TOWARDS INDUSTRIAL APPLICATION OF STENCIL PRINTING FOR CRYSTALLINE SILICON SOLAR CELLS

Benoît Heurtault and Jaap Hoornstra
ECN Solar Energy, PO Box 1, 1755ZG Petten, the Netherlands
heurtault@ecn.nl

ABSTRACT: A two-step stencil printing concept for front side metallization of crystalline silicon solar cells has been demonstrated in previous work [1] using a stencil to deposit the fingers and a screen for the busbars. In the present work, this concept is further developed and optimized towards industrial application. Line width can be reduced through improved stencil design, lines of 42µm wide and 15µm high after firing have been achieved. Using a rheological test, a paste with appropriate characteristics for stencil printing was identified and resulted in reduction of line width by 10µm. By optimizing the process sequence, paste usage can be reduced by 6% as compared to standard screen printing approach. Finally, to demonstrate the industrial application of the process, a test on 2000 cells in a production environment was successfully conducted and is reported here.
Keywords**:** c-Si, metallization, screen and stencil printing

1. INTRODUCTION

In order to reduce power losses associated with front side metallization, efforts converge in producing fine conductors with high aspect ratio. Fine lines reduce shadows losses and allow finer pitch which reduces the resistive losses in the emitter. High aspect ratio, thus large cross sectional area, reduces resistive losses in the conductor.

Screen printing has been for the past decades the dominant technology for front side metallization. Screen printing is a robust, versatile and low cost process which has been constantly improved in the past years. A combination of improvements in screen manufacturing (emulsion quality, meshes) and paste, and also solar cell surface have pushed the limits so that line widths below 100µm are now feasible in industry.

However, in pursuing printing of finer lines with higher aspect ratio, the effective open area in the screen is reduced and the quality of the opening in the emulsion layer deteriorates. Considering the dimensions of meshes, the open area in the screen will be dominated by the mesh for openings narrower than 60µm. This increases the risks of line interruptions and poor cross sectional uniformity.

A stencil, on the other hand, does not suffer from this limitation, since the opening can be designed for maximum open area and strength.

In previous work [1], optimal paste transfer and release to realize the finest line width and the highest aspect ratio was demonstrated using a single layer stencil. Since a single layer stencil is fully open and does not have supporting bridges, a full H-pattern can not be deposited in one printing step. Hence, a two-step metallization process is used where busbar and fingers are printed separately.

In this work, the most important aspects of this two-step process are presented and analyzed. Finally, the results of a test on a large quantity of cells in a production environment is reported.

2. EXPERIMENTAL

We used 156 mm x 156 mm multi & mono-crystalline silicon wafers with SiNx coating and a 60 Ohm/sq emitter. Print quality after firing was characterized with a 3D CNC visual measuring system (Mitutoyo QV Apex 404 PRO). Electrical characterization was obtained using a 4-point multi-probe system to measure the busbar-to-busbar resistance and obtain the line resistance [2]. For the time dependent recovery tests a Anton Paar Physica MCR Rheometer was used.

Various stencils (electroformed nickel and laser cut stainless steel) with a range of thicknesses and test patterns of only fingers of different width were tested.

3. LINE WIDTH OPTIMIZATION

3.1. Opening design

In [1] we showed that full transfer of paste is optimal for openings with aspect ratio smaller than 1:1. For an aperture narrower than the stencil thickness, the ratio of tack force to the adhesion force in the stencil interior is reduced. In this situation, paste is only partially transferred and interruptions appear. As a result, line cross sectional area and conductivity are reduced.

In order to be able to deposit continuous fine lines with an effective line cross sectional area, our first approach was to reduce the stencil thickness. By doing so, paste can be transferred through finer apertures.

As depicted in Figure 1, for apertures finer than 50µm in a 50µm thick stencil, the cross sectional area does not follow a linear trend but is greatly reduced. In this case, it shows that the paste is partially transferred and leaves only an imprint of low cross sectional area on the wafer. Moreover, line interruptions appear which will further increase the line resistance. On the other hand, by using a 30µm thick stencil, paste can be fully transferred for all the opening widths investigated.

