INDUSTRIALLY FEASIBLE MC-SI SOLAR CELLS WITH FINE LINE PRINTED FRONT CONTACTS ON HIGH EMITTER SHEET RESISTANCE TOWARDS 17% EFFICIENCY

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ABSTRACT: To achieve higher efficiencies without extra-cost is the major goal of research and development in crystalline silicon solar cell production technology. This goal can be addressed by fine line printing. Therefore, the focus of this work will be the combination of fine line printed front contacts and high emitter sheet resistances. A detailed study of fine line front contacts is presented. Therefore, an electrical analysis based on solar cell results as well as an optical analysis based on microscope pictures are carried out. Furthermore, the contact characteristic of different silver pastes as a function of the emitter sheet resistance is analyzed. As additional approach fine line printed front contacts as seed layer for a two-step metallization are discussed within this work. Both concepts, the one- and two-step metallization, will be compared with each other. Moreover, the use of MWT (metal wrap through) solar cells [1] allows a further efficiency increase [2]. Hence, MWT solar cells with fine line screen printed front contacts are developed and characterized in this paper. Efficiencies up to 16.8% are realized with mc-Si MWT solar cells.
Keywords: MWT, aerosol printing, screen printing

1 INTRODUCTION

Reducing costs per W_p at low economical risks is a major goal of research and development in crystalline silicon solar cell production technology. This goal can be mainly addressed by efficiency increase, thinner silicon material as well as production cost reduction. With fine line printing the objective of efficiency increase is selected. Therefore, the focus of this work will be the combination of fine line printed front contacts and high emitter sheet resistances. A main advantage of printing thinner lines is that the power losses caused by the emitter sheet resistance can be decreased by increasing the amount of printed fingers with equal or even less shaded area, simplifying the application of high emitter sheet resistances [3]. An additional approach is to use fine line printed front contacts as seed layer for a two-step metallization concept. Moreover, by the use of MWT (metal wrap through) solar cells [1] the efficiency will be increased further [2]. Due to a design and process sequence which is very similar to that of conventionally processed screen-printed solar cells, the rear contact MWT solar cell is a very promising alternative. The absence of the front bus bars leads to a gain in active cell area and thus an efficiency gain compared with conventionally processed screen-printed solar cells is reached. Particularly recent R&D results in cell and module production show a very high potential for the MWT cell concept [2,4-9]. Hence, the transfer of the MWT solar cell process to industry is still ongoing [10]. First cell and module producers successfully implemented the MWT solar cell in their production lines [11,12].

To achieve fine line printed front contacts different approaches will be discussed in this work. First, a new, screen printing technique [13] which allows significantly reduced printed finger width on textured surfaces in comparison to conventional screen printing is presented. This can be reached by using a heated print nest that keeps the wafer at a defined temperature while printing, leading to less spreading effects of the printed structure. Second, a two-step metallization process including seed layer printing and light induced inline silver plating (LIP) [14] is shown. For the seed layer metallization step two different techniques are compared: screen-printing and metal aerosol jet printing [3,15]. The presented metallization techniques are applied to conventional and MWT solar cells within this work.

A detailed study of fine line front contacts is presented in this paper. An electrical and optical analysis is carried out. Moreover, different emitters with high sheet resistances are considered. Hence, a gain in short circuit current J_{SC} and open circuit voltage V_{OC} is expected caused by a better conversion of blue light due to a lower emitter and front surface recombination velocity [16]. But, a decrease of the fill factor in consequence of increased contact resistances is possible. Thus, the contact characteristic of different silver pastes as a function of the emitter sheet resistance is analyzed. Recombination losses due to the penetration of the space-charge region as well as losses caused by shunting are also discussed, especially for the rear bus bar region of MWT cells.

2 CELL PROCESSING

For solar cell processing a conventional process flow is chosen including Al-BSF as rear metallization and a one- or two-step front metallization as well as different emitters with high sheet resistances [5]. In a first batch (I) MWT and conventional solar cells with an emitter sheet resistance $R_{SH} \approx 65\ \Omega$/sq and screen-printing as one-step front metallization are processed (process A). In a second batch (II) conventional and MWT solar cells are processed with $R_{SH} \approx 80\ \Omega$/sq and a two-step front metallization including seed layer printing and light induced silver plating. For seed layer printing screen printing (process B) and metal aerosol jet printing are used (process C). The process flow for conventional mc-Si solar cells is presented in Figure 1. All process steps except the metal aerosol jet printing were carried out with the pilot-line equipment of the PV-TEC (Photo-Voltaic Technology Evaluation Centre, [17]).

