PROCESSING OF HIGHLY-EFFICIENT MWT SILICON SOLAR CELLS

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ABSTRACT: This paper focuses on the latest developments from research on MWT (metal wrap through) solar cells at Fraunhofer ISE. An overview of the current cell results for mc-Si and Cz-Si material with both Al-BSF and passivated rear side is presented. Recent progress in cell technology and the challenges in order to reach efficiencies for industrially processed large area MWT solar cells towards 20% are discussed. Up to now MWT cell efficiencies up to 19% for Cz-Si and up to 17.5% for mc-Si are reached with industrially feasible processing. Improvements of the MWT cell design in order to increase cell efficiency further and to allow an easy module assembly are shown. Furthermore first calibrated IV measurements of MWT solar cells are presented.
Keywords: Silicon Solar Cell, Screen Printing, Back Contact, Metal Wrap Through, MWT

1 INTRODUCTION

The common industrial cell and module production is mainly based on screen-printed H-patterned silicon solar cells. Therefore today's modules suffer from high front surface shading and from series resistance losses in the tabbing material. Both loss mechanisms are caused by the presence of an external contact, the so called busbar, on the front surface. To reduce these losses significantly, the busbar has to be transferred to the rear surface. This can be realized by the metal wrap through (MWT) technology [1] while using only industrial applicable production technologies [2]. The main advantage of the MWT technology among the rear contact cell technologies is the need of only two additional process steps for cell production in comparison to the conventional technology: laser via drilling and rear contact isolation. The via-metallization can be done in the same process step as the rear solder pad metallization [3].

Hence, the MWT technology allows high efficiencies [4-6, 8] while production costs are still on a low level. Therefore the costs per W_p can be reduced at low economical risks. The transfer of the MWT technology from laboratory to industry is already ongoing and successful so far [3, 7-9]. This paper presents a detailed overview of the current status of MWT research and development at the PV-TEC pilot-line [10, 11] at Fraunhofer ISE, focusing on recent progress in cell processing and characterization.

Moreover, the combination of the MWT technology with rear surface passivation is shown. The combination of industrial wrap through cell technologies like the MWT technology with passivated emitter and rear cell (PERC) technologies is the most important part of the technology roadmap of Fraunhofer ISE (see Figure 1) in order to improve cell efficiencies for large area lab scale series processed solar cells towards 20%. The so-called MWT-PERC approach should enable a clear increase in cell efficiency.

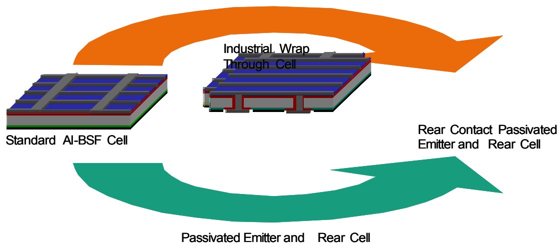

Figure 1: Fraunhofer ISE technology roadmap for future cell devices

2 APPROACH

In order to develop a highly-efficient MWT solar cell and module technology on a cost-efficient level we have chosen to use a multi-stage approach. On the one hand we focus on the development of a MWT pilot-line process for industrial mc- and Cz-Si material which can be transferred to industry in a short time scale. On the other hand we have developed an industrially feasible process with a very high-efficiency potential (over 19%) on FZ-Si [12] in order to characterize MWT cells in detail and thus to improve processing of MWT cells.

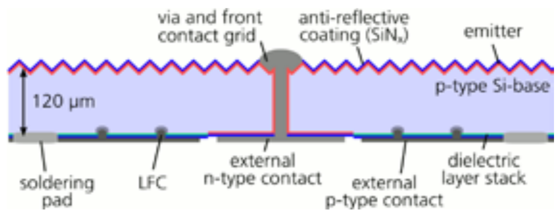

Figure 2: Schematic structure of the MWT-PERC devices presented in this work.

