Current status of MWT silicon solar cell and module technology

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ABSTRACT

This paper reviews metal wrap through (MWT) solar cell and module technology. As MWT solar cells and modules have received more and more attention in recent years, many highly efficient MWT cell types have been presented by research institutes and industry and are summarized herein. The MWT cell structure benefits from a reduced silver consumption compared with a conventional H-pattern cell, and its realization can be easily combined with novel metallization technologies such as dispensing or stencil printing. The introduction of a rear-surface passivation into the MWT structure is feasible with the high-performance MWT (HIP-MWT) concept developed at Fraunhofer ISE. The resulting fabrication sequence includes only one additional process step – laser drilling of vias – compared with an H-pattern passivated emitter and rear cell (PERC). Furthermore, the synergistic effects of MWT and PERC boost the conversion efficiency gain of MWT-PERC-type cells beyond the expected sum of what could be achieved individually from these two approaches. According to the calculations made by Fraunhofer ISE, conversion efficiencies of up to 21.5% (annealed) are feasible for p-type Cz silicon MWT-PERC cells. Because via metallization is one of the challenges in the fabrication of MWT cells, different via pastes are investigated with regard to their series resistance and contact behaviour. With cell-to-module losses in conversion efficiency of only 0.9% abs., both the interconnector-based MWT module technology and the conductive backsheet concept show promising results.

Introduction

In terms of the competitiveness of PV compared with other energy sources, innovations in solar cell and module manufacturing technology are a prerequisite for further reductions in specific costs (€/Wp). The current crisis that is affecting a major part of the solar industry is putting more pressure on the requirement for technological innovations as instruments for increasing manufacturers' margins.

To date, most of the crystalline p-type silicon solar cells produced worldwide still feature the conventional and long-established double-side contacted solar cell structure, consisting of an H-pattern silver metallization grid on the front and a full-area aluminium metallization with a back surface field (BSF) on the rear (H-pattern BSF, Fig. 1(a)). This type of silicon solar cells suffers from high rear-surface recombination velocities, parasitic absorption at the rear contact and increased front-surface shading due to the presence of the external busbar contacts; thus the H-pattern BSF solar cell conversion efficiency potential is limited. Moreover, at the module level, the interconnection ribbons shade the front of the cell. Their optimization, with the aim of achieving lower series resistances, is limited by thermomechanical stresses resulting from larger cross-sections of the ribbon.

To overcome the drawbacks of H-pattern BSF solar cells, the introduction of a rear-surface passivation and/or the reduction of front-surface shading by using back-contact cell structures with both external polarities only on the rear are possible options. Furthermore, back-contact structures permit the optimization of series connection in the module for the lowest series resistance-related losses. So far, only modules with interdigitated back-contacted solar cells (IBC) from SunPower [1] have made their way into industrial production and are available on the PV market.

Another very promising back-contact cell and module concept close to market introduction is the metal wrap through (MWT) concept [2], shown in Fig. 1(c). Various solar cell manufacturers revealed ramp-up plans for MWT cell production during last year's MWT workshop in Freiburg, and presented pilot-line results at this year's Intersolar trade fairs in Europe and North America, as well as at the SNEC in Shanghai.

In our opinion, the MWT concept is one of the above-mentioned innovations which should be quickly brought into industrial production.

Advantages of MWT technology

MWT technology combines various advantages that allow high conversion efficiencies at both cell and module levels. As the MWT concept is part of back-contact solar cell technology, the external contacts of the device are located on the rear of the cell. This results in up to 50% less shading of active cell area on the front and therefore increases the conversion efficiency by around 0.5% abs. at the cell level compared with conventional H-pattern BSF solar cells [3]. In addition, the absence of front busbars allows a greater range of

