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Development towards 20% efficient Si MWT solar cells for low-cost industrial production

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Abstract

Low "Euros per Watt-peak" and ease of industrialization are the main drivers towards successful introduction on the market. In this regard, back-contact solar cells on n-type silicon offer significant benefits. The efficiency of back contact cells, such as Metal Wrap Through (MWT) cells, compared to the traditional H-pattern cells is higher at cell level, thanks to the reduced shading losses, and is higher at module level, thanks to the reduced interconnection resistance losses. N-type silicon benefits from improved electrical properties of n-type silicon compared to p-type (higher minority carrier diffusion lengths, lower sensitivity to many impurities). Furthermore, the availability of an industrial cell process designed by ECN, resulting in bifacial cells (good rear surface passivation and light trapping), makes n-type silicon a perfect candidate for high efficiency solar cells and requires only modest changes to the current wafer and cell production processes. In order to reduce processing costs and increase module efficiencies, we have started two years ago the development of the Metal-Wrap-Through (MWT) solar cell technology on n-type mono-crystalline silicon wafers. Within the last year, efficiency of our MWT silicon solar cells manufactured from n-type Cz silicon wafers has been improved by 1% absolute. Based on common industrial cell processing steps such as diffusion, screen-printing metallization and firing through, we have obtained efficiencies up to 19.70% (in-house measurements) on large area wafers (239 cm^2, 5 Ωcm), with clear potential for further improvement. In this article, we present a first direct comparison experiment between n-type bifacial MWT and "conventional" n-type bifacial H-pattern technologies, in which an efficiency gain of 0.30% absolute for MWT is demonstrated. At the moment, series resistance and, as a result, fill factor are still sub-optimal. Nevertheless, with current density (Jsc) values approaching 40mA/cm^2 and open circuit voltage of 644mV, n-type MWT solar cells already outperform n-type H-pattern cells manufactured with a comparable process.

C-Si, back contact, metal wrap through, high efficiency

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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 H-pattern technology. However, to improve competitiveness with other energy sources, low-cost (cost/Wp) and high efficiency solar cell technologies have to be developed, preferably combined with lower use of resources and improved environmental footprint.

Back contacted solar cell concepts such as Interdigitated Back Contact (IBC), Emitter Wrap Through (EWT) or 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, which 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 screen-printed processing has become active in the last 4-5 years. N-type silicon solar cells 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 be described in the first section of this paper. Recently a high efficiency industrial n-type H-pattern technology has become available through ECN which shows that production of low-cost n-type cells has become a real possibility [1]. We designate this technology, with H-pattern non-wrap-through contact grids on front and rear, as "n-PasHa" (for n-type cells, Passivated all sides H-pattern grids). In order to further increase cell and module efficiencies and decrease cost per Watt-peak, we have combined the strength of the n-type doped crystalline silicon with the development of our back contact MWT solar cell technology [4].

In this paper, after a brief description of the benefits of n-type crystalline silicon material and the advantages of the ECN's MWT cell and module technology, results from a simple process designed for high-efficiency n-type MWT (n-MWT) crystalline silicon solar cells [5] will be described, as well as a direct comparison between n-type mono-crystalline H-pattern and MWT concepts, 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, to understand the limitations to the cell efficiency gain of MWT compared to H-pattern.

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

2.1. 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. In addition to a current gain due to reduced front-side metallization coverage, implementation in the module is easier as the cell is fully back-contacted. The mechanical stress induced on the cells by conductive adhesive based interconnection 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 cell-to-cell distance can be significantly reduced 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 of MWT, cell and module 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. Recently ECN, Yingli Solar and Amtech brought ECN's high-efficiency industrial cell process developed for n-type wafers, using the conventional H-pattern cell structure to production [1]. In addition to benefiting from high base diffusion length, this cell design has other benefits, 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 [13] and 19.89% in production [14] 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, in addition to the complexity of the cell processing, both of the above mentioned cell structures 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 H-pattern cell and module level has been demonstrated. By merging these two successful technologies, even higher cell and module efficiency 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.