Moreover, we successfully finished first experiments with screen-printed MWT-PERC devices (see Figure 2) on mc-Si and Cz-Si by applying a dielectrically layer, e.g. silicon oxide [13, 14] or aluminum oxide [15-17], on the rear surface. Cell thicknesses down to ~120 µm are realized with the MWT-PERC approach without any bowing effects and thus a high yield. A typical process sequence for the MWT-PERC approach with thermal oxide as rear passivation layer is presented in Figure 3. In this approach the oxide acts also as masking layer during diffusion and texturing processes. Within this work cell processing of Cz-Si MWT-PERC devices is based on this process sequence (see Figure 2). Additionally, for some MWT cells the front metallization was performed by a seed and plate approach with Aerosol jetting for seed layer formation followed by light induced silver plating (LIP) [26]. More details about Cz-Si MWT-PERC devices are presented by B. Thaidigsmannn [18].

For mc-Si MWT-PERC devices a process based on aluminum oxide as rear passivation layer and screen-printed front and rear contacts is used within this work. The Aluminium oxide is deposited by PECVD. Current results about Aluminium oxide processing and characterisation at Fraunhofer ISE can be found in [15-17]. In order to prevent the Al_2O_3 passivation layer from the screen-printed Aluminium rear contact during the contact firing a SiN capping layer is applied by PECVD on the rear side. The rear side emitter is structured by a diffusion barrier. The backend processing (ARC deposition…) is similar to the process sequence presented in Figure 3.

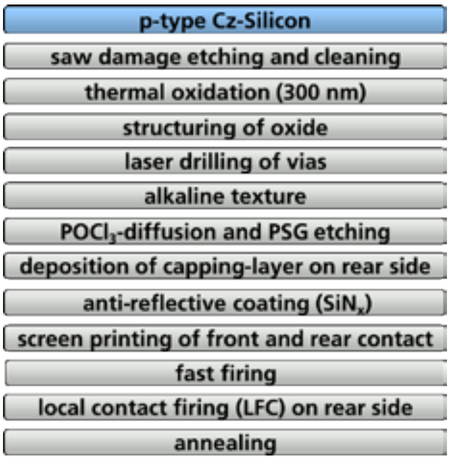

Figure 3: Process sequence for the fabrication of Cz-Si MWT-PERC devices.

To achieve high cell efficiencies screen printing pastes for the front and via-metallization are developed in a joint project with Heraeus. Especially, the development of the via-metallization paste is of high importance in order to reduce shunting and series resistance losses in the via-contact and therefore to optimize MWT cell processing. More details about current results with mc-Si MWT cells and the challenges of the MWT via paste development were presented by R. Hoenig and M. Neidert [19][20].

For processing of MWT cells the PV-TEC pilot-line [10] was used. In case of Cz-Si MWT cell processing with Aluminum back surface field (Al-BSF) the experiments were carried out mainly at the PV lab of Bosch Solar Energy AG. More details about the current status of MWT cell development at Bosch can be are given by D. Lahmer and K. Meyer [9][21]. A MWT layout with three continuous rear busbars (see Figure 4) is used for all MWT cells unless noted otherwise.

To confirm the advantages of the MWT technology also on module level first MWT prototype modules were processed and compared to conventional modules. New MWT cell designs for easy module assembly are developed together with partners from cell and module industry [22].

In order to achieve high-precision and fast IV measurements for MWT cells a new measurement system was developed which is capable of inline processing. The fixation of the MWT cells during the IV measurement is realized by vacuum [23]. First calibrated IV measurements performed at the Fraunhofer ISE CalLab PV Cells are presented in this work.

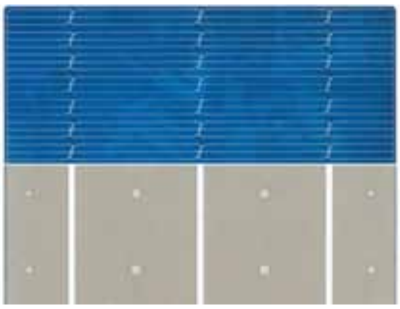

Figure 4: Picture of the front and rear of a typical mc-MWT solar cell (156x156 mm²) with three continuous rear busbars processed at Fraunhofer ISE [24].