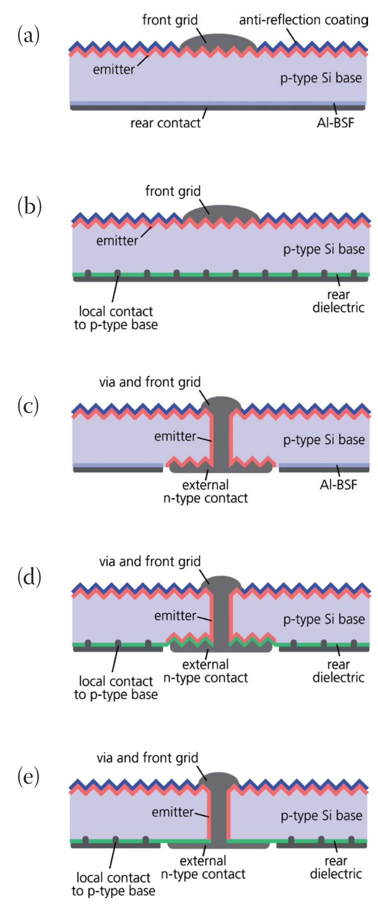

Figure 1. Schematic drawings of different p-type device structures considered in this paper [16]: (a) H-pattern BSF; (b) H-pattern PERC; (c) MWT-BSF; (d) MWT-PERC; (e) HIP-MWT.

Published by	Type of base doping	Base material	Cell concept	Edge length [mm]	Best η_{Cell} [%]
ITRI [45]	p	mc-Si	Al-BSF	125	16.65
Hyundai [46]	p	mc-Si	Al-BSF	156	17.60
Bosch [47]	p	Cz-Si	Al-BSF	156	19.39
Canadian Solar [48]	p	cast mono Si	Al-BSF	156	19.61
ECN & Yingli [49]	n	Cz-Si	phosphorus-BSF with passivation layer	156	19.70
Canadian Solar [50]	p	monocrystalline Si	?	156	21.10

Table 1. Recently published cell results for large-area silicon-based MWT solar cells from other research institutes and industry. Note that none of the results has been confirmed by a calibration laboratory.

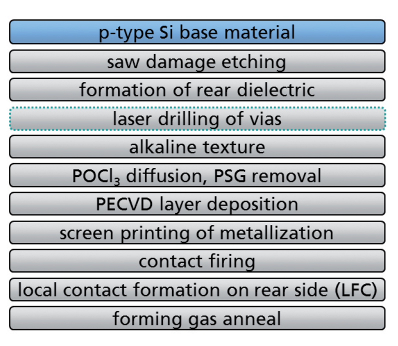

Figure 2. Typical process sequence for p-type HIP-MWT solar cells. Compared with a typical PERC-type solar cell process, a single additional process step (laser drilling of vias) makes the full benefit of the MWT concept accessible.

applicable deposition methods for the front grid, as well as enabling alternatives to the industrially common screen-printing process to be used. Novel innovations such as stencil printing [4,5] or dispensing [6,7] are promising technologies for realizing finger widths below 50µm while maintaining high electrical conductivity and low contact resistance.

> "Another major benefit of the MWT cell concept is the reduced silver consumption."

Another major benefit of the MWT cell concept is the reduced silver consumption. As the consumption of this material is one of the main cost drivers of cell production it should be kept to a minimum [8]. For MWT solar cells with an edge length of 156mm, a reduction in silver of ~50mg/cell (~30% of the total silver amount used) compared with a conventional H-pattern cell is expected because of the different designs of external n-type contacts [5]. Assuming a silver paste price of US$1.04/g (August 2012), this leads to a cost reduction of US$0.05/cell.

The fact that the module interconnection of MWT cells is performed on the rear of the cell broadens the possibilities for cell interconnection. Since the constraints related to conventional front-to-back tabbed interconnection are absent, it is possible to optimize the shape of the applied cell connectors with respect to electrical and thermomechanical features. This allows fill-factor losses and cell stress at the module level to be reduced. Within this optimization, the amount of conductive interconnection material to use on the rear simply becomes a question of material cost. Moreover, a higher packing density is feasible.

