

19.5% EFFICIENT SCREEN PRINTED CRYSTALLINE SILICON METAL WRAP THROUGH (MWT) SOLAR CELLS FOR CONCENTRATOR (2-25x) APPLICATIONS

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Abstract: : One of the main barriers on the way to mass production of concentrator silicon solar cells is the lack of industrially feasible process sequences. Therefore, a concentrator silicon based Metal Wrap Through (C-MWT) solar cell completely processed at the Fraunhofer ISE PhotoVoltaic Technology Evaluation Center (PV-TEC) is introduced. This means no clean room or photolithographic steps have been used. Under one-sun conditions, a conversion efficiency of 18.6% could be reached which is so far the highest efficiency reported for a MWT silicon solar cell. The highest efficiency achieved was 19.5% at 6 suns and even 18.1% at 23 suns. The series resistance as major loss mechanism concentrator solar cells are suffering from is the main focus in this work. Concerning this matter an investigation of the Light Induced Plating (LIP) step is presented. A simulation tool containing an analytical series resistance model has been developed and the 2-diode-model was added providing the calculation of the efficiency and the fill factor in dependency of the concentration at given parameters.

Keywords: Silicon, Concentrator, MWT.

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INTRODUCTION

Silicon concentrator applications are under research since the seventies. The reason for this is obvious: On the one hand concentrator solar cells are smaller according to the concentrating ratio which saves silicon and on the other hand due to the focused light there is a gain in the open circuit voltage corresponding to an increased efficiency.

Several optical concepts to concentrate light on a solar cell have been developed. Approaches like holographic concentrators from Prism Solar [1] V-Trough concentrator systems from JX Crystal [2] or Solaria [3] and refractive point focus systems from CPower [4], Amonix [5] or ENEA [6] showing a broad availability of optical concentrator systems. Most of them have in common that they suffer more and less from a lack of silicon concentrator cells on the market. So there is a strong demand of industrial producible solar cells optimized for concentrator applications.

The PhotoVoltaic Technology Evaluation Center (PV-TEC) [7] at the Fraunhofer ISE is equipped with an entire pilot line allowing industrial orientated processing of solar cells.

In this paper a Concentrator Metal Wrap Through (C-MWT) silicon solar cell completely assembled at the PV-TEC is presented. A similar approach is the CEP (Contacto Exclusivamente Posterior) solar cell from Castro and Sala ([8], [9]) reaching 17.3% at 5 suns. The advantages of a MWT solar cell first presented from E. van Kerschaver [10] compared to a conventional screen printed solar cell are: up to 50% less shading due to the missing busbars on the front and reduced series resistance losses due to receiver interconnections only at the rear are minimized. Additionally electrons can be captured with the rear n-junction increasing the collection probability of electrons locally.

For concentrator applications the MWT concept offers an intrinsic advantage compared to the standard cell concept, since the grid can easily be adapted to inhomogeneous light intensities. Additional holes can be drilled where more current is generated. This leads to a reduction of the series resistance without an increase in shading losses. Furthermore, due to the absence of front side busbars silicon can be saved which gives additional potential in cost reduction.

PROCESSING THE C-MWT SOLAR CELL

Based on the existing MWT process at Fraunhofer ISE [11] an improved process was developed. The major improvements were the utilization of a Si-oxide layer as a diffusion barrier for the POCl_3 diffusion. After a cleaning step the Si-oxide is grown and afterwards structured wet-chemically with a screen-printed etch resist lacquer.

Figure 1 shows a cross-section of a C-MWT solar cell. The Si-oxide assures the electrical separation of the n- and p-area and substitutes the conventional laser contact isolation on the rear side. Hence less damaged silicon leads to a lower recombination and the Si-oxide provides a good surface passivation. Furthermore, wafer breakage can be reduced due to the missing laser trenches.

The small size of the C-MWT solar cells (active cell area 10.2cm^2) compared to the standard size of 243cm^2 makes the edges much more important. Thus, in this design the bulk is embedding the emitter which is called emitter window. This avoids shunting and recombination losses at the edges of the C-MWT solar cell.