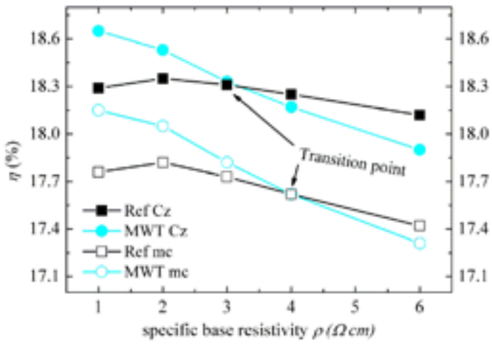

Figure 5: 2D "Sentaurus Device" simulation of a MWT and conventional solar cell [25]. The simulation shows a transition point depending on the bulk lifetime (mc, Cz) and base resistivity. Boron-oxygen induced degradation effects of the bulk lifetime are not regarded. The absolute values for the bulk lifetime are based on estimated input parameters, so especially for mc-Si an overestimation is probable.

Furthermore, loss mechanisms in MWT cells (e.g. losses due to via resistance [24], lateral base resistance [2], j0 related recombination [3], etc.) have to be analyzed and minimized. To understand the origin of MWT loss mechanisms in more detail a 2D simulation is carried out by "Sentaurus device". In Figure 5 the calculated efficiency is plotted against the base resistivity for low (mc-Si) and high (Cz-Si) bulk lifetime. The simulation is based on the design of a typical MWT solar cell (156x156 mm²) with three rear busbars without interruptions as shown in Figure 4. As reference (Ref) a conventional H-patterned solar cell with three busbars is used.

In Figure 5 is shown that especially for mc-Si with low base resistivity (< 2 Ωcm) a high efficiency gain can be achieved for MWT cells. For Cz-Si especially with high base resistivity (> 3 Ωcm) the cell design according to Figure 4 leads to efficiency losses for MWT cells caused by lateral resistance losses in the base and by recombination losses in the rear n-contact region [25].

Hence, the base resistivity has to be reduced or the rear MWT cell design must be optimized to achieve an efficiency gain. One possibility for an optimization of the cell design is presented in this work; other ones are discussed by K. Meyer [21].

3 RESULTS AND DISCUSSION

Most current-voltage (I-V) measurements are carried out with the newly developed measurement equipment [23]. All cell measurements are performed by an industrial cell tester. The best cells are partly measured by the Fraunhofer ISE CalLab PV Cells.

3.1 Results for MWT Cell with Al-BSF

In Table I the best results of MWT cells with Aluminium BSF rear side are listed. The mean difference Δ to conventionally processed solar cells is also presented for all IV parameters in absolute values. For a precise comparison only sister wafers are used.

Table I: I-V-data for the best MWT cells with Al-BSF rear measured on an industrial cell tester and partly independently confirmed by the Fraunhofer ISE CalLab PV Cells. The mean difference Δ to conventionally processed solar cells (sister wafers) is also presented (absolute values). The Cz-Si results labelled with "new" are based on a new rear side design. The cell area is 156x156 mm². The base resistivity for mc-Si is ~0.5-2.0 Ωcm, for Cz-Si ~2-4 Ωcm.

device type	V_{OC} (mV)	J_{SC} (mA/cm^2)	FF (%)	η (%)
mc-Si[1]	614	34.9	78.3	**16.8**
Δ (mc-Si)	+2	+1.0	-0.5	**+0.5**
Cz-Si[1]	619	37.2	77.2	17.7
Δ (Cz-Si)	0	+0.9	-1.6	0
Cz-Si[2] (new)	626	37.8	77.0	**18.2**
Δ (Cz-Si new)	+3	+1.0	-1.0	**+0.3**

[1] independently confirmed by Fraunhofer ISE CalLab PV Cells (after degradation), measurement uncertainty: ±2%rel. for η
[2] IV measurements with cell tester after processing, measurement uncertainty: ±3%rel. for η

For mc-Si a sufficient efficiency level (up to 16.8%) is reached. However, the moderate voltage level indicates that the used mc-Si material has not the highest material quality. Nevertheless, a clear efficiency gain of 0.5% absolute (~3% rel.) is achieved with the MWT cell technology. The estimated efficiency gain in Figure 5 (~0.5% @ 1 Ωcm) is confirmed. This underlines the high potential of the MWT concept for mc-Si material.