As mentioned above, improved surface passivation leads to highly efficient solar cells. By applying the passivated emitter and rear cell concept (PERC, [9], Fig. 1(b)), recombination losses are significantly reduced. Passivation is realized by forming a thin dielectric layer on the rear of the cell. Local contacts through the passivation layer ensure the electrical interconnection of the full-area aluminium to the silicon base. Additionally, the dielectric layer serves as an internal rear-surface reflector, improving the light-trapping of the solar cell, leading to increased short-circuit currents. The PERC approach allows a gain in conversion efficiency of up to 1% abs. compared with state-of-the-art H-pattern BSF technology [10].

Another concept to consider for boosting cell conversion efficiency is the application of a selective emitter on the front of the cell [11]. Here, a low contact resistance between silicon and front metallization is realized by heavy doping of the emitter underneath the metal grid. The more lightly doped emitter in the photoactive cell area leads to reduced Auger recombination and increased quantum efficiency, raising short-circuit current and open-circuit voltage [12].

In recent years, PERC technology has gained increasing recognition in the PV industry when it comes to the production of highly efficient solar cells [13]. In the field of MWT solar cells, the application of a conventional BSF passivation approach is still predominant (see Table 1).

The application of the PERC approach to the MWT cell concept results in a MWT-PERC device [14,15], shown in Fig. 1(d). By combining both technologies, the achieved conversion efficiency gain is even higher than expected from the sum of the two approaches because of synergistic effects [16], whereas the complexity of the process sequence is comparable to conventional PERC sequences.

With the high-performance MWT solar cell HIP-MWT [5,17] (see Fig. 1(e)), a simplified MWT-PERC design is available

Base material	Metallization technology	Edge length [mm]	Best η_{Cell} [%]	Publication reference
mc-Si	screen printing	156	18.2	[51]
Cz-Si	screen printing	125	19.7	
Cz-Si	dispensing	125	20.1	[7]
Ga-doped Cz-Si	stencil printing	156	19.9	[5]
mCz-Si	stencil printing	156	20.2	[5]
FZ-Si	screen printing	125	20.3	
FZ-Si	dispensing	125	20.6	[7]

Table 2. Conversion efficiencies (annealed) achieved at Fraunhofer ISE for large-area silicon-based p-type MWT-PERC solar cells (confirmed by Fraunhofer ISE CalLab PV Cells).


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that requires only one additional process step, namely the laser drilling of vias, for the integration of the MWT structure in an industrial PERC cell fabrication line (Fig. 2). In the HIP-MWT structure there is no rear emitter, so rear structuring steps are not necessary in the production line.

Overview of recently published MWT solar cell results

Table 1 summarizes recent results of large-area silicon-based MWT solar cells from research institutes and industry. MWT research at Fraunhofer ISE focuses on the MWT-PERC approach. A wide range of metallization processes and base materials have recently been characterized. Table 2 shows the results of p-type MWT-PERC solar cells processed on the pilot line of the Photovoltaic Technology Evaluation Center (PV-TEC) [18] at Fraunhofer ISE.

The highest conversion efficiency so far of 20.6% is achieved by applying dispensed front fingers and using float-zone silicon (FZ-Si) base material [7]. The dispensing approach allows a decrease in width of the gridlines while maintaining a high aspect ratio of ~0.9 [19]. Dispensing and stencil printing offer an increased homogeneity of the gridlines compared with screen-printed fingers, leading to a lower series resistance contribution of the front grid [5]. Advanced printing technologies such as dispensing and stencil printing are especially suited to MWT cells because of the absence of front busbars; this eliminates the need for a second printing step. In the case of stencil printing, the stability of the stencil is increased owing to the simplified stencil design [5,19].

“The highest conversion efficiency so far of 20.6% is achieved by applying dispensed front fingers and using float-zone silicon (FZ-Si) base material.”