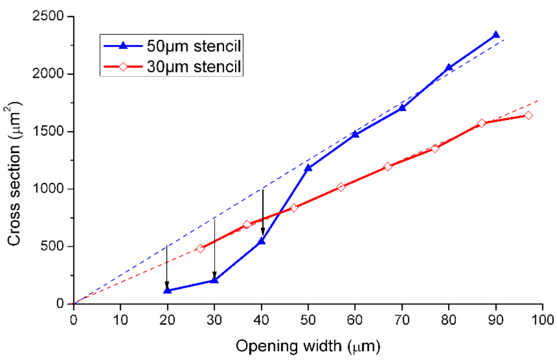

Figure 1: Line cross sectional area as a function of stencil opening width for a 50µm and a 30µm thick stencil

Figure 2 shows the corresponding line widths for a 30µm and 50µm thick stencil. It is interesting to note that the 50µm thick stencil can produce finer lines than the 30µm thick stencil. However these fine lines are just an imprint of paste, they do not have an effective cross sectional area and are interrupted, thus not of interest. Yet, what is important on this graph is that spreading, being the difference between opening width and printed line width, occurs and its magnitude remains relatively constant (20-30µm) for the whole range of opening widths tested. Ultimately, spreading will limit the aspect ratio for smaller openings as it becomes proportionally larger.

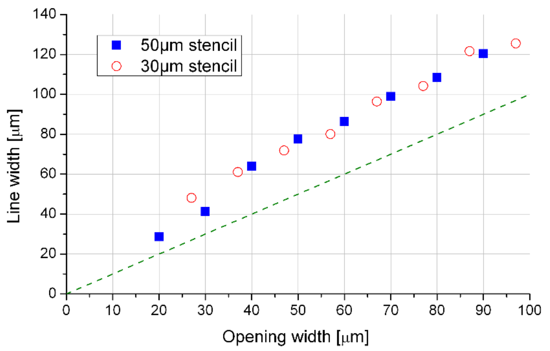

Figure 2: Printed line width as function of stencil opening width for 50µm and 30µm thick stencil,. Dashed line gives line width without spreading

Line spreading results from competition between capillary forces whose amplitude is given by the surface tensions of the paste and the substrate and viscous dissipation given by the viscosity of the paste [3]. In order to reduce spreading, the optimization of both surface tension and viscosity should be considered.

We observed that surface tension of the substrate plays an important role in line spreading. For instance, a 15µm difference in line width, meaning a reduction of 50% in spreading, was observed between fingers printed on bare silicon compared to on SiNx under identical experimental conditions, as depicted in Figure 3.

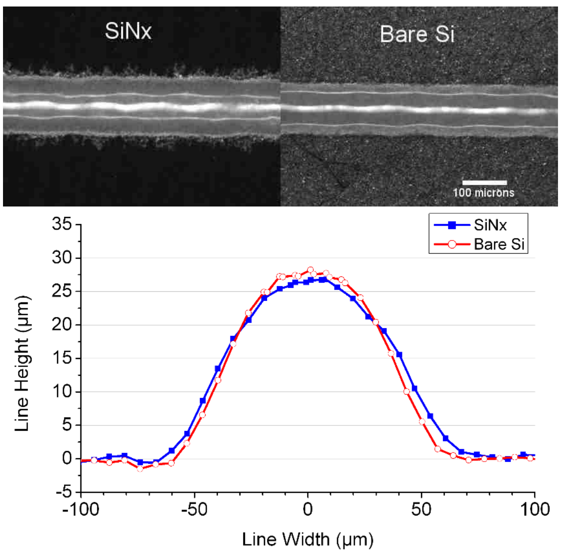

Figure 3: Top views and cross sections of a finger deposited on SiNx, and on bare Si

The optimization of surface tensions has not been addressed in this work, but optimization of paste viscosity is reported in the next section.

As a result of this set of experiments, An optimized stencil opening design was selected. Using a 30 µm thick stencil and 30 µm wide openings, lines of 42 µm wide and 15 µm high have been achieved after firing (Figure 4). The resulting line resistance is 500mΩ/cm. This can potentially lead to a 0.3% gain in efficiency as compared to a standard industrial screen printed finger of 115 µm wide and 135mΩ/cm through improved current and fill factor.