For Cz-Si material (~2-4 Ωcm) the efficiency level is ~1% absolute higher than for mc-Si as expected, but no significant efficiency gain can be observed for MWT cells with three continuous rear busbars (cell design as presented in Figure 4). A similar behaviour is shown by the simulations which were carried out (see Figure 5). For Cz-Si material with a base resistivity of ~3 Ωcm no efficiency increase is expected for the MWT approach. The reasons for this behaviour are discussed by T. Fellmeth and K. Meyer [25] in detail. A main reason is the rear busbar region without p-contact (Al-BSF) which leads to significant FF losses especially for high quality material with high base resistivity. Due to strong Boron-oxygen induced degradation effects for a low base resistivity the Cz-Si base material is not changed. But, a modification of the rear busbar region can significantly improve the FF for MWT cells [25]. Therefore, the MWT rear design was optimized. The rear n-contact region was significantly reduced.

A new MWT cell batch ("Cz-Si new") was processed with an optimized rear design. This leads to higher efficiencies up to 18.2%. This is so far the highest MWT efficiency achieved for AL-BSF rear sides within this work. Due to the rear design optimization, an efficiency gain of about 0.3% absolute (~1.7% rel.) mainly based on decreased fill factor losses is observed for MWT cells. Hence, the high potential of the MWT concept is also shown for Cz-Si material.

3.2 Results for passivated MWT cells (MWT-PERC)

To improve cell efficiencies further the MWT cell concept is combined with the PERC concept [18] as described in section 2. The results of the best so-called MWT-PERC devices are listed in Table II.

For mc-Si material sufficient efficiencies up to 17.3% are reached in the first run. Hence, an efficiency gain compared to the Al-BSF approach of about 0.5% absolute (~3% rel.) is achieved due to rear side passivation. Further cell batches including the mentioned optimization of the MWT rear design are already in process focusing cell efficiencies towards 18%.

For Cz-Si material efficiencies up to 18.8% are achieved so far within the first runs using screen printed front and rear contacts. With the seed (Aerosol jetting [26] and plate (Ag-LIP) approach for the front contact efficiencies of 19.0% are achieved. Hence, the MWT efficiency is increased by over 0.5% absolute (>3% rel.) due to rear side passivation. The slightly increased efficiency for the thicker Si material can be probably explained by an optimized front grid which was used in this batch and by more effective light capturing due to the thicker base material. Both effects lead to a clear increase in J_{SC}. The FF decrease for the thicker Cz-Si can be probably explained by the higher base resistivity (see Figure 5). The J_{SC} and V_{OC} gain as well as the FF loss for the seed and plate approach can be explained by a reduction of the finger width (reduced shading) and by the use of an emitter with higher sheet resistance.

Hence, in the next cell batches efficiencies towards 20% should be achieved either by the use of higher doped base material and/or by the mentioned optimization of the MWT rear side design as well as by the introduction of the seed and plate approach for the front contact.

The final cell thicknesses of ~120 µm show the feasibility of the MWT-PERC approach to be used for industrially feasible processing of very thin mc-Si and Cz-Si wafer material.