2.2. Cell processing approach

In order to keep future production costs as low as possible, the n-type MWT process under investigation is very similar to our industrial processes 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 on industrial emitters an excellent passivation quality. Metallization is applied using screen-printing and is fired through the passivating layers.

The printing process of the metal contacts is very similar to the printing process used in the n-PasHa industrial process and has no further requirements regarding alignment. The electrical contact is formed during a co-firing step. The front and rear side metal grid patterns are based on a H-pattern grid design combined with the ECN unit cells concept developed to reduce series resistance in MWT cells when up-scaled to larger wafers [15]. We have chosen this design because it is well suited for a comparison of losses between n-MWT and n-PasHa. 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. As a result, total metallisation related shading losses 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 has also an open structure which enhances the internal 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.

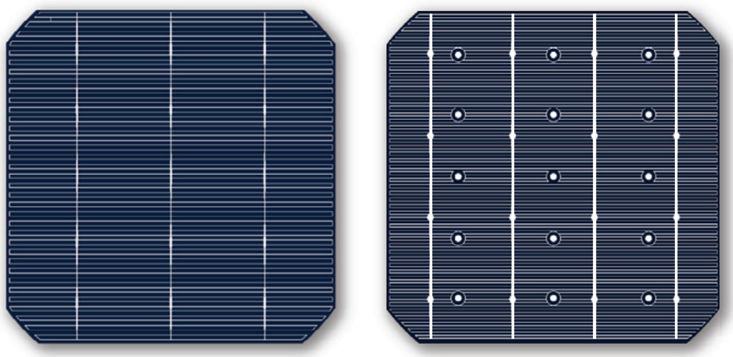

Figure 1: Image of n-type MWT silicon solar cells with a H-pattern based unit cell design: front side (left picture) and rear side (right picture).

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

3.1. Experimental conditions and results

The n-type MWT and PasHa solar cells were prepared from 200 µm thick and neighbouring n-type Cz wafers (239 cm^2, 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 contacting only 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, current calibration and temperature control are more reliable when using this I/V measurement system. On the other hand, the contacting method of n-PasHa cells is not representative from the module interconnection procedure, because the rear-side grid is contacted on its full area by the conductive 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 regarding current and voltage, these two cell types were evaluated based on the IV data acquired by the second measurement system (continuous light source, class AAA). 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 Jo 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 2nd diode model. Jsc's were corrected for spectral mismatch.
*FF overestimated by approx. 0.2% absolute

	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF (%)	η (%)	R_{se} (Ω)
H-pattern (average - 4 cells)	38.40	638	79.10*	19.38	4.5E^{-3}
MWT (average - 4 cells)	39.50	644	77.10	19.61	5.8E^{-3}
H-pattern (best cell efficiency)	38.50	638	79.20*	19.45	4.4E^{-3}
MWT (best cell efficiency)	39.62	644	77.20	19.70	5.7E^{-3}

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 6mV (≈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 1.3mΩ. Correspondingly, the average fill factor (FF) of the n-MWT cells is 2% absolute lower than the FF of n-PasHa. 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 in the next section, using FF values of n-PasHa 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 1.2mΩ, and to a FF lower by 1.8% absolute compared to n-PasHa. Note that by applying this FF correction, the efficiency gain of MWT over n-PasHa becomes 0.3% absolute.

3.2. Results analysis and discussion

3.2.1. MWT series resistance and fill factor loss analysis

The analysis of fill factor losses observed for the n-MWT cells is based on the evaluation of additional series resistance 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 thinner 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. At this optimum, the series resistance losses are evaluated at 0.6 mΩ resulting in an absolute FF loss of 0.9%.