For MWT solar cells of batch (I) and (II) only two additional laser process steps – via hole drilling and rear contact isolation – and one screen-printing step – via hole metallization [18] – compared with the conventional cell process are used. The process flow for mc-Si MWT solar cells is presented in Figure 2. In reference [4] and [2] the process is described in more detail. For a good comparison between MWT and conventional solar cells the same mc Si-block (neighboring wafers) is used within each batch.

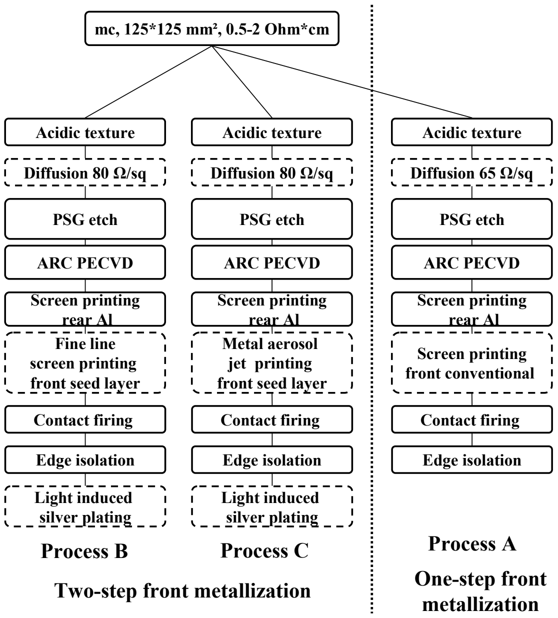

Figure 1: Process flow of conventional mc-Si solar cells with a one- (process A) or two-step front metallization process (process B and C). All process steps which are varied, for example the front printing process, are marked (dashed boxes).

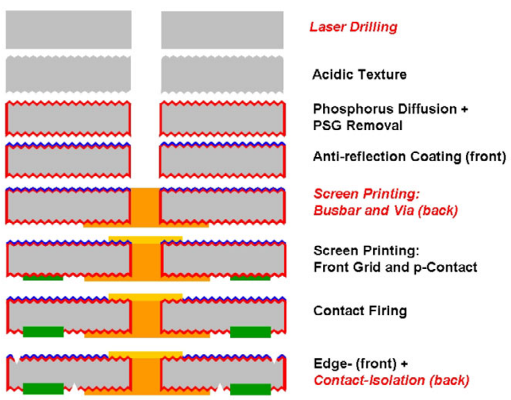

Figure 2: Process flow for mc-Si MWT solar cells. All additional or modified process steps compared with the conventional solar cell process *are in italics*

A third batch (III) including conventional Cz-Si (3-6 Ωcm) solar cells is used to compare the one-step front metallization process with screen printing (similar to process A in Figure 1) and the two-step front metallization process with metal aerosol jetting and light induced plating (similar to process C in Figure 1) directly.

In each batch, the front grid (finger width and pitch) is independently optimized for the one- and two-step metallization processes. The bus bar width and the number of bus bars is the same for all cells within each batch. Hence, a suitable comparison is guaranteed.

3 EXPERIMENTS AND RESULTS

3.1 Solar cell results

As described above MWT and conventional solar cells were processed in several batches (process flows see Figure 1 and Figure 2).

In Table I the I-V and SunsVoc [19] results achieved in batch (I) including the one-step front metallization (process A, see Figure 1) are presented. FF_0 is the ideal fill factor according to M. Green [20]: no series resistance and shunting losses are considered. *pFF* is the pseudo fill factor according to R. Sinton [19]: no series resistance losses are considered. The maximum efficiency of 16.4% is a good result for an industrially processed multi-crystalline screen-printed silicon solar cell. Compared with conventional cells an efficiency gain up to 0.5% absolute is reached for MWT cells. This efficiency increase is primarily caused by a gain in the short circuit current J_{SC} (up to 3.5%rel.) which can be mainly explained by less shading (about 3%abs.) on the front side. Furthermore, a gain in the open circuit voltage V_{OC} is measured probably due to less metallization on the front and thus less recombination losses at the metal contact. The small fill factor decrease between MWT and reference cells can be mainly explained by the decrease in the pseudo-fill factor *pFF* for MWT cells. Due to high parallel resistances (more than 10 kΩcm²) this decrease can be only explained by an increase of non-linear shunting (j_{02}) in the region of the rear silver bus bar [21,22] .