Besides the rather costly FZ-Si, other materials such as gallium-doped Cz-Si (Ga-doped Cz-Si) and boron-doped magnetically cast Cz-Si (mCz-Si) enable the production of solar cells with reduced, or even absent, light-induced degradation (LID) [20]. The best mCz-Si MWT cells presented so far achieve annealed conversion efficiencies of up to 20.2% and exhibit an efficiency drop of only 0.3% abs. after degradation. The reduced LID of the mCz-Si material originates from a lower oxygen content of mCz-Si compared with conventional Cz-Si. Because of the absence of boron in Ga-doped Cz-Si, this material does not show boron–oxygen-related degradation at all [5].

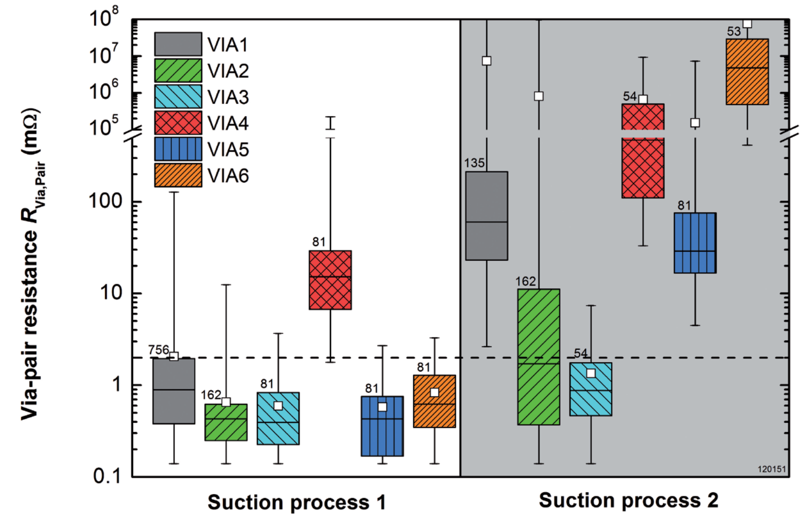

Figure 3. Measured series resistance values $R_{Via,Pair}$ (from four-point probe measurements [44]), for six different via pastes (VIA1–VIA6) and two different suction processes (different time and low-pressure value). The number of measured via-pairs is stated above the boxes. The horizontal dashed line indicates $R_{Via,Pair}$ = 2mΩ.

Via pastes for MWT solar cells

Since the external front contact in MWT solar cells is relocated to the rear, a reliable and continuous via metallization is essential, otherwise high via series resistances lead to decreased fill factors and thus to low conversion efficiencies [21].

Not only are the vias metallized using via pastes but the external rear contacts are as well (e.g. the external n-type contacts in Fig. 1(a),(d),(e)). Therefore, the via pastes should show low shunting behaviour in the crucial regions where the external n-type contact is located next to the p-type silicon base [14,22] (respectively the external p-type contact for n-type base doping).

This is of major importance especially for the HIP-MWT structure (Fig. 1(e)), since this type of solar cell does not have an emitter on the rear (thus the n-type via paste overlaps the p-type base), and therefore reliable forward and reverse bias behaviour is crucial. In forward bias up to the open-circuit voltage, no significant current flow should occur. As partial shading of a photovoltaic module may lead to reverse bias conditions for the shaded cells, reverse breakdown and hot-spot generation are issues that need to be addressed [23]. A low reverse breakdown voltage can lead to an application with an integrated bypass diode at the cell level allowing a controlled reverse current flow (fewer, or even no, external bypass diodes required). For conventional module configurations, a high reverse bias stability is the desired behaviour.

Both forward and reverse bias behaviours can be manipulated either by the use of an intermediate rear dielectric (Fig. 1(d),(e)), as already demonstrated on p-type silicon [24], or by choosing a suitable via paste. In the following section, six different via pastes are investigated with regard to their via series resistance values and their contact behaviour with p-type silicon without an intermediate dielectric in forward and reverse bias conditions.

