STENCIL PRINT APPLICATIONS AND PROGRESS FOR CRYSTALLINE SILICON SOLAR CELLS

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ABSTRACT:
This paper describes laboratory testing to research the capabilities of stencil printing, as compared to screen printing, with a focus on fine line high aspect ratio printing on crystalline silicon wafer material. Scanning of potential of screen and stencil printing moving to finer fingers shows advantages for stencil printing. Testing of electroformed, laser cut, single and double layer stencils, and using various pastes, demonstrates the need for improved paste rheology. Optimal line definition with an aspect ratio of 0.37 was obtained with single layer stencils with fully open fingers. In a two step process, with a stencil for only fingers, followed by screen print of the busbars, +0.4% efficiency gain was reached for industrial type mc-Si cells.
Keywords**:** c-Si, metallization, screen and stencil printing

1 INTRODUCTION

Current practice of industrial metallization uses screen printing as the deposition method of thick film conductor pastes. Screen print is done using a framed mesh screen with patterned emulsion layer as a mask for the deposition of the required patterned metal contacts. With stencils we refer to framed and tensioned metal foils prepared as a mask. There is however some confusion, since others also refer to stencils as the actual masks being prepared from a framed mesh with emulsion. Stencil print was introduced for PV in 1998 [1, 2], although earlier studies on stencil print for solar go back to the 1970s [3].

As for the introduction of stencil print for PV, practice showed that cell manufacturing industry was not ready for stencil technology for solar cell metallization. The largest drawback was that the electroformed stencils that were found to be most suitable for PV application were relatively expensive. Further, available pastes were not suited at all for the potential of the stencils, allowing printing finer and higher fingers. Because of paste rheology properties the deposited fine and high finger would dramatically slump, lose its benefits and so gain in cell efficiency through finer fingers and better cross-section could not be materialized [1, 4]. Since also at that time stencil life time would suffer from cell breakage and associated scrap in the printing machines, stencils did not make it into production.

Over time more work has been done on solar stencil printing. At IMEC stencil printing was performed [5] and, in UNSW PhD theses [6, 7] and related work [8-11] research was focused on application of laser cut stencils. Amongst others, a double layer stencil approach for laser cut stencils was developed, and demonstrated fired fingers of 75 µm with aspect ratio (= height over width) of 0.33, as compared to screen printed of 0.08. On a 4-cm^2 cell this resulted in a 1.6% absolute gain in efficiency. Also stencil print was made applicable on selective emitter, the laser buried grid and N-type cells.

Lately, further interest is noticed for the application of stencil printing. At PV exhibitions, now SMT material manufacturers show up with their stencils, and even stencil printers. Also, other types of stencils have been shown, and at various labs and industrial locations stencil trials are being done.

Current cell manufacturing conditions have largely improved since the first introduction of stencil printing. Now better quality printing equipment is being used.

Improved wafer handling and control, so less scrap, are common. Better quality pastes are available, and finally, today's cells are flat through the acidic textures, as compared to the alkaline etched mc-Si surface with height variation on the surface.

In this work we have investigated current status and possibilities of stencil print for crystalline silicon solar cell application. Various types of stencils have been used in double and single layer fashion for the deposition of full H-patterns and solely the fingers. We look at stencil printing as compared to screen printing, and results on wafers and cells from laboratory testing are given.

2 STENCIL APPLICATION IN COMPARISON TO SCREEN PRINT

Stencils are widely used for the last 20 years in the Surface Mount Technology/ Printed Circuit Board industry for printing solder paste onto boards. Their application has been well supported by technology improvements over years, enabling printing finer patterns and pitch for the continuously miniaturization of boards and the electronic components. Since an SMT-board is very much different from a thin, fragile silicon solar cell, and solder paste is far different from silver paste, we can learn from the SMT stencil print application, but not copy their practice. Moreover, solar cells are printed with considerable higher print speeds. Finally, the pattern for solder paste printing exists of many small pads, while solar cells are printed with long continuous patterns. Just producing openings in a foil to create a mask for a letter "O" or an H-pattern is however not possible. This is the main reason that for a full front H-side pattern a double or dual layer electroformed stencil was developed [1]. The layer on the substrate side has fully open fingers and busbar while the paste side layer has a grid pattern forming bridges in the finger and busbar to keep the stencil together; and thereby mimicking the emulsion and mesh of standard screens (see Figure 1 right). Yet it is possible to print fingers only with a single layer stencil, just as where the SMT world can use single layer, laser cut stencils for printing solder pads.