Table I: Results (best cells) of I-V and SunsVoc-measurements of mc-Si MWT and conventional solar cells of batch (I) with screen printed front and 65 Ω/sq emitter (see process A in Figure 1). All IV measurements are based on the spectrum AM1.5G IEC60904-3Ed.2 (2008). For all measurements a mismatch correction was done. The cell area is 156.25 mm².

Cell type	MWT	Conventional
V_{OC} [mV]	615	612
J_{SC} [mA/cm²]	34.8	33.7
FF [%]	76.8	77.3
η [%]	**16.4**	**15.9**
FF_0 [%]	83.0	83.0
pFF [%]	80.6	80.9

In Table II the I-V and SunsVoc [19] results achieved in batch (II) including the two-step front metallization (process B and C see Figure 1) are presented. The maximum efficiency of 16.7%, confirmed by ISE CalLab, confirms the high efficiency level reached with screen printing. However, it is shown that the same efficiency level could be reached for a screen-printed (process B) and metal aerosol jetted (process C) seed layer on the front. Hence, both techniques are suitable for seed layer printing in combination with high emitter sheet resistances. The contact characteristic of the paste/ink used in this batch seems to be comparable. Further results show that even for emitter sheet resistances over 100 Ω/sq very good cell results can be achieved with metal aerosol jetting [3].

The maximum efficiency of 16.8% for a MWT cell (see Table II) is also a very good result for a multi-crystalline silicon solar cell. However, compared with conventional cells only a small efficiency gain of about 0.1% absolute is achieved with MWT cells. This can be explained by the low *pFF*-value for the MWT cell which indicates that shunting losses limit the fill factor. Due to a shunt resistance of about 3 kΩcm², high values of j_{02} are probably the reason for shunting losses. A high shunting characteristic of the via paste especially for thin emitters with high sheet resistances (here: 80 Ω/sq) might be an explanation. However, a further optimization of the via paste [23] should allow higher pseudo fill factors and thus efficiencies over 17%.

Table II: Results (best cells) of I-V and SunsVoc-measurements of mc-Si solar cells of batch (II) with screen printed (SP) and metal aerosol jetted (MAJ) seed layer on the front and 80 Ω/sq emitter (see process B and C in Figure 1). For MWT cells only metal aerosol jetting was applied. All IV measurements are based on the spectrum AM1.5G IEC60904-3Ed.2 (2008). For all measurements a mismatch correction was done. The cell area is 156.25 mm².

Cell type	Conventional		MWT
Seed layer	SP	MAJ	MAJ
V_{OC} [mV]	616	615	615
J_{SC} [mA/cm²]	34.9	34.7	35.9
FF [%]	77.9	78.1	76.0
η [%]	**16.7***	**16.7**	**16.8**
FF_0 [%]	83.0	83.0	83.0
pFF [%]	81.0	80.7	79.5

*independently confirmed by ISE CalLab.

Table III: I-V results (mean values) of conventional Cz-Si (3-6 Ωcm) solar cells of batch (III) processed with screen printing (SP) as one-step front metallization (see process A in Figure 1) as well as with metal aerosol jetting (MAJ) and light induced silver plating (LIP) as two-step front metallization (see process C in Figure 1). All IV measurements are based on the spectrum AM 1.5 G IEC60904-3Ed.2 (2008) and are performed directly after cell production. The cell area is 243.4 mm².

Cell type	Conventional	
Front contact	SP	MAJ+LIP
Amount of cells	25	17
V_{OC} [mV]	605±2	609±2
J_{SC} [mA/cm²]	36.2±0.1	36.8±0.1
FF [%]	76.8±0.4	77.0±0.2
η [%]	**16.8**±0.1	**17.2**±0.1

In Table III I-V results achieved in batch (III) are presented. In this batch the one-step front metallization with screen-printing (process A in Figure 1) is directly compared with the two-step front metallization including metal aerosol jetting as seed layer printing and light induced silver plating (process C in Figure 1). An efficiency gain of about 0.4% is achieved with the two-step front metallization. The increase can be mainly explained by less shading (J_{SC} increase) due to smaller fingers and less recombination losses (V_{OC} increase) probably due to a lower shunting characteristic of the aerosol ink in comparison with the screen printing paste used in this batch. However, in batch (II) no V_{OC} difference is observed (see Table II) between screen printing and metal aerosol jetting. This can probably be explained by the use of different silver pastes for screen printing in batch (II) and (III). Nevertheless, a clear advantage of the two-step metallization process is shown by batch (III), results achieved by A. Mette [24] are verified.