Via series resistance

Since each external rear contact is connected to the front contact by two vias, the measured series resistance value $R_{Via,Pair}$ is a combination of two vias in parallel (via-pair). Fig. 3 shows the measured series resistance values $R_{Via,Pair}$ for six different via pastes (VIA1–VIA6), using two different suction processes performed after the screen-printing step [25]. Four-point probe measurements were carried out on MWT solar cells with a wafer thickness of ~160µm, fabricated according to a process sequence similar to that shown in Fig. 2. Via radii are ~90µm on the rear and ~60µm on the front. Note that the calculated [21] minimum via-pair resistance value is 0.14mΩ, assuming an optimally filled via and using $3 \cdot 10^{-8}$Ωm as a typical specific conductivity of a via paste. The lower measured values are attributed to measurement uncertainty and corrected to this value.

Application of the two-diode model reveals that a series resistance of 1Ωcm^2 causes a fill factor loss of ~5.5% abs. when calculating the dependency of fill factor from series resistance using latest cell parameters. If a fill factor loss smaller than 0.1% abs. is considered to be negligible for a MWT cell with an edge length of 156mm, and assuming 54 vias, the maximum tolerable series resistance value of a single

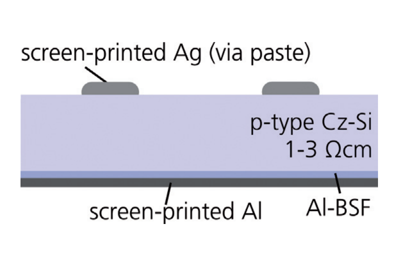

Figure 4. Test structure used for the investigation of the six via pastes.

via R_{Via} is calculated to be ~4mΩ. In our case, the value for $R_{Via,Pair}$ should therefore be lower than ~2mΩ (assuming that both vias in parallel contribute the same proportion to the measured value).

As can be seen for suction process 1 in Fig. 3, all via pastes (except via paste VIA4) show low series resistance values $R_{Via,Pair}$, with mean values below 2mΩ. Only a few outliers lead to higher maximum values. Nevertheless, suction process 1 provides a stable and reliable via-metallization process. Significantly greater via resistance values are measured when using the non-optimal suction process 2. Only via paste VIA3 exhibits comparable values for both suction processes. Suction process 1 is therefore selected for reliable via metallization.

Forward and reverse bias behaviour

To investigate the *I-V* characteristics of the six via pastes in forward and reverse bias conditions, p-type silicon test structures (Fig. 4) were fabricated. In order to examine the behaviour of the via pastes in the most challenging application (as for example in MWT-BSF cells without a rear/via emitter), the pastes are in direct contact with the silicon base material (no intermediate dielectric). The entire back is contacted by screen-printed aluminium. The two silver busbars (via pastes VIA1–VIA6), with a contact area of 3.7cm^2, are screen printed directly onto the front of p-type silicon wafers with a thickness of ~200µm and an edge length of 125mm without any dielectric in between.

