HIGH ASPECT RATIO SCREEN PRINTED FINGERS

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ABSTRACT: To reduce shading losses and maintain good finger conductivity, screen printed solar cells with high aspect ratio fingers were processed. Finger width was reduced down to 60 µm by using a new screen. Finger height was increased by multiple printing. 51 solar cells were processed. Three-fold and five-fold printing was used, standard screen printed cells were made as reference. As a result of the reduced shading losses, short circuit current increases of 0.7 to 0.8 mA/cm^2, compared to the standard screen printed solar cells were achieved. In another run with 12 solar cells, good fill factors of up to 76.8% were reached with five-fold printing and different firing parameters. The best five-fold printed 12.5x12.5 cm^2 mc-Si reached 16.0% efficiency. By ten-fold printing, 60 µm wide and 60 µm high fingers were achieved.
Keywords: Shading, Screen Printing, Contact

1 INTRODUCTION

The screen print solar cell process is relatively simple and well suited for multi- and mono-crystalline silicon. About 90% of the industrially produced solar cells are processed with screen printing [1]. Screen printing is used to form metal contacts on the front (silver) and rear-side (aluminium back surface field and silver soldering pads). This study focuses on the front grid. A typical screen finger opening is 100 µm. Finger broadening occurs after the screen detaches from the wafer because of the flow behaviour of the paste - leading to 120-140 µm wide and approximately 15 µm high fingers after firing. For screen printed silicon solar cells, the typical shading loss due to the front grid is about 7%. To reduce the shading loss thin fingers are desirable.

Different approaches can lead to thin fingers. Reis *et al.* reached 70 µm finger width and 4.7 µm finger height on a rough surface by using a screen with 65 µm finger opening [2]. With pad printing line widths down to ~30 µm were realised [3], unfortunately cell results suffered from a low fill factor. Stencil printed cells can outperform standard screen printed cells by printing fingers with fired dimensions of 90 µm wide and 16 µm high [4]. Thin fingers can also be made by printing into grooves [5] or by roller printing [6].

In this work, a method was used leading to thin and high screen printed fingers. By using a modified screen (smaller finger openings, adjusted mesh count and coating thickness) one is able to print thinner fingers. With only a single print, the reduced amount of printed paste would result in a lower finger conductivity, which would degrade the fill factor. The multiple printing technique was used in this work to overcome this problem.

2 THE MULTIPLE PRINTING TECHNIQUE

Figure 1 shows a schematic drawing of a typical screen printed finger (left) and the “built up” concept achieved with multiple printing (right).

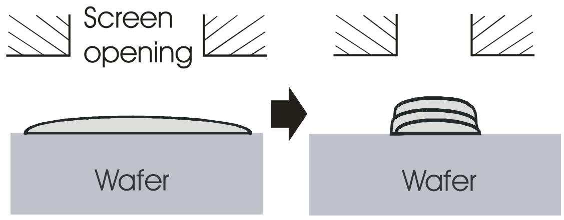

Figure 1: Left: Cross section of a standard screen printed finger (typical screen opening: 100 µm, finger width 120-140 µm). Right: Cross section of a triple stack finger, made by printing three times with intermediate drying. Thinner fingers can be printed using a modified screen.

The screen used for multiple printing allows to print thin fingers. Compared to a standard screen, the mesh count is higher, the wire diameter is smaller, the emulsion layer thickness is thinner and the mesh is calendered (rolled). These changed parameters reduce the printed paste volume and thus should reduce the finger broadening. A small wire diameter is also required to have big enough openings and therefore prevent finger interruptions. A 500 mesh screen with 18 µm wire diameter, emulsion layer (direct) thickness of 10 µm and finger opening of 50 µm fulfils the request. A microscope image of our screen is shown in Figure 2. We used an industrial silver paste and no additional paste thinner.

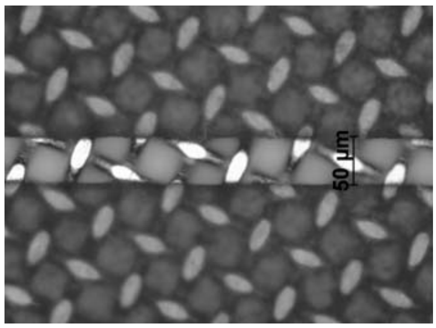

Figure 2: Optical microscope image of modified screen. Finger opening is only 50 µm wide. Outside the opening, the mesh is covered with the emulsion layer. The mesh is calendered, visible at the flattened crossing points of the wires.