To date available are laser cut stainless steel stencils, electroformed nickel stencils, and etched stencils. In the SMT industry roughly 84% is laser cut, 13% for etched types, and some 3% electroformed; and where 98% of all produced stencils is applied for solder paste printing [12]. A special type is the "E-type" stencil where onto a stainless steel mesh a masked nickel sheet is fabricated, see [13]. This stencil type looks most like a standard screen, but now with a non wearing emulsion layer. Where, on the metal stencils the paste has to roll in front of the squeegee over a smooth metal surface, with the E-stencil, the paste rolls over the mesh.

Laser cut stencils dictate the market and are the cheapest. Electroformed and etched stencils allow for better specifications, are more expensive, and therefore mostly used for dedicated and precise print jobs.

In pursuing printing of finer lines with higher aspect ratio, the effective open area in the screen mesh becomes smaller and the quality of the opening in emulsion layer poorer. The open area (see for definition and technical details [14]) and interior finish are important for paste transfer into the screen mask area and for the release of the paste onto substrate. Finer gauze mesh, better emulsion material, and improved screen manufacturing will help, but ultimately these parameters will limit screen printing. In stencil printing the open area can be larger and the interior quality better. For typical front side screen with 280 mesh gauze, the open area is 53%, and for a double layer stencil with bridges to keep the pattern together, the open area can be up to 77% (Figure 1).

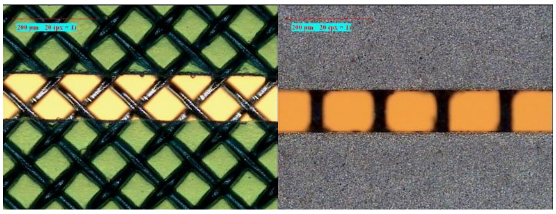

Figure 1: Screen opening (left) and dual layer stencil opening (right)

Moving to finer line width, the mesh angle relative to the finger becomes more prominent in the effective open area. Besides, it is likely that emulsion remainders block triangle areas between mesh and emulsion wall, leading to non smooth print definition. A stencil allows for the largest opening and would not suffer from these artifacts, since the opening can be carefully designed for maximum open area and strength.

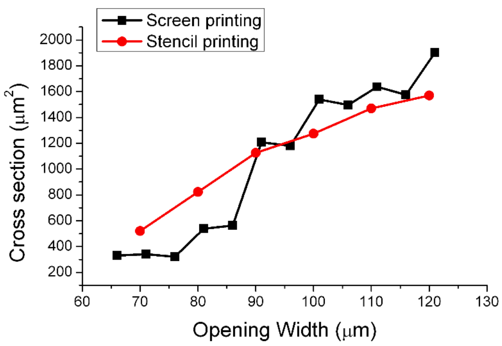

Figure 2 : Cross section as function of opening width for stencil and dual layer stencil

In order to demonstrate the benefit of stencils for fine line, printing tests are done using an electroformed double layer stencil with total thickness of 62µm and fingers of variable width. Results are compared to screen print with similar specifications. Results show that fired line widths are comparable. For the screen, the height becomes smaller for the finer lines, indicating better paste transfer and release for the stencil print. Figure 2 depicts the measured fired cross section as function of line width, and shows the benefit for stencil printing below 90 µm finger opening.

Testing with the E-type stencil demonstrated relatively easy and low pressure printing, and showed low sensitivity to printer settings and print conditions. Among others, printing tests were done with full pattern stencil with finger width of 105µm and a paste with an adapted rheology to reduce slumping, and compared to a screen with standard paste. Because of the easy printing the "emulsion" height was increased to 35µm; 10 µm higher as compared to the screen. Fired finger results are compared in Table I. Due to paste rheology, the relatively high fingers have the camelback shape. Some slumping is observed to 129 µm width, through shearing of paste by being forced through the mesh. E-stencil shows an improved paste transfer reducing line resistance by a factor of 2. Using simulation, this shows a potential gain in efficiency of 0.15%.

Table I: Averaged fired finger print results

	Width [µm]	Height [µm]	R_{line} [mΩ /cm]	η gain [%]
Screen	135	16 ± 2	180	-
E-Stencil	129	39 ± 10	90	0.15

Finally, important for the release of fine line high aspect ratio fingers is the relation between wetted contact area on substrate and mask interior. This relation together with the "tack" of paste and relative surface tension will dictate optimal paste release from the mask. Wetting tests show that the relative surface tension between mask and paste is in favor for the stencil. Currently, some stencil manufacturers apply selective surface coatings to improve paste release.