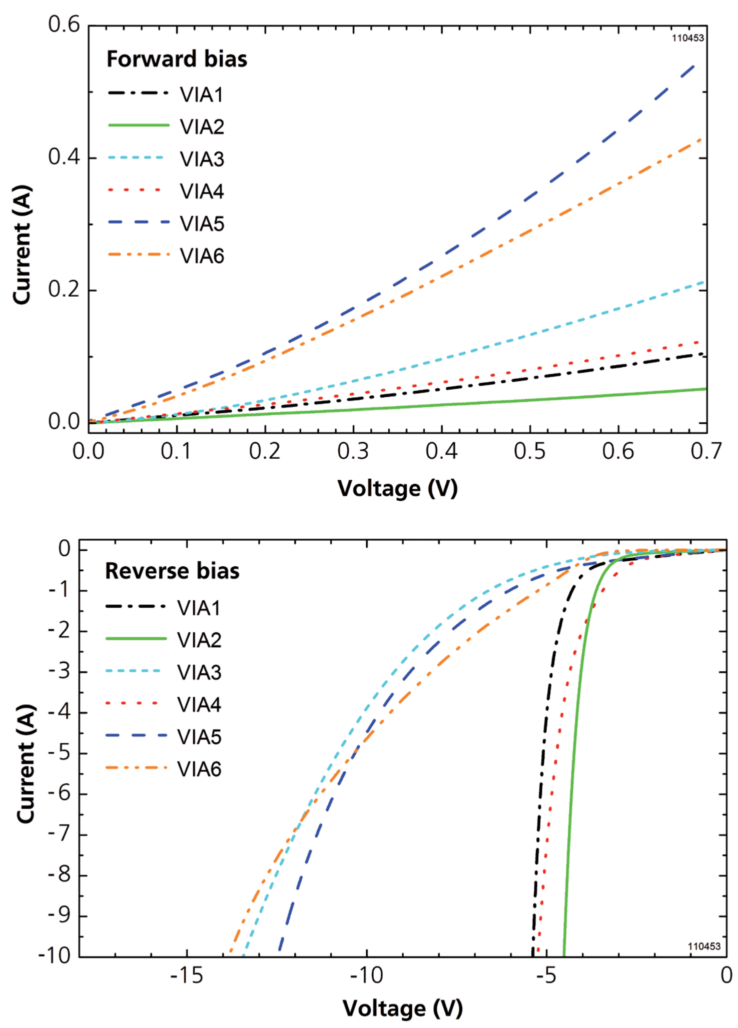

Figure 5. Forward (top) and reverse (bottom) bias dark *I-V* characteristics for the six via pastes (VIA1-VIA6) on p-type test structures shown in Fig. 4. The curves represent the mean values of three to five test structures for each via paste [25].

The measured dark *I-V* characteristics [25] are shown in Fig. 5; as can be easily seen, the six via pastes behave quite differently. The VIA2 paste exhibits the lowest current flow in the forward direction (~0.05A at 0.7V) and a low reverse breakdown voltage. VIA1 and VIA4 also show low reverse breakdown voltages, but somewhat higher forward currents. VIA3, VIA5 and VIA6 show even higher values of forward current, and the reverse breakdown voltage is markedly shifted to higher values. In conclusion, the VIA2 paste best meets the requirements of a non-contacting silver paste on p-type silicon.

Conversion efficiency potential of MWT-PERC solar cells

A loss analysis using analytical and numerical device modelling [26–29] reveals the most important loss mechanisms of p-type MWT-PERC cells [19]. Regarding the short-circuit current density, the major contributors to short-circuit current losses are shading caused by grid lines, non-ideal light trapping and rear recombination. Future technological improvements such as stencil printing, dispensing or more advanced seed and plate approaches are expected to further decrease the shading-related losses. Emitter recombination is another important loss mechanism, which reduces the blue response of the cell and thus the short-circuit current.

With decreasing rear-surface recombination – especially for PERC-like structures – the impact of emitter recombination on open-circuit voltage is increasingly pronounced. Emitter optimization should therefore be in the focus of future investigation. Recently, considerable progress in the development of novel diffusion processes and emitters with low dark saturation current densities was presented by several research institutes [30–32]. These results form the basis for future low-cost but high-performance industrially applicable emitter structures.

For solar cells with passivated rear-side and local base contacts, an adapted base doping is of major importance. The optimum dopant concentration required for maximum performance is higher than for conventional full-area aluminium rear contacts. Besides a gain in open-circuit voltage, a low base resistivity leads to a reduction in PERC-related spreading resistance and MWT-related series resistance contributions. Since Auger recombination and LID (in the case of boron-doped Cz-Si) increase with heavier base doping, the optimum base doping is a trade-off between series resistance and recombinative losses [5].