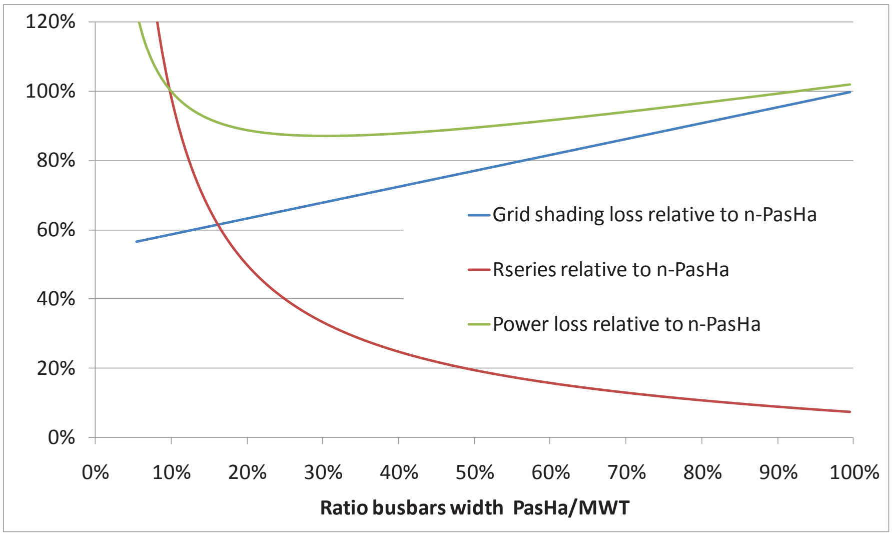

Figure 2: Calculated grid shading loss, series resistance, and resulting power loss of n-MWT cells relative to n-PasHa cells.

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 10µm less than the front side grid fingers printed on the n-PasHa cells, most likely due to the evolution 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 induce line resistance losses as well as contact resistance losses. From analytical modeling, these Rseries losses are evaluated at 0.2 mΩ corresponding to an absolute FF loss of around 0.3%.

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

Source of series resistance in MWT cell	**Rseries loss**	**FF loss**
Metal vias resistance	0.20 mΩ	0.30% abs.
Front side busbars in MWT versus tabbed busbars in n-PasHa	0.60 mΩ	0.90% abs.
Front side fingers in MWT versus front side fingers in n-PasHa	0.20 mΩ	0.30% abs.
Total	**1.0 mΩ**	**1.50% abs.**

From these modelling results, approx. 1.5% of the observed approx 1.8% additional FF losses present in the n-MWT cells, compared to n-PasHa cells, can be well evaluated and explained. The majority of these losses can be further reduced by improving front side metal grid design and metal paste properties. A remaining 0.3% 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 modeling uncertainties.

3.2.2. 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 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 function of: n=ideality factor; k=Boltzmann constant; T=temperature; q=electronic 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. From equation 1, an increase of 1% relative in Voc with a 34% relative front metal contact area reduction is consistent with a saturation current density of the metal contacts of approximately 3200 fA/cm^2 which is a typical value for metalized area of such devices. The outcome of this straightforward calculation shows that the Voc difference between PasHa and MWT observed in this experiment is roughly consistent with the reduction of busbar width. Such impact of busbar- related recombination on the Voc is also described by G. Laudisio [16] and by A. Schneider [17].

4. Conclusion

We have further improved the efficiency of our metal-wrap-through silicon solar cells manufactured from n-type mono-crystalline Czochralski (Cz) silicon wafers. Based on industrial cell processes including screen-printed metallization and firing through, we have obtained efficiencies up to 19.70% (in-house measurements) on large area wafers (239 cm², 5 Ωcm). With current density (Jsc) values approaching 40mA/cm^2 and open circuit voltage of 644mV, n-MWT solar cells outperform n-PasHa solar cells (“conventional” n-type bifacial H-pattern cells) manufactured with a comparable process. In a first direct comparison experiment, between n-MWT and n-PasHa technology, an efficiency gain of 0.3% absolute for MWT was achieved. Loss evaluation assisted by analytical modelling demonstrates a clear potential for series resistance and fill factor improvements. By simple optimisation of metal grid designs and paste properties, efficiencies of 20% or higher are within reach. Furthermore, low efficiency loss is expected after cell encapsulation using the ECN-MWT module technology [4]. From this alliance, the n-type MWT technology has the potential to become a breakthrough for the production of very high efficiency back contacted modules for low cost solar energy generation.

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