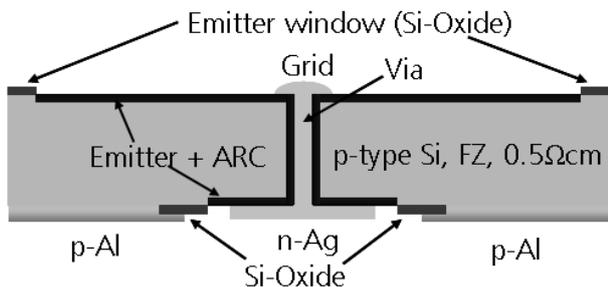


Figure 1: The drawing shows a cross section of the C-MWT solar cell. The Si-oxide on the front side provides the emitter window and the Si-oxide on the rear side contact separation.

Three front metallization grids (finger pitch: 2.05, 1.15 and 0.75 mm) have been realized with the screen-printing technique and two emitters (sheet resistance $R_{sh}=50\Omega/\text{sq}$ and $75\Omega/\text{sq}$) have been diffused in order to investigate the influence of the series resistance on the performance under concentration. A finger pitch of 1.15mm means a finger clearance of 1.15mm. For further decreasing the series resistance light induced silver plating (LIP) [12] has been utilized.

Figure 2 shows a picture of a C-MWT solar cell with a total size of $3.6 \times 3.2\text{cm}^2$

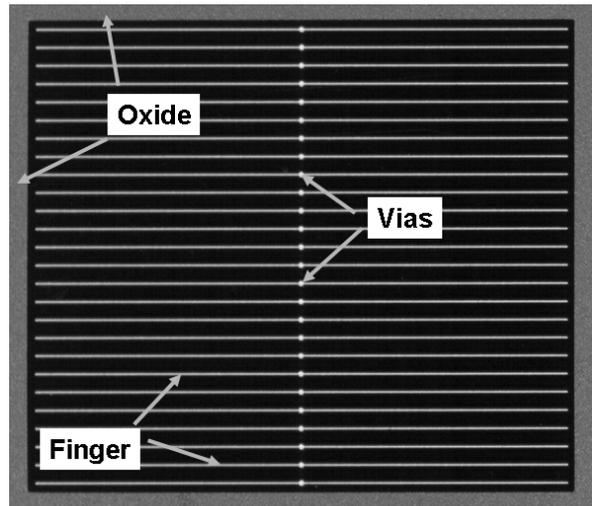


Figure 2: The picture shows the front side of a C-MWT solar cell with a finger pitch of 1.15mm. The front and rear metallization have been screen-printed.

CHARACTERIZATION THE C-MWT SOLAR CELL

The front metallization

Figure 3 shows a screen-printed finger reaching finger width down to $65\mu\text{m}$. The finger reaches an average height of $18\mu\text{m}$ resulting in an aspect ratio of 0.28.

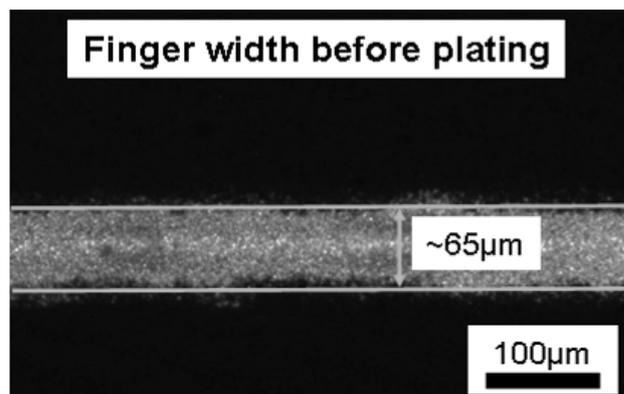


Figure 3: A screen-printed contact finger is shown reaching finger width of $65\mu\text{m}$.

Screen-printed silver does not reach the conductivity of pure silver. In order to reduce the series resistance a short lip step ($<1\text{min}$) has been carried out plating silver on top of the screen-printed seed layer. The LIP process utilizes the voltage which is generated in open circuit conditions when the solar

cell is irradiated with light. This leads to a deposition of silver ions where an electrical contact to the emitter exists.

