-foils. Also, because light reflected from the back-foil in the space between the cells contributes the larger part of the cell-to-module Jsc increase (especially when the back-foil is highly reflective), the cell-to-module Jsc gain can easily be optimised by adjusting the spacing between the MWT cells.

## Cost-efficiency study of ECN's foil-interconnection technology

As shown earlier in this paper, the high efficiency of n-MWT cells as well as the low cell-to-module efficiency loss make n-MWT technology a serious candidate to replace the conventional and widely used double-side contacted p-type H-pattern modules as leading PV technology. However, in addition to the conversion efficiency increase, module manufacturing costs are also of importance and require full attention. The main contribution to the cost of an n-MWT module are the material costs due to the price of the copper interconnection foil which remains so far more expensive than standard TPT foils. Varying the thickness of the Cu sheet has two opposing effects on the costs per Wp. First, with increasing layer thickness the costs of the metal sheet and of some of the processes used to create the specific design pattern will increase. In contrast, the resistive losses in the module will reduce with increasing layer thickness. These two effects will consequently result in an economic optimum. Figure 7 shows the cost per watt peak for the n-MWT technology as a function of the copper foil thickness. In this calculation, costs related to the foil fabrication processes are not included. The module cost variation is estimated from the metal prize variation only, which is assumed to be a representative foil cost variation in the case of a large scale production where fabrication processes are negligible compared to consumables costs. The economic optimum for such copper back-sheet with a current market price of 5.5 euro/kg (large dashes) is reached for a foil thickness of approximately 35 µm. Logically, if the price of copper doubles, the cost/efficiency optimum will increase and shift toward lower foil thicknesses as shown by the dotted line in figure 7. Development of cheaper alternative foils, e.g. Aluminium-based interconnection foil, has recently become active. Aluminium is 1.7 times less conductive but currently 3 times cheaper than copper, and therefore optimum cost per Watt peak can be reduced by 1.3% using thicker back-sheet foil as shown by the solid line in figure 7. Also here, as for the copper foil case, the costs related to the fabrication process of the Aluminium based foil are not included in this calculation and are assumed to be similar to the one of a copper based foil.

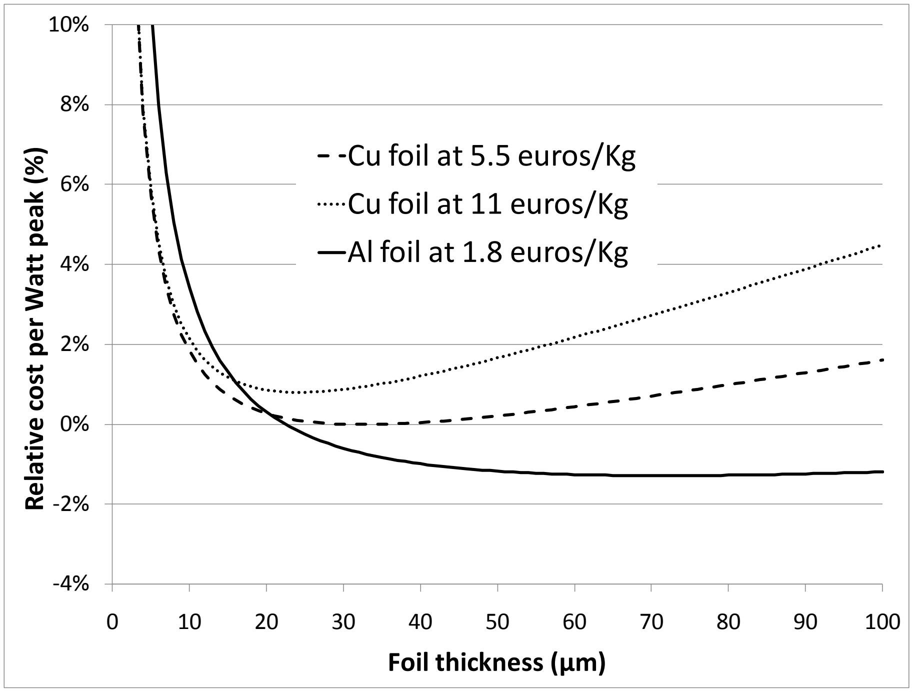

Figure 7: Relative cost per watt peak of the n-MWT technology as a function of the foil thickness for copper based and Aluminium based foils calculated based on the metal prize variation only. Costs related to the conductive foil fabrication processes are not included.

## Conclusion

Based on industrial cell processes we have developed metal-wrap-through silicon solar cells manufactured from n-type mono-crystalline Czochralski (Cz) silicon wafers leading to efficiencies up to 19.70% (in-house measurements) on large area wafers (239 $cm^2$, 5 Ωcm). With current density (Jsc) values approaching 40 $mA/cm^2$ 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 first direct comparison experiment, between n-MWT and n-PasHa technologies, 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 simple optimisation of metal grid designs, paste properties and contacting layout, efficiencies above 20% are within reach.

Further performance enhancement is obtained thanks to the ECN-MWT module manufacturing technology. Promising results were obtained in a first full size module (60 cells), in a comparison to an equivalent n-PasHa module. Tthe efficiency increase of MWT cells relative to n-PasHa cells, together with the use of ECN's foil interconnection concept, resulted in a power increase of approximately 3% for the n-MWT module over the corresponding n-PasHa tabbed module. This initial module power gain demonstration for the n-MWT technology can be increased further by optimizing the back-sheet reflectivity together with the packing density. Finally, the cost/efficiency ratio of the n-MWT technology, for as far as governed by the price of the interconnection conductor layer, can be significantly reduced by using cheaper alternatives such as Aluminium based foil which are currently under development. 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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