Increased finger height can be achieved by multiple printing. After printing, a drying step has to be done. The dried fingers maintain their shape. The dried front grid can be printed and dried again several times until the desired height and thus finger conductivity is reached.

The difficulty of printing exactly on the same position again was solved with an optical positioning system. The wafer is automatically aligned at two edges. The positioning system is integrated in the printer. For the multiple printing steps only one screen was used to be sure to always print the same front grid.

3 EXPERIMENTAL

51 neighboring multi-crystalline wafers (Solsix) with the dimension of 12.5x12.5 cm^2 were used in the experiment. Cells with high aspect ratio screen printed fingers were processed with the multiple printing technique. It is a standard screen print process except for the repeated front grid printing and drying. The first step was isotexturing and cleaning. The emitter diffusion was done in a $POCl_3$ furnace. The sheet resistance was 50 Ω/sq. Edge isolation was done by plasma etching. The phosphorous glass was removed by dipping the wafers in diluted hydrofluoric acid. The silicon nitride layer serves as an antireflection coating and passivates the front surface and bulk, it is deposited using a PECVD reactor. The silver front grid was produced with the multiple printing technique discussed above. The back-side contact was printed with an aluminium paste. Firing was done in a conveyor belt furnace with standard firing parameters. This process sequence is shown in Figure 3.

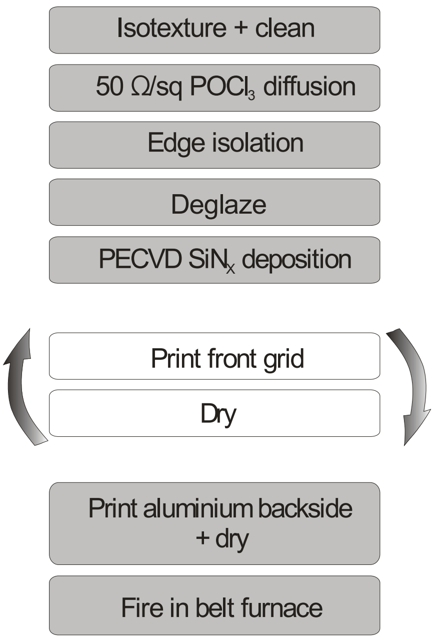

Figure 3: Process sequence used for the “built up” solar cells. It is a standard screen print solar cell process except for the repeated front grid printing and drying.

The wafers were divided into three groups. The first group served as a reference group. The front grid was printed only once using a standard screen with 100 µm finger openings. The second group of solar cells were processed with three-fold printing, the third with five-fold printing. For the 2nd two groups the above screen with 50 µm finger openings was used. The busbar width was 1.3 mm on both screens.

4 RESULTS

4.1 Finger dimensions

Finger widths and heights are shown in Table I. Finger width of three-fold and five-fold printed cells is 60-70 µm - approximately half of the reference cells. The screen finger opening is 50 µm so broadening still occurs. The absolute finger width, however, is small. Finger height of the five-fold printed cells is approximately double that of the standard cells.

	Printed front paste (mg)	Finger width (µm)	Finger height (µm)
Standard	101	120-130	~15
Three-fold	84	60-70	~25
Five-fold	126	60-70	~30

Table I: Comparison of the finger dimensions and printed front paste mass.

The printed front paste mass was obtained by weighing the wafers before and after printing and drying the front grid. The front paste mass includes fingers and busbars mass. The three-fold printed cells have less paste on the front grid, compared to the standard cells. Whereas the five-fold printed cells have about 25 mg more silver paste than the standard cells.

In Figure 4 cross sections of two fingers after firing are shown. The left SEM image shows a standard screen printed finger, the right one a finger after three-fold printing.