By investigation of finger cross-sections (figure 4) it appears that the plated silver does not grow isotropic on the seed which leads primary to a reduction in contact resistance and secondary to a reduction in line resistivity. This effect has been investigated and published in [13] and [14]. The anisotropic silver deposition leads to a growth in width which is 2 times faster than in height. This results in an increased finger width of $4\mu\text{m}$ each side and an increased finger height of only $2\mu\text{m}$ leading to an aspect ratio of 0.27 which is slightly below the screen-printed finger. The short LIP step is necessary in order achieve the trade off between a reduction in series resistance and shading losses.

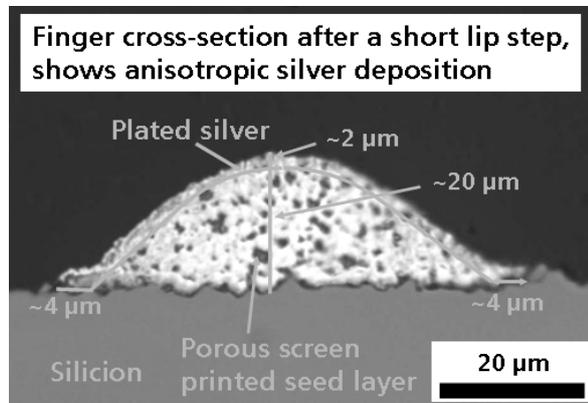


Figure 4: The picture shows a screen-printed contact finger after LIP. The anisotropic silver deposition ($4\mu\text{m}$ width, $2\mu\text{m}$ height) is clearly visible.

Results under concentration

The major loss mechanism by which concentrator solar cells are limited is the series resistance. In order to investigate the impact of the series resistance three front grids have been designed by varying the finger pitch (2.05, 1.15 and 0.75mm). In figure 5 the efficiency versus the concentration ratio C is plotted for three plated MWT solar cells with different metal grids (compare with table 1).

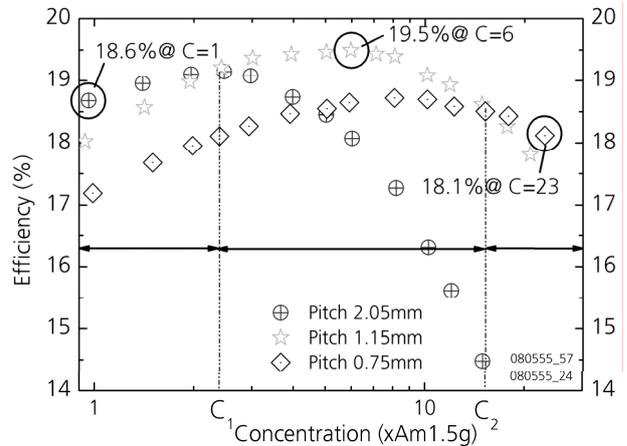


Figure 5: The graphs shows the different regions where the MWT solar cells perform best in dependency of the finger pitch and concentration C . Up to $C_1 \sim 2.5$ the MWT cell whose grid is optimized at one sun achieves the highest efficiencies, however, over $C_1 = 2.5$ the cell with a reduced pitch of 1.15mm exceeds and reaches 19.5% at $C=6$. Over $C_2 \sim 15$ the cell with the lowest pitch provides the best performance due to the low series resistance of $0.11\Omega\text{cm}^2$ (spectrum Am 1.5g).

Figure 5 clearly shows a strong dependency between finger pitch and concentration dependent efficiency. The cell optimized for one sun conditions with a finger pitch of 2.05mm achieves the best results at very low concentration ratios up to $C_1 \sim 2.5$. However, for higher irradiances the efficiency drops fast, due to the power loss induced by the series resistance. Solar cells with a denser grid suffer from higher shading and enhanced recombination below the metalized areas, thus the efficiency at very low concentrations is reduced. But in this case the series resistance is also reduced, so for increasing irradiation the fill factor remains high and an efficiency gain is achieved due to an increasing open circuit voltage, since $V_{oc} \sim \ln(C)$. This can be seen in figure 6 where the fill factor and the open circuit voltage are plotted versus the concentration. Lowering the pitch to 1.15mm reduces the series resistance leading to highest efficiencies between C_1 and $C_2 \sim 15$. A further reduction of the pitch to 0.75mm shifts the region where the MWT solar cells perform best to concentration ratios exceeding $C_2 \sim 15$.