3.2 Optical analysis of the front contact finger

For the comparison of the geometric parameters of screen-printed contacts achieved with the one-step and the two-step front metallization light microscope pictures are analyzed and compared in Figure 3. Additionally, the mean maximum finger height is measured by a confocal microscope and the aspect ratio AR (height/width) of the contact finger is calculated.

In Figure 3a and 3c a screen printed contact finger processed within process A (see Figure 1) is shown. In Figure 3b a screen printed contact finger after seed layer printing and in Figure 3d after light induced silver plating is presented (process B in Figure 1). It is shown that the screen printing process developed at ISE [13] allows contact fingers widths of about 60 µm with already high aspect ratios on mc-Si material, very good values for screen printed lines. After light induced plating the finger width increases up to 80 µm, but is still a little bit below the width of the finger processed with process A. At the same time the aspect ratio is even higher. Hence, the finger conductivity is probably higher and the shading is reduced for the two-step metalized finger (process B). The high efficiency potential of the two-step front metallization process (see Table II and III) is figured out.

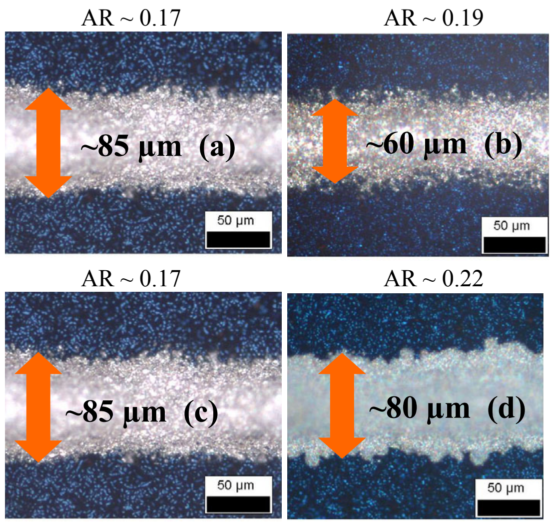

Figure 3: Microscope pictures of a screen printed contact finger (**3a, 3d**) processed within process A (see Figure 1) and a screen printed contact finger (process B in Figure 1) after seed layer printing (**3c**) as well as of a screen printed contact finger after light induced plating (**3d**) is shown. Mean values of the finger width and the aspect ratio are given.

For the metal aerosol jetted line as seed layer finger widths of about 40-50 µm are measured. However, after light induced plating the finger width is almost the same (70-80 µm) compared to the plated finger with screen printed seed layer. This can be explained by the fact that aerosol printed lines are plated for a longer time in order to achieve the same line resistivity with both seed layers. Hence, the finger width increases more during the plating process. The same J_{SC}-level for both processes (see Table III) can be explained.

3.2 Electrical analysis

In this chapter the influence of the contact R_C and the emitter sheet resistance R_{SH} on the series resistance R_S of the solar cell is analyzed. Therefore, the series resistance loss caused by the emitter sheet resistance $R_{S,E}$ is calculated by:

$$R_{S,E} = \left(\frac{R_{SH} * d_f^{\,2}}{12} \right) \qquad (1)$$

The contact finger spacing d_f is the same value for all emitters. Hence, the value for $R_{S,E}$ should be the same for both pastes.

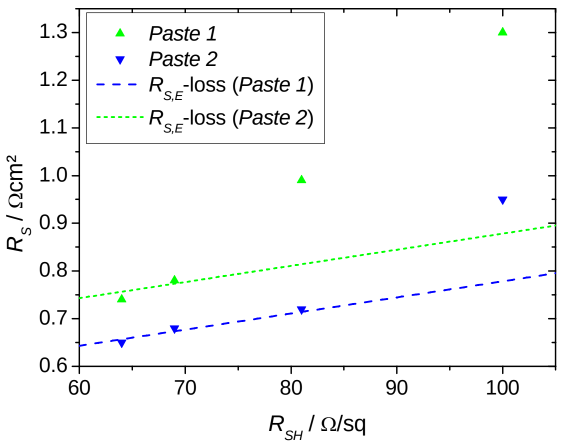

Figure 4: Series resistance R_S of the solar cell plotted against the emitter sheet resistance R_{SH} for two different front side silver pastes. The dashed lines show the linear influence of series resistance losses of the emitter $R_{S,E}$ calculated with the formula presented in (1).