For high-efficiency MWT-PERC solar cells, device modelling reveals an

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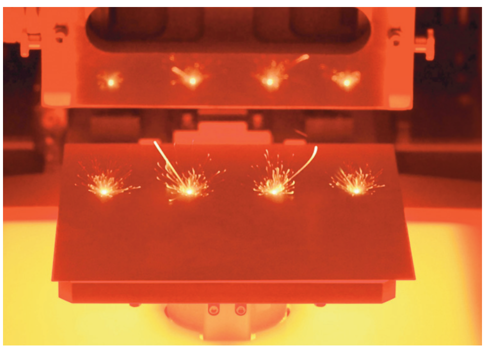

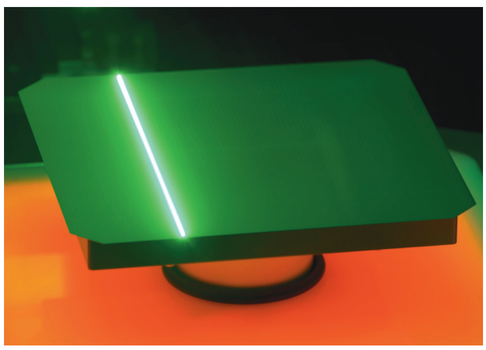

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optimum resistivity of less than 1Ωcm [19]. The above-mentioned MWT-related series resistance arises in the region of the rear n-type contact, where the p-type bulk is not directly connected to the aluminium contact. Majority charge carriers generated in this area have to travel laterally to reach the p-type contact. This loss is reduced by an adaptation of the rear n-type contact geometry to small solder islands. One possible way to further reduce the n-type area on the base rear is to decouple the external solder pad from the base by applying an insulating layer while maintaining the solderability of the external n-type contact.

The use of front-grid printing technologies that allow the processing of thin lines with a high aspect ratio offers several advantages. Besides the reduction of shading, the emitter-related series resistance losses are decreased owing to reduced finger pitches. Furthermore, a smaller cell area is metallized, leading to a reduction in recombinative losses at the semiconductor–metal interface. By replacing screen printing with advanced metallization technologies, not only is a conversion efficiency gain achieved, but also the finger homogeneity is increased, making a further reduction in silver consumption per cell feasible [5].

"Conversion efficiencies up to 21.5% (annealed) for p-type Cz-Si MWT-PERC cells are feasible in a short to medium time frame."

According to the calculations made by Fraunhofer ISE, conversion efficiencies up to 21.5% (annealed) for p-type Cz-Si MWT-PERC cells are feasible in a short to medium time frame, when combining the advances in cell layout and processing with adapted base material properties [19]. For PERC solar cells, the high conversion efficiencies of 19.5% obtained for multicrystalline silicon (mc-Si) [13] and 20.2% for Cz-Si (deactivated boron-oxygen complex) [13] support the reasoning that the simulated values for Cz-Si MWT-PERC cells are not far from being reached.

Most of the improvements presented for further exploiting the conversion efficiency potential of p-type MWT-PERC solar cells are likewise effective for corresponding n-type cells.

MWT modules

For the interconnection of MWT cells two different concepts have been developed and implemented by researchers and manufacturers [33]. In the first concept the conventional tabbing-stringing of standard H-pattern cells is modified so that only the rear of the cell is addressed, with interconnectors that reach over two neighbouring cells [34]. Depending on the design of the interconnector and on the layout of the contacts on the cell rear, an electrical insulation is required to avoid direct contact of the interconnector to opposite cell polarities. The subsequent manufacturing steps are identical to standard module manufacturing, as the interconnected cell strings are placed on the front glass with one layer of encapsulant, followed by cross connection of the strings.