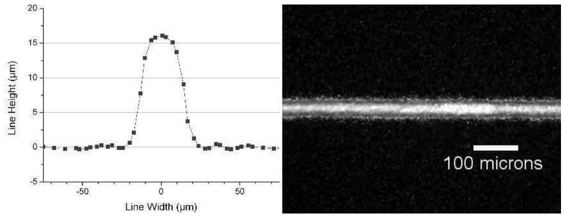

Figure 4 Best print from optimized stencil opening design

3.2. Paste viscosity

Single layer stencil enables the use of more viscous pastes that cannot be screen-printed. Obviously, a more viscous paste spreads less than a low viscosity paste and therefore finer lines with higher aspect ratio can be achieved.

To describe this behavior, the dynamic viscosity at a specific shear rate is commonly used. Our reference stencil paste has a higher viscosity than a typical screen printing paste (190 Pa*s *versus* 100 Pa*s).

Our reference stencil paste has been modified to reach higher viscosities, and the effect on line spreading has been quantified. Two modified paste with 204 Pa*s and 217 Pa*s respectively have been tested *versus* the reference stencil paste (190 Pa*s). Resulting line widths as a function of stencil opening width is depicted in Figure 5.

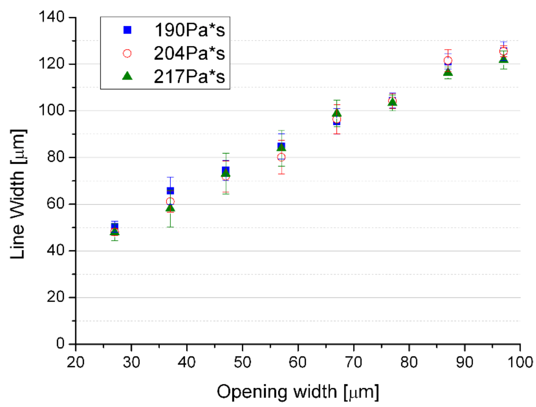

Figure 5: Printed line width as a function of stencil opening width for 3 different viscosities

The performances of the 3 pastes are not significantly different; they all give similar line definition. It means that the reference paste is already optimal in terms of viscosity and that other parameter should be considered to limit spreading.

As described in [4], dynamic viscosity at a certain shear rate is applied for quality control and assurance by the paste manufacturer, but is of limited practical use in case of fine line, thick film printing. Silver paste exhibits a shear thinning, or pseudo-plastic, behavior, meaning a reduction in viscosity or an increase in shear stress at increasing shear rate. Simple shear experiments are not sufficient to completely characterize the paste. Since silver paste, being a particle suspension, also shows visco-elastic behavior, dynamic measurements such as oscillation measurements can be performed to describe the viscous and elastic behavior.

The approach to describe the paste proposed in this work [4] is a time dependent recovery test, where the paste is subjected to three intervals (Figure 6): A-pre-print, B-print and C-post-print. During the time test the storage modulus G' and loss modulus G" are measured, representing the elastic and viscous behavior of the paste.

A convenient way to interpret experimental printing data is to use the loss angle $\delta=\arctan(G''/G')$. During the print interval, a high shear rate is applied, the paste thins and the elastic component drops dramatically under the viscous component ($\delta>>45°$). In the post-print interval, the elastic component quickly exceeds the viscous component; paste is recovered when $\delta<45°$. The quicker the loss angle reaches 45°, the faster the paste recovers and the least spreading is expected.

Out of the various pastes tested, one paste with an improved rheology showed faster recovery than the stencil reference paste (Figure 6) which resulted in less spreading (Figure 7 and Figure 8) The line width was reduced by 10µm.

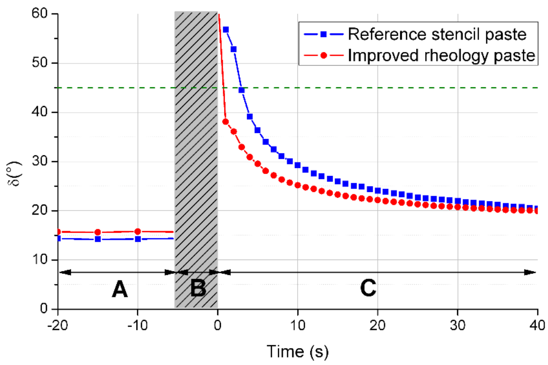

Figure 6: Rheological time test showing loss angle as function of time in the three intervals.