In order to profit from being able to realize optimal paste transfer and release, so to print fine fingers with relatively large cross section, single layer stencils with fully open fingers are used in the cell testing, as further described.

3 SINGLE LAYER STENCIL EXPERIMENTS: PRINT TESTING AND CELL PROCESSING

In our testing we used 156 mm x 156 mm multi-crystalline silicon wafers, with thickness of 210 µm. Wafers were pre-processed until SiN, including cleaning, texturization in an acidic solution, and diffusion (R_{sheet}=60-65Ω/□).

For characterizing print definition and cell results we used, next to IV measurements and SunsVoc, a busbar-to-busbar resistance measurement to determine finger resistance and the print quality. We used SEM and a video-scope [15] to characterize stencils and screens, and also a Mitutoyo QV Apex 404 PRO microscope to measure in detail printed and fired fingers. ECN Pattern Optimizer software [16] was applied to calculate optimal number of fingers, and predict results.

Various stencils (electroformed nickel and laser cut stainless steel) with test pattern of only fingers of different width and with various thicknesses were used to determine optimal stencil specifications.

4 RESULTS AND DISCUSSION

4.1 Paste comparison

In order to assess paste performance for stencil printing, various “improved” pastes from different manufacturers and a standard screen print paste have been tested using a 50µm thick stencil with a finger width of 70µm. The fired finger cross-sections are depicted in Figure 3, and corresponding top views in Figure 4.

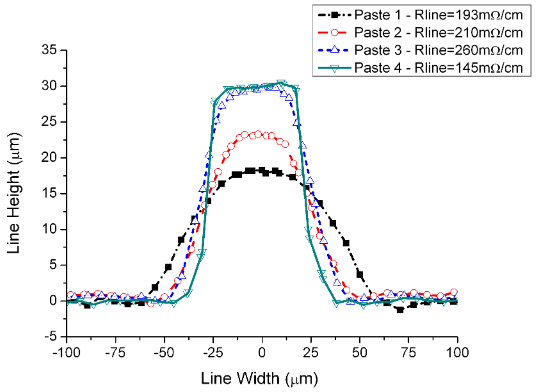

Figure 3: Cross section comparison

Results show that standard screen print paste does not materialize the benefit of the stencil. The paste cannot withstand the aspect ratio imposed by stencil printing and slumps massively. The best paste has a width and height of 84x30µm, as compared to the reference paste with 130x18µm, pushing up the aspect ratio to 0.35 versus not even 0.15.

The best performing paste also demonstrates better line resistance, as can be seen in the legend in Figure 3.

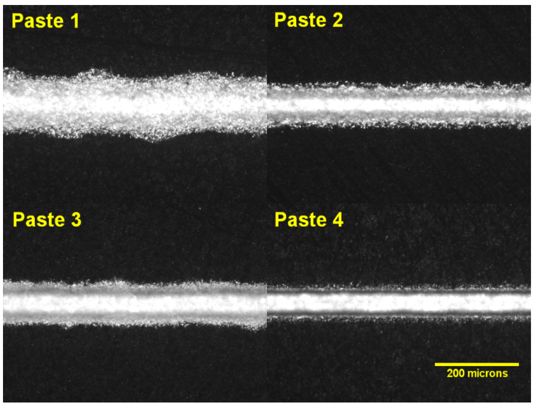

Figure 4: Top view comparison

4.3 Single layer test stencil

In Figure 5 results are shown from printing with improved paste and using a 50µm thick laser cut stencil with and without a nano-coating. Results show that printability with the uncoated stencil is good as long as the opening has an aspect ratio smaller than 1:1. Openings with higher aspect ratio cannot properly release paste. For finer fingers, the coating assists in keeping up with paste transfer and release down to 40µm opening, where the uncoated stencil does not release paste well below 50µm. The aspect ratio of print definitions stays the same, yet paste transfer is improved through a given opening in case of a coating. Because more paste is deposited, slumping gives rise to lightly broader fingers. Ultimately, through the balance between shadowing and conduction the resulting performance on cell level is comparable between coated and uncoated stencil for openings below 1:1 aspect ratio.