In Figure 4 the series resistances R_S of conventional solar cells (process A in Figure 1) extracted from I-V results is plotted against the emitter sheet resistance R_{SH}. The obvious difference between the linear characteristic of R_S due to the emitter losses $R_{S,E}$ (calculated with formula (1), dashed lines in Figure 4) and the measured R_S-values can be only explained by the influence of the emitter sheet resistance and the front side paste on the contact resistance. Moreover, the difference between the two pastes is caused by different finger conductivities (constant difference for all sheet resistances) and a reduced contact resistance of *paste 2* compared with *paste 1*, especially for high emitter sheet resistances. Thus, it is shown that only *paste 2* is suitable to contact emitter sheet resistances up to 80 Ω/sq very well. Hence, *paste 2* was used for screen-printing in case of the two-step metallization process (process B in Figure 2). For emitter sheet resistances over 80 Ω/sq both pastes, especially *paste 1*, result in an increased contact resistance caused by the low surface concentration of phosphorous for these emitters (below 5×10^{20} cm^{-3}).

4 CONCLUSIONS

In this work cell efficiencies up to 16.4% are reached for mc-Si MWT solar cells with a one step metallization process based on screen-printing. An efficiency gain up to 0.5% absolute is achieved by the use of MWT cells instead of conventional solar cells.

By the use of a two-step metallization process and an emitter sheet resistance of about 80 Ω/sq efficiencies up to 16.7% are achieved with screen-printed seed layers for conventional solar cells. For metal aerosol jet printed seed layers efficiencies up to 16.7% are measured for conventional solar cells and up to 16.8% for MWT solar cells. Contact widths down to 40 µm are reached with aerosol seed layer printing and down to 60 µm with a screen printed seed layer. After light induced silver plating line width of about 70-80 µm and aspect ratios over 0.2 are achieved for both seed layers.

However, both printing techniques (screen printing and aerosol printing) are suitable for seed layer printing on high emitter sheet resistances. Furthermore, due to the two-step metallization process a clear efficiency increase (up to 0.4% absolute) is reached compared with the one-step metallization process.

Moreover, it is shown that the contact resistance increases dramatically for screen-printed contacts if the emitter sheet resistance increases and the surface concentration of phosphorous drops below 5×10^{20} cm^{-3}. But, this characteristic strongly depends on the silver paste used for front side metallization.

Primary low values of the pseudo fill factor probably caused by shunting due to the via paste limit the efficiency of MWT cells compared with conventional cells, especially for emitters with high sheet resistances. Hence, a further optimization of the via pastes is suggested. Thus, higher pseudo fill factors and therefore efficiencies over 17% will be possible.

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6 REFERENCES

[1] E. van Kerschaver et al., "A Novel Silicon Solar Cell Structure with Both External Polarity Contacts on the Back Surface", *Proceedings of the 2nd World Conference on Photovoltaic Energy Conversion*, Vienna, Austria, 1998, pp. 1479-1482

[2] F. Clement et al., "Industrially Feasible Multi-Crystalline Metal Wrap through (Mwt) Silicon Solar

Cells Exceeding 16% Efficiency", *Solar Energy Materials & Solar Cells* **93**, 2009, pp. 1051-1055.

[3] M. Hörteis et al., "Fine Line Printed Silicon Solar Cells Exceeding 20% Efficiency", *Progress in Photovoltaics: Research and Applications* **16**, 2008, pp. 555-560.

[4] F. Clement, *Die Metal Wrap through Solarzelle - Entwicklung Und Charakterisierung*. (Verlag Dr.-Hut, München, 2009).

[5] F. Clement et al., "Industrially Feasible Mc-Si Metal Wrap through (Mwt) Solar Cells with High Emitter Sheet Resistances Exceeding 16% Efficiency", *Proceedings of the 23rd European Photovoltaic Solar Energy Conference*, Valencia, Spain, 2008, pp. in print

[6] A.A. Mewe et al., "Mwt 'Plug' Metallization: Improved Performance and Process Stability of Pum and Aspire Cells", *Proceedings of the 23rd European Photovoltaic Solar Energy Conference*, Valencia, Spain, 2008, pp.