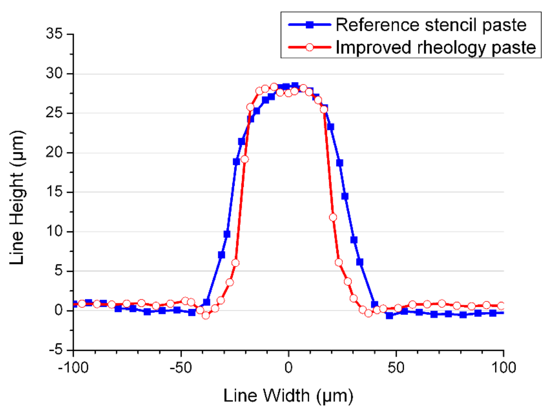

Figure 7: Cross section comparison of reference stencil paste and improved rheology paste printed through a 60µm opening in a 50µm thick stencil

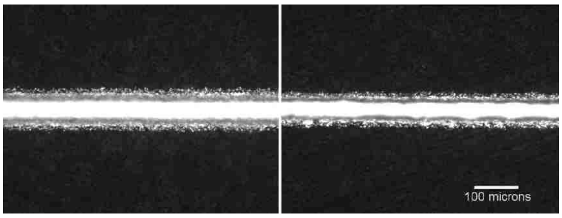

Figure 8: Top view comparison of reference stencil paste and improved rheology paste printed through a 60µm opening in a 50µm thick stencil

4. PROCESS VARIATIONS

In our two-step stencil process, the deposition of busbars and fingers is decoupled. Seen at first as a drawback as two instead of one printing steps are necessary to accomplish the full front side metallization it can actually be turned into an advantage.

For instance, Laudisio, *et.al* [5] reported better efficiencies using a non-firing through paste for the busbars. As the emitter region under the busbar does not contribute to current generation, contact of this area to the front metal grid is not necessary. It is even undesirable as the contact formation in thick film metallization involves the removal of the passivation layer and introduction of impurities. By applying a non-firing through paste for the busbar, a reduced recombination and shunting yielding to 1% relative gain in efficiency was reported as compared to firing through busbar [5]. The gain in efficiency results from improved open circuit voltage and fill factor. A concept like this can also be implemented in the two-step stencil printing process and is under our investigation.

In this section, 2 variations are presented: (4.1) the process sequence (printing busbar before or after the fingers) and (4.2) a Metallization Wrap Through application.

4.1. Process sequence

To realize the electrical contact between fingers and busbar, the finger and busbar patterns overlap. The fingers contact the busbar on each side over a length of 500µm. Thus the required alignment accuracy is only ±250 µm.

Two print sequences are possible in a two-step process: first print fingers and then busbars, or first print busbars then fingers. In case the fingers are first stencil printed, it offers a smooth surface and excludes perturbations in the stencil printing. On the other hand, the fingers previously printed can be damaged during the deposition of busbars. The effect of the process sequence, printing of the busbar before or after the fingers was investigated.

No significant effect on cell performance was observed, but a dramatic influence on the paste consumption is observed. When printing the busbar after the fingers, because of the presence of dried and high fingers on the surface (in the range 35-50µm), an intimate contact between screen emulsion and solar cell surface cannot be reached. As a result, the busbar paste can slip between the fingers, increasing busbar coverage (Figure 9). The effect on total metal coverage and cell output is marginal, but a much larger amount of paste is deposited when busbars are printed on top of the fingers. By first printing the busbar, the amount of paste deposited on the busbar can be reduced by 35%. Ultimately, the total consumption of paste per wafer becomes even lower than a reference screen printed H-pattern cell (see Table I). The reference H-pattern refers to a one-step screen printed front side metallization, with 58 fingers 115µm wide and with a line resistance of 135mΩ/cm. Efficiency is 0.2% lower than for the two-step stencil process.