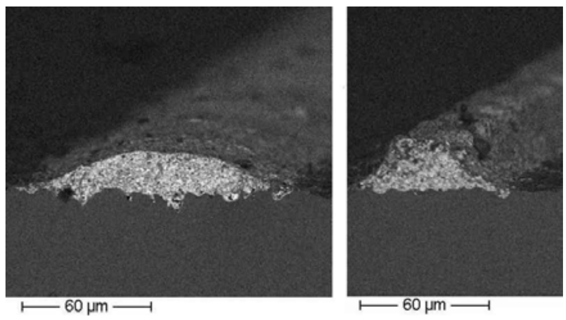

Figure 4: SEM images. Left: Standard screen printed finger (120µm width, ~15 µm height). Right: three-fold printed finger (60µm width, ~25 µm height).

To test the limits of this printing procedure, a wafer was ten-fold printed to realize a very high finger aspect ratio. In Figure 5 a SEM image of the ten-fold printed finger is shown. The width and the height are about 60µm. The image demonstrates the feasibility of precise multiple printing.

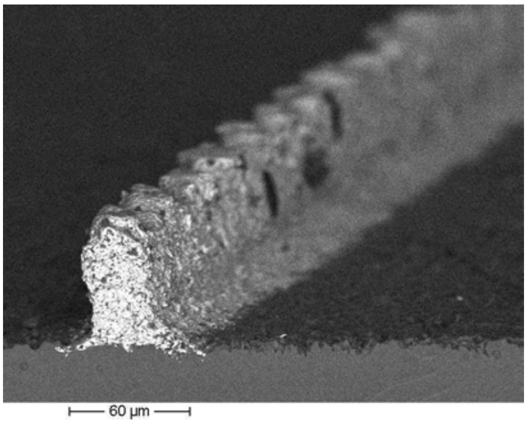

Figure 5: SEM image of ten-fold printed finger after firing (60µm width, 60 µm height).

4.2 Cell parameters

The IV-results are shown in Table II. Short circuit current of the three- and five-fold printed cells is 0.7 to 0.8 mA/cm^2 higher than the reference cells as a result of the reduced shading losses. Unfortunately, the fill factor decreases. The efficiency of the three-fold cells is therefore not increased compared to the reference cells. The five-fold printed cells from this run perform even worse than the reference cells.

	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF (%)	η (%)
Standard	32.6	609	76.7	15.2
Three-fold	33.4	610	75.0	15.2
Five-fold	33.3	609	73.7	14.9

Table II: IV-results: mean values of 16-17 cells per group.

In Figure 6 short circuit current as a function of cell number is shown. In Figure 7 fill factors as a function of cell number is shown. Cell 1 and 51 were neglected in the analysis due to exceptionally low fill factors.

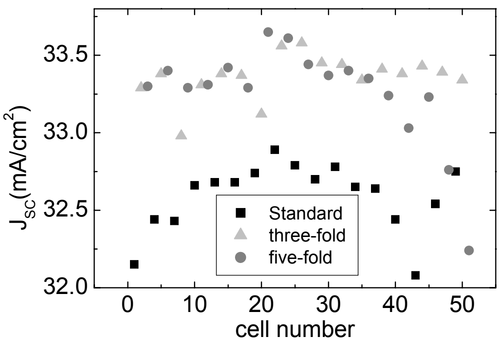

Figure 6: Short circuit current values of all cells. Three-fold and five-fold printed cells show higher J_{SC} values due to lower shading losses.

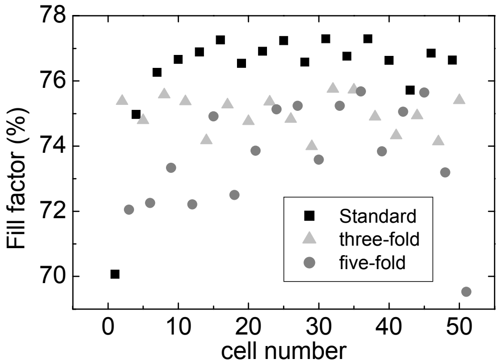

Figure 7: Fill factors as a function of cell number. Standard screen printed cells had higher fill factors compared to the three-fold and five-fold printed cells. Cell 1 and 51 were neglected in the analysis due to exceptionally low fill factors.