[7] M. Späth et al., "First Experiments on Module Assembly Line Using Back-Contact Solar Cells", *Proceedings of the 23rd European Photovoltaic Solar Energy Conference*, Valencia, Spain, 2008, pp.

[8] I.G. Romijn et al., "An Overview of Mwt Cells and Evolution to Aspire Concept: A New Integrated Mc-Si Cell and Module Design for High Efficiencies", *Proceedings of the 23rd European Photovoltaic Solar Energy Conference*, Valencia, Spain, 2008, pp.

[9] N. Nakatani et al., "High Efficiency Multicrystalline Silicon Back-Contact Solar Cells", *Technical Digest of the 17th International Photovoltaic Solar Energy Conference*, Fukuoka, Japan, 2007, pp. 401-403

[10] F. Clement et al., "Pilot-Line Processing of Screen-Printed Cz-Si Mwt Solar Cells Exceeding 17% Efficiency", *Proceedings of the 34th IEEE Photovoltaic Specialists Conference*, Philadelphia, USA, 2009, pp. in print

[11] M.N. van den Donker et al., "The Starfire Project: Towards in-Line Mass Production of Thin High Efficiency Back-Contacted Multicrystalline Silicon Solar Cells", *Proceedings of the 23rd European Photovoltaic Solar Energy Conference*, Valencia, Spain, 2008, pp.

[12] F. Dross et al., "High-Efficiency (Average 16.0%) Industrial-Type Rear-Contactes Multicrystalline Silicon Solar Cells", *Technical Digest of the 17th International Photovoltaic Solar Energy Conference*, Fukuoka, Japan, 2007, pp. 410-411

[13] D. Erath et al., "Advanced Screen Printing Technique for High Definition Frontside Metallization of Crystalline Silicon Solar Cells", *Solar Energy Materials & Solar Cells* **doi:10.1016/j.solmat.2009.05.018**, 2009, pp. in print.

[14] A. Mette et al., "Increasing the Efficiency of Screen-Printed Silicon Solar Cells by Light-Induced Silver Plating", *Proceedings of the 4th World Conference on Photovoltaic Energy Conversion*, Waikoloa, Hawaii, USA, 2006, pp. 1056-1059

[15] A. Mette et al., "Metal Aerosol Jet Printing for Solar Cell Metallization", *Progress in Photovoltaics: Research and Applications* **115**, 2007, pp. 621-627.

[16] M. M. Hilali et al., "High-Efficiency (19%) Screen-Printed Textured Cells on Low-Resistivity Float-Zone Silicon with High Sheet-Resistance Emitters", *Progress in Photovoltaics: Research and Applications* **14**, 2005, pp. 135-144.

[17] D. Biro et al., "Pv-Tec: Photovoltaic Technology Evaluation Center - Design and Implementation of a Production Research Unit", *Proceedings of the 21st European Photovoltaic Solar Energy Conference*, Dresden, Germany, 2006, pp. 621-624

[18] F. Clement et al., "High Throughput Via-Metallization Technique for Multi-Crystalline Metal Wrap through (Mwt) Silicon Solar Cells Exceeding 16% Efficiency", *Solar Energy Materials & Solar Cells* **doi:10.1016/j.solmat.2009.06.020**, 2009, pp. in print.

[19] R. A. Sinton et al., "A Quasi-Steady-State Open-Circuit Voltage Method for Solar Cell Characterization", *Proceedings of the 16th European Photovoltaic Solar Energy Conference*, Glasgow, UK, 2000, pp. 1152-1155

[20] M. A. Green, *Silicon Solar Cells: Advanced Principles and Practice*. (Centre for Photovoltaic Devises and Systems UNSW, Sydney, NSW, 1995).

[21] F. Dross et al., "Impact of Rear-Surface Passivation on Mwt Performances", *Proceedings of the 4th World Conference on Photovoltaic Energy Conversion*, Hawaii, USA, 2006, pp. 1291-1294

[22] F. Clement et al., "Processing and Comprehensive Characterisation of Screen-Printed Mc-Si Metal Wrap through (Mwt) Solar Cells", *Proceedings of the 22nd European Photovoltaic Solar Energy Conference* Milan, Italy, 2007, pp. 1399-1402

[23] M. Neidert et al., "Development of Via pastes for high efficiency MWT cells with a low shunting behavior", this conference

[24] A. Mette, *New Concepts for Front Side Metallization of Industrial Silicon Solar Cells*, Dissertation, Universität Freiburg (2007).