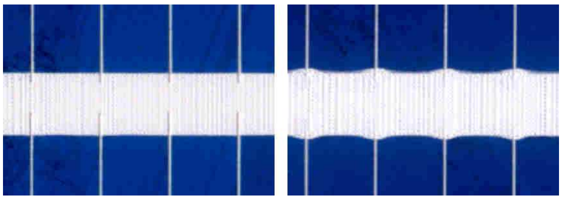

Figure 9: Effect of process sequence on busbar definition, busbar printed 1st (left) and busbar printed 2nd (right)

Table I: Paste consumption for 2-step stencil printing (busbar first or second) and reference screen printing

	Stencil Busbar 1st	Stencil Busbar 2nd	Reference
Total paste consumption [mg/wafer]	236	270	253

This differences is surprising considering the larger number of fingers in the stencil than in the screen (69 *versus* 58 respectively) and the similar line resistance of stencil and screen printed fingers (145 *versus* 135 respectively). It can be explained as follows: Stencil printing enables deposition of finer structure than screen printing with comparable line resistance. Stencil printed fingers are smooth and have an uniform cross sectional area. For comparison, the standard deviation of finger height is 1µm for stencil printed fingers and 5µm for screen printed fingers. As a result the silver paste is optimally used for electrical conduction in stencil printing. In screen printing, fingers suffer from mesh imprint and non uniform cross sectional area. In the finger tops, the cross sectional area is large but the conduction is limited by the low cross sectional area in the fingers valley. As a consequence, paste is not optimally used in case of screen printing. Therefore, for similar electrical performances, more paste is needed with screen printing. Moreover, in the stencil printing two-step process, as the deposition of busbar is decoupled from the fingers, the amount of paste on the busbar can be optimized specifically for the needs by the busbar screen specifications, i.e. emulsion thickness and mesh type. In the reference screen printing process, the amount of paste in the busbar is fixed by the H-pattern screen which ultimately results in larger amount of paste needed per cell.

To sum up, printing the busbar prior to finger deposition allows a lower amount of paste to be deposited and better definition of the busbar than printing the busbar after the fingers without affecting the performance. Ultimately, the paste consumption becomes competitive with screen printed cells.

4.2. Metallization Wrap Through (MWT) cells

Over the last several years ECN has developed a metal-wrap-through (MWT) cell and module concept. This technology has several advantages over standard H-pattern cells [6]: current gain due to reduced cell front metallization coverage, higher fill factor for larger cells due to the unit cell design, higher packing density in the module, less resistance losses in the module and less cell breakage during module manufacture as the cell is fully back contacted.

The standard MWT front side pattern usually consists of a network of lines converged in each of the 16 via-holes of a 156x156mm² cell. These kind of line patterns cannot be produced with a single layer stencil. The latter can only print longitudinal simple shapes providing the stencil keeps its coherence

In order to benefit from the fine line and high aspect ratio offered by stencil printing, a two-step MWT stencil printing process has been developed. Each unit cell now consists of a small H-pattern with a small busbar connected to the rear of the cell. Preliminary experiments have shown that is possible to reach a reduction of more than 30% in metallization coverage over screen printed MWT cells. This resulted in a 2% gain in short circuit current Optimization of the stencil and screen print pattern for MWT solar cells are under investigation. .

5. LARGE SCALE TEST RESULTS

In order to demonstrate the industrial application of two-step stencil printing, a test was conducted in a production environment to test the stability and the durability of the process.

The standard stencil two-step process as presented in [1] has been selected for this test as it had already demonstrated its robustness in the laboratory. A 50 µm thick stencil with 60 µm wide openings was used.