The second concept is an adaptation of surface-mount technology concepts from microelectronics, whereby a conductive backsheet provides the electrical interconnection circuit [35,36]. The backsheet therefore exhibits a structured metallization layer, usually copper, on the side that faces the cell, along with a finish for electrical insulation. Following the process of Eurotron/ECN [37], the conductive adhesives or solder pastes are then applied to the contact points, and the encapsulant, with punched holes, is placed on the backsheet. Subsequently, all cells are assembled on the encapsulant with their sunny side pointing upwards, followed by the lay-up of the second encapsulant layer and the front glass. Prior to lamination the stack is flipped, and the module enters the laminator with the glass facing downwards.

Interconnection

The use of solder and of conductive adhesives has been demonstrated [38,39] for the interconnection of MWT cells. The advantages of conductive adhesives are: (i) lower processing temperature (below 180°C) and lower material stiffness compared with solder (resulting in low-stress interconnections [40]); (ii) the compatibility for heterojunction concepts [41]; and (iii) the option to cure the adhesive during the lamination process in the case of the conductive backsheet concept. On the other hand, silver-containing conductive adhesives are more expensive than soldering pastes and require high levels of accuracy in processing [42]. As well as being cost-effective, solders are well proven in the PV industry and provide high electrical conductivity.

To avoid high thermomechanical stress on the cell and excessive cell bow after soldering, the interconnection of MWT cells at Fraunhofer ISE is performed with structured interconnector ribbons. Their geometric design yields a high conductivity for low fill-factor losses and low mechanical stress after soldering. The most recent performance tests using this approach [43] have indicated a conversion efficiency loss from cell to module of 0.9% abs. and a module conversion efficiency (aperture area) of 17.0%. These results demonstrate the competitiveness of the interconnector-based MWT technology compared with the conductive backsheet concept, in which cell-to-module losses of 0.9% abs. and module conversion efficiencies of 17.0% have also been reported [38].

Conclusion

Clearly, the MWT approach is of major interest for research and industry, when low-cost production of highly efficient solar systems is an issue. The MWT-PERC solar cell in particular, which benefits from synergistic effects arising from the union of MWT and PERC technology, is a promising candidate for achieving high conversion efficiencies. For p-type MWT-PERC solar cells processed and measured at Fraunhofer ISE, the best conversion efficiency achieved is 20.6% with FZ-Si. Analytical and numerical simulations reveal the huge potential of Cz-Si p-type MWT-PERC cells, with conversion efficiencies of up to 21.5% forecast. With the HIP-MWT approach, a MWT-PERC cell process is available that can be easily adopted by existing PERC production lines, requiring only one additional process step, namely the laser drilling of vias.

"With the HIP-MWT approach, a MWT-PERC cell process is available that can be easily adopted by existing PERC production lines, requiring only one additional process step, namely the laser drilling of vias."

It is noteworthy that the metallization process in particular offers the opportunity to further increase the conversion efficiency of MWT solar cells. Recent developments concerning advanced front-grid printing technologies such as dispensing and stencil printing have demonstrated promising results, where conversion efficiency is improved and silver consumption is reduced at the same time.

In the case of via metallization, special attention has to be given to the right choice of both metallization paste and suction process, in order to ensure a low via-related series resistance. The dark *I-V* characteristics in forward and reverse bias conditions show quite different behaviours for each of the via pastes tested.

Two different interconnection concepts for MWT solar cells are available:


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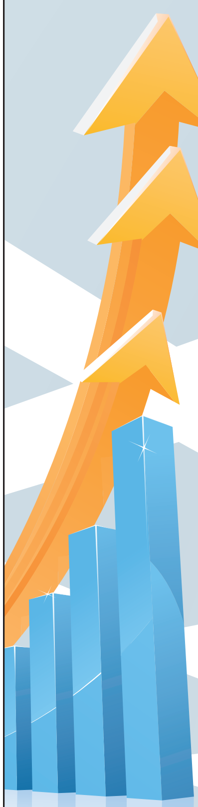


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interconnector-based technology and a conductive backsheet concept. Both of these show promising results, demonstrating cell-to-module losses in conversion efficiency of only 0.9% abs.

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