To measure the finger line resistance, the busbars from one cell of each group were disrupted between the fingers with a dicing saw. The results are shown in Table III. The series resistance, shunt resistance and J_{02} values were obtained by fitting the illuminated IV-curves to a two diode model. The line resistance of the three-fold finger was 0.22 Ω/cm higher than the standard finger. The calculated contribution of the line resistance to the total cell series resistance is given in the 3rd column of Table III. Series resistance of the three-fold and five-fold cells was about 0.25 Ωcm^2 higher than the reference cells. For the three-fold printed cells, the higher series resistance can be deduced from the higher line resistance. The line resistance of the five-fold printed finger was comparable to the standard finger. Nevertheless, the five-fold printed cells show approximately the same series resistance as the three-fold printed cells. This could be explained with a higher contact resistance and printing inhomogeneities, e.g. variations of the finger cross-section. Shunt resistance was best for the reference cells and worst for the five-fold printed cells. The absolute shunt resistance values were rather low, probably due to not optimal edge isolation.

Printing	$\mathbf{R_{Line}}$	$\mathbf{R_{series}}$		$\mathbf{R_{Shunt}}$
		Contribution by R_{line}	Total	
	Ω/cm	Ωcm^2	Ωcm^2	kΩcm^2
Standard	0.29	0.23	0.79	1.8
3x	0.51	0.40	1.04	1.6
5x	0.33	0.26	1.06	1.2

Table III: Comparison of line resistances, series resistances and shunt resistances: mean values.

The fill factor loss of the five-fold printed cells by 3% compared to the reference cells can be attributed to a higher series resistance (1.3%), a lower shunt resistance (0.3%), a higher J_{02} (1.0%) and a slight deviation of the IV curves from the ideal double diode model. An increase of J_{02} correlated with the number of printing steps can be seen in Figure 7. A J_{02} variation depending on the front contact scheme is probably connected to a high recombination in the space charge region below the fired contacts, which in turn is influenced by the etching behaviour of the paste during contact formation. The increased glass frit amount per contact area in the case of multiple printed fingers might lead to deep etch pits in the emitter reaching the space charge region. Adaptation of the firing parameters or the glass frit content might therefore be necessary.

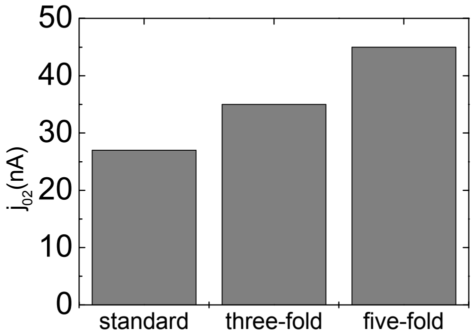

Figure 7: j_{02} values obtained by fitting the illuminated IV-curves to a two diode model: mean values.

The fill factor loss described above can be solved in principle as in another five-fold printing run with 12 mc-Si wafers (12.5x12.5 cm^2) good fill factors were obtained, using slightly higher firing temperatures. This adaptation of the firing conditions seem to be contradictory to the fill factor explanation given before, emphasizing the need for further investigations to clarify the contact formation process [7]. The best cell reached a fill factor of 76.8% and an efficiency of 16.0% (Table IV).

	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF (%)	η (%)
Av. five-fold	33.5	613	76.7	15.7
Best five-fold	33.8	615	76.8	16.0

Table IV: Additional run: 12 five-fold printed cells. Different firing parameters resulted in good FF.

Because five-fold printing is extensive, a trade-off between the 50 µm finger opening screen and a standard screen could be useful if a double printing technique can gain enough cell performance. This modified process could be industrially applicable and cost effective. For an industrial application drying time would have to receive attention. Because drying in a belt furnace takes more time than screen printing, repeated printing with the same screen (and thus the same printer) and drying would slow down the whole process unacceptably. One could imagine an integrated printer and quick drying device to solve this problem.

5 CONCLUSIONS

High aspect ratio fingers were achieved by multiple printing. A minimum finger width and a maximum height of 60 µm were reached. The gain in short circuit current was 0.7 to 0.8 mA/cm^2 due to lower shading losses. A five-fold printed mc-Si cell reached a good fill factor of 76.8 % and an efficiency of 16.0 %. Nevertheless, homogeneous printing without finger interruptions with the 50 µm finger opening screen was difficult. Three-fold and Five-fold printing is extensive compared to standard printing.

Further work will concentrate on the more industrially applicable double-printing technique.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

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[7] see for instance G. Schubert *et al.*, this conference.