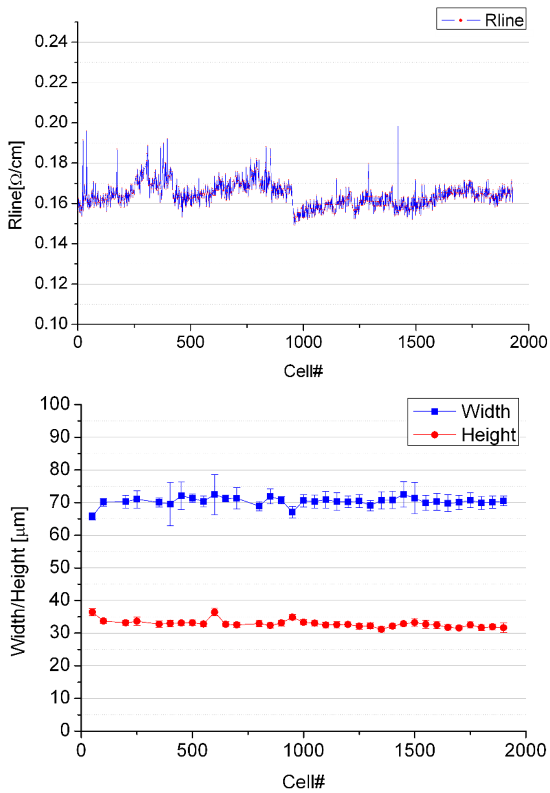

Figure 10: Line resistance, line width and height as a function of cell number

Approximately 2000 cells have been printed using one stencil and one screen to print the busbars. Because of time constrains, testing was done in two subsequent runs. The stencil was cleaned after the first half of the test and reused in the next. Line resistance and line width/height have been monitored for all cells and every 50 cells respectively. Width and height values are averaged from nine measurement points per cell. Results are given in Figure 10 and Table II .

Table II: Average line width and height, line resistance and standard deviations

Width [μm]	Height [μm]	R_{line} [mΩ/cm]
70 ±1	32±1	164 ±11

The geometry of the lines is within specifications along the test with a low standard deviation.

Line resistance is stable and below 200mΩ/cm, but appears to increase slightly in time during both tests. Variations in line resistance were related to paste supply and the appearance of interruptions with time. No paste dispensing was used during this testing and it was found that the manual supply of paste influenced the line resistance. Rline was reduced as soon as paste was added. An automatic continuous dispensing system should alleviate this issue. An effective cleaning procedure was established during the second half of the test to remove line interruptions. As soon as a break in a line was detected, the stencil was cleaned locally while on the printer.

Finally, the stencil did not show any sign of wear or tear and kept its integrity along the tests. This first trial is promising regarding the robustness of stencil. A more extensive test will be necessary to quantify lifetime of the stencil. This test demonstrated the potential stability and reliability of stencil printing and highlighted some of the important aspect of the process.

6 CONCLUSIONS

In this paper, the two-step stencil printing process has been optimized and tested in a production environment:

- Various stencil design have been tested and an optimal stencil opening design has been selected for further experiments
- The importance of line spreading was highlighted for fine line stencil printing. Spreading becomes proportionally larger as the line width is reduced. Surface tensions play a considerable role in line spreading and will require more attention in future development.
- Increase in viscosity did not help to reduce line spreading, rheological parameters of the paste should be considered instead. Using a time dependent recovery test in a rheometer, an optimized paste showed appropriate rheological characteristics for stencil printing and actually printed finer lines than the reference stencil paste.
- The process sequence was investigated. Printing the busbar before the fingers helped to decrease the paste consumption without affecting the electrical performance. Compared to the standard screen printing approach the paste consumption per cell can be reduced by 6%.
- The two-step stencil process was successfully demonstrated on a large number of cells (2000) in a production environment. The print quality remained stable and the stencil did not show any sign of wear.

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REFERENCES

[1] J. Hoornstra & B. Heurtault, “Stencil Print Applications and Progress for Crystalline Silicon Solar Cells”, *Conference Proceedings, 24th EPSEC*, Hamburg, Germany, 2009, 989-992.
[2] www.sunlab.nl.
[3] S. Rafai, *etal*, “Spreading Of Non Newtonian Fluids On Hydrophilic Surfaces”, *J. Fluid Mech*. (2004), vol. 513, pp. 77–85.
[4] J. Hoornstra, *etal*, “The Importance of Paste Rheology in Improving Fine Line Thick Film Screen Printing Front Side Metallization”, *Conference Proceedings, 14th EPSEC, Barcelona, Spain*, 1997, 404-407.
[5]G. Laudisio, *etal*, “Improved C-Si Cell Performance Through Metallizations Adapted To Reduce Recombination Effects”, *Conference Proceedings, 24th EPSEC*, Hamburg, Germany, 2009, 1446-1448.
[6] A.A. Mewe, *etal*, “Reaching 16.4% Module Efficiency With Back-Contacted Mc-Si Solar Cells *Conference Proceedings, 24th EPSEC*, Hamburg, Germany, 2009, 946-949.