Table II: I-V-data for the best MWT-PERC cells with passivated rear side measured on an industrial cell tester and partly independently confirmed by the Fraunhofer ISE CalLab PV Cells. The cell area is 125x125 mm² for Cz-Si and 156x156 mm² for mc-Si. The cell thickness after processing is given in brackets. The base resistivity for mc-Si is ~0.8 Ωcm, for Cz-Si 1.7 Ωcm (~120µm) and 2.7 Ωcm (~170µm). For one Cz-Si group the seed and plate approach was used for front metallization.

device type	V_{OC}	J_{SC}	FF	η

	V_{OC} (mV)	J_{SC} (mA/cm²)	FF (%)	η (%)
mc-Si (~130µm)[1]	628	36.0	76.6	17.3
mc-Si (~130µm)[2]	630	36.0	76.9	17.5
Cz-Si (~120µm)[2]	628	39.0	75.9	18.6
Cz-Si (~170µm)[2]	630	39.9	74.8	18.8
seed and plate approach (front contact):				
Cz-Si (~170µm)[2]	639	40.3	73.6	19.0

[1] independently confirmed by Fraunhofer ISE CalLab PV Cells (after degradation), measurement uncertainty: ±2%rel. for η
[2] IV measurements with cell tester after processing, measurement uncertainty: ±3%rel. for η

3.3 MWT module results

Two mini modules (one MWT and one conventional) each consisting of 6 Cz-Si solar cells were processed [9]. In Table III the IV results are presented for both modules. An efficiency increase of ~0.2% absolute (~1.5% rel.) is reached on module level for the MWT technology. This increase is driven by the decrease of series resistance losses due to an optimized MWT tabbing technology which allows more tabbing material on the rear without additional shading. The reduced FF difference ΔFF for the MWT technology confirms the reduction of the series resistance losses on module level. The clear increase in J_{SC} for the MWT technology can be explained by less shading due the absence of front busbars and tabs.

Table III: IV results of a MWT and a conventional Cz-Si mini-module (each consisting of 6 cells) compared against each other. ΔFF and Δη are the following differences in % absolute: FF/η (module) minus FF/η (cell), measurement uncertainty: ±3%rel. for η

device type	V_{OC} (V)	J_{SC} (mA/cm²)	ΔFF (%)	$\Delta\eta$ (%)
MWT	3.64	35.6	-3.8	-1.3
Conv.	3.60	34.4	-5.5	-1.5
Δ (MWT-Conv.)	+0.04	+1.2	+.1.7	+0.2

Moreover first mini-modules with very thin (~120 µm) MWT-PERC devices were processed. For Cz-Si material module efficiencies of ~16.5% are achieved. The moderate value can be explained by a non optimized MWT rear side for module interconnection so far. Further experiments with an optimized MWT rear design are already ongoing. More details about the module technology for back-contacted solar cells are presented by H.Wirth [22].

4 CONCLUSION

We demonstrated the industrial fabrication of large area metal wrap through (MWT) silicon solar cells with Al-BSF rear sides as well as with passivated rear surfaces (MWT-PERC approach) in our PV-TEC pilot-line using Cz- and mc-Silicon material.

For mc-Si MWT cells with Al-BSF an efficiency gain of about 0.5% absolute is achieved compared to conventionally processed cells (sister wafers). For Cz-Si efficiencies up to 18.2% are achieved with an optimized rear side with less rear n-contact metallization. Hence, the high-potential of the MWT concept is shown on both materials.

MWT-PERC devices reach efficiencies up to 19.0% on Cz-Si and up to 17.5% on mc-Si so far, confirming the high efficiency level which is achievable with the MWT-PERC approach. Moreover, MWT-PERC devices with thicknesses down to ~120 µm are successfully processed on industrial equipment, showing the high cost reduction potential of the MWT-PERC concept for very thin wafer material.

A further efficiency gain for the MWT technology is demonstrated on the module level by using an optimized MWT tabbing technology.

To achieve MWT efficiencies towards 20% two main strategies are selected. First, an optimization of the MWT rear side design, which is mainly based on the reduction of the rear n-contact area, will increase the MWT efficiency. Second, the use of wafer material with low base resistivity will push the MWT efficiencies further; if Boron-oxygen induced degradation effects can be neglected.

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