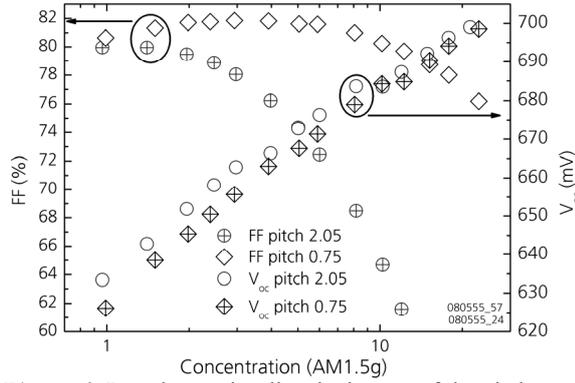


Figure 6: In order to visualize the impact of the pitch on the fill factor two MWT solar cells are shown with a pitch of 2.05mm and 0.75mm (efficiency shown in figure 11). A low series resistance which corresponds to a low pitch keeps the fill factor high. Thus, an increasing Voc is leading to a gain in efficiency (spectrum AM1.5g).

MWT solar cells utilizing an emitter with a sheet resistance of $50\Omega/\text{sq}$ and $75\Omega/\text{sq}$ have been processed. The advantages of lower doped emitters are higher short-circuit-currents and higher open-circuit-voltages ($\Delta j_{sc}=+0.5\text{mA}/\text{cm}^2$ and $\Delta V_{oc}=+5\text{mV}$ at 1 sun). This is due to a better blue response leading to an increased current and a higher average lifetime of the minority charge carriers which in turn affects the V_{oc} positively. In contrary the ability to contact emitters with screen-printed pastes is positive correlated with the surface doping density. Thus, high doped emitters lead mostly to lower series resistance and higher fill factors. The best results under concentration achieved by MWT solar cells with a sheet resistance of $50\Omega/\text{sq}$ and $75\Omega/\text{sq}$ before and after LIP are listed in table 1.

TABLE 1. Results of concentration dependent, plated and non-plated Si MWT solar cells are shown (spectrum AM1.5g).

Pitch (mm)	η (%)	Rsh (Ω/sq)	FF (%)	Voc (mV)	LIP
2.05	18.6 @C=1	75	79.7	631	☑
1.15	19.5 @C=6	75	79.6	676	☑
0.75	18.1 @C=23	50	76.2	699	☑
2.05	18.4 @C=1	50	80.5	627	
1.15	19.1 @C=4	50	80.2	667	
0.75	17.2 @C=23	50	71.9	702	

The non-plated MWT solar cells with an emitter sheet resistance of $50\Omega/\text{sq}$ reach higher efficiencies at all concentration ratios and even under one-sun conditions due to the lower contact resistance. However, the plated cells perform different. Due to a reduction in contact and finger resistance by LIP the MWT solar cells with a sheet resistance of $75\Omega/\text{sq}$ profit more compared to cells with an emitter sheet resistance of $50\Omega/\text{sq}$ thus achieving higher efficiencies up to C~15. For C>15 the higher fill factor achieved

by MWT solar cells with the higher doped emitter results in higher efficiencies, since at higher concentration the impact of the sheet resistance is dominant

In general it was demonstrated that MWT solar cells with emitter and contact pitch optimized for the target concentration ratio can be fabricated with very high efficiencies of up to 19.5% at 6 suns and exceeding 18% at 23 suns.

COMPARISON OF EXPERIMENTAL RESULTS WITH A TWO-DIODE-MODEL BASED SIMULATION

For calculating all contributions of the series resistance a simulation tool has been developed. Taking into account the material dependent parameters like the resistivity of the metal pastes and finger geometry it is possible to calculate an optimal finger pitch in dependency on the concentration ratio. This could be done by adding the 2-diode-model to an analytical resistivity model allowing calculations like presented in figure 6.

Fitting the one sun I-V-curve allows extracting the dark current densities j_{01} , j_{02} and the parallel resistance for the 2-diode-model.

In figure 6: the measured and the calculated concentration dependent data are plotted. All the calculated curves are showing good agreement with the measured data. An underestimation of the FF generates a maximum deviation between calculated and measured data of 0.8%-rel. in the efficiency. The deviation in the fill factor is produced from an overestimation of the open circuit voltage.