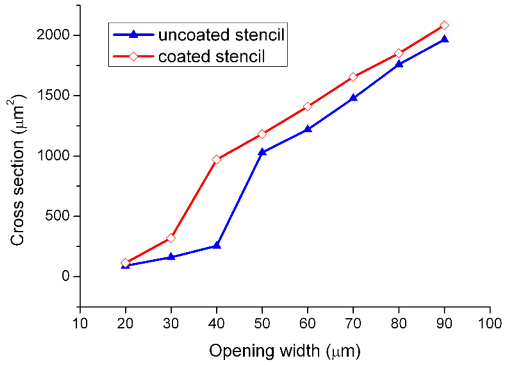

Figure 5: Cross section as function of opening width for coated and uncoated stencils

4.4 Cell testing using single layer stencils

Based on print test results and cell efficiency simulation, a stencil was designed to demonstrate the potential of stencil printing on cell level. We choose the 50µm thick stencil, because of robustness, and select 60µm wide openings, being on the safe side. Using the Pattern Optimizer and print results as input, a pattern was designed consisting of 69 fingers.

To assess the benefit from this stencil design, cells were produced using - fingers only - stencil and improved rheology paste. The results are compared to standard screen printing with 58 fingers of 105 µm width using standard paste. For the stencil printed cells, busbars were separately printed after drying the fingers. Further cell processing was the same. Test was performed using groups of 18 neighboring cells. Figure 6 shows the fired finger cross sections. Average print results and line resistances are given in Table II.

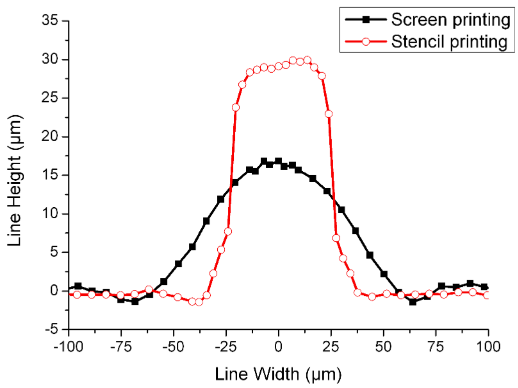

Figure 6: Finger profile comparison between stencil (60µm) and screen (105µm opening)

Table II: Average print results

	Width [µm]	Height [µm]	R_{line} [mΩ/cm]	Total metal coverage [%]
Reference	134	17	180	7.0
Stencil	75	28	150	5.7

With the 60 µm finger opening we were now able to print fired fingers with an average aspect ratio reaching 0.37 as compared to 0.13 for the screen printed fingers.

Print results (metal coverage and line resistances) have been used as input in Pattern Optimizer to predict the resulting effect on cell level. Simulation together with experimental cell results are shown in Table III.

Table III: Average cell results

	Voc [V]	Jsc [mA/cm2]	FF [%]	η [%]
Experimental				
Reference	0.611	34.2	77.8	16.2
Stencil	0.614	34.9	77.6	16.6
Simulation				
Reference	0.611	34.2	77.8	16.2
Stencil	0.612	34.7	78.5	16.6

Stencil printing gives an absolute gain of +0.4% in efficiency over reference. Gain is mainly obtained through higher current and slightly improved Voc because of reduced metal coverage. However, simulation predicts less gain in Jsc than from experimental results.

Lower metal coverage in case of stencil printing cannot fully explain the benefit observed in current. Basically, the current would be consistent with a line width of 65µm for stencil printed cells while 75µm is measured. For this, the following explanations can be considered:

- Effective optical finger width might be smaller than the line width as measured with the microscope. Thin residues of paste next to finger edges resulting from shrinking can overestimate the finger width measurement.
- Effective optical finger width can differ from geometrical line width as demonstrated in [17]. Due to direct reflection from edges of the fingers into the cell, effective width is reduced compared to the geometrical width. This seems likely as stencil printed fingers are high and smooth.

On the other hand, no gain in fill factor has been observed whereas simulation predicts a gain of 0.7% through more conductive and numerous fingers. Series resistances less fill factor showed an average difference of 0.7% in favor of screen printing, suggesting stencil printed cells were not optimally fired.

6 CONCLUSIONS

From our work we can conclude the following:

- Solar cell stencil printing is not the same as SMT stencil printing: we can learn, but not just copy.
- For improved fine line high aspect ratio printing, needed for high efficiency cells, beneficial specifications of stencils are demonstrated as compared to screens.
- For optimal stencils print results, low-slumping pastes are identified.
- With test stencils and improved paste optimal finger width and stencil height were assessed to reach best print results.
- Easy printing (lower pressure), with better paste transfer and release was identified with E-stencil.
- Fine line and high aspect ratio fingers were obtained with single layer stencils on **industrial type cells**. Results on cells show improvement in current and better efficiency.
- An improvement of efficiency of +0.4% absolute was found versus screen printing, through finer fingers with higher aspect ratio.
- This work was performed on a laboratory scale; further work needs to be done to demonstrate stencil printing on industrial scale.

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