Further investigations indicate that a network effect is responsible for reducing the open circuit voltage. Publications from Cuevas [15], Harder [16] and Greulich [17] report a decreasing V_{oc} due to diodes working at different voltages under the active and shaded area of a solar cell generated from recombination currents through the local series resistance. Under high open circuit voltages this produces a high recombination current and hence a high voltage drop at the series resistance. Thus, the overestimation of the V_{oc} can be explained.

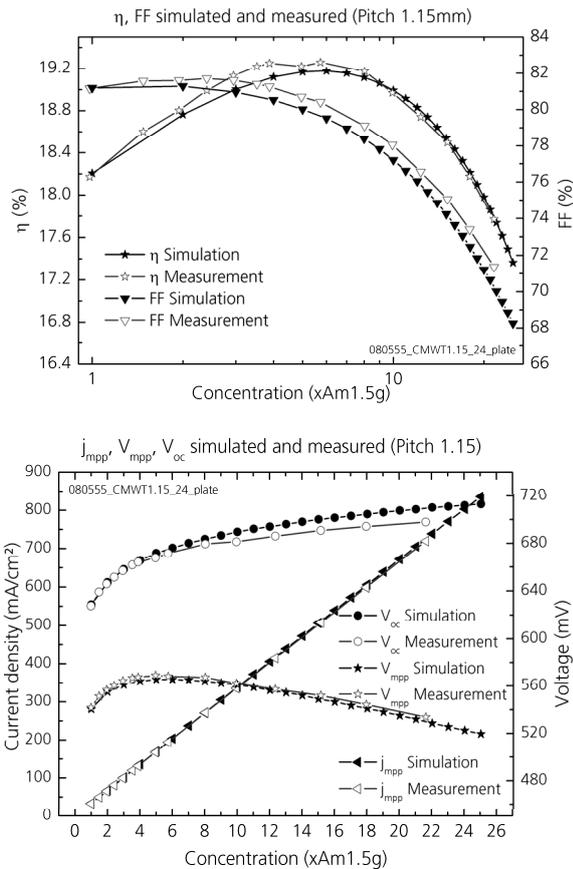


Figure 6: Measured and calculated data showing good accordance. The maximum relative aberrations in efficiency and fill factor are low and negligible.

The simulations using this analytical rather simple approach corresponds very well to the experimental findings thus an simulation based further optimization will be the next step

CONCLUSION

By only using industrial related equipment like screen-printing and high throughput pilot line processing in the Fraunhofer ISE PV-TEC a concentrator MWT solar cell has been developed using FZ silicon and an oxide as diffusion barrier for the POCl₃ diffusion step. The oxide substitutes the laser trenches on both sides of the MWT solar cell separating the polarities electrically. This avoids laser damaged silicon which in turn reduces recombination losses resulting in high fill factors of up to 80.5% (pitch 2.05mm) at one sun. Fine line screen-printing for the front silver contact grid has been used resulting in fine grid fingers of ~65μm with aspect ratio of 0.28.

Under one sun conditions efficiencies up to 18.4% are achieved using an emitter with a sheet resistance of 50Ω/sq and screen-printed rear and front metallization.

MWT solar cells with an emitter sheet resistance of 75Ω/sq are limited by increased contact resistance, but profiting from an additional light induced plating step not only by enhanced finger conductivity but also by reduced contact resistance resulting in front contact fingers of 73μm in width and 20μm in height. An efficiency of 18.6% is reached which is apparently the highest efficiency reported for a MWT solar cell so far.

Adapting the front grid by reducing the finger pitch a maximum conversion efficiency of 19.5% could be measured at an incident irradiation of 0.6W/cm² corresponding in a concentration factor of C=6. At a concentration ratio of C=23 (equates 2.3W/cm²) an efficiency of 18.1% is achieved. Even non-plated just screen-printed MWT solar cells reach 18.4% at one sun, 19.1% at four suns and 17.1 at C=23.

By adding the 2-diode-model to a analytical tool important values like efficiency and fill factor in dependency on the series resistance can be obtained. This enables further improvements like the finger pitch of the front metallization in dependency on the concentration. The comparison with measured data is showing good approximation.

Due to the rather simple process the cells can be adapted easily in design to the required module concept. Due to the PV-TEC pilot line also large quantities of cells could be processed.

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