IMPROVED FRONT SIDE METALLIZATION ON SILICON SOLAR CELLS WITH STENCIL PRINTING

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ABSTRACT: This paper summarizes recent testing with single and double layer stencil printing in comparison with screen-printing. The comparative electrical test results for cells produced by screen and stencil printing during experiments utilizing various numbers of cells are reported. Pastes are evaluated for their printing definition. With stencil printing a more consistent cell output and a higher output over a full production run of several thousand wafers are obtained. Further it is demonstrated that, when selected pastes are used stencils allow for printing high aspect ratio fingers.
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1. INTRODUCTION

Stencils were first described a few years ago for printing the front side metallization of silicon solar cells [1]. Advantages of stencil printing lie in the improved release properties, the non-wear character and the ability to print finer lines with a high aspect ratio. So-called double layer stencils allow for printing the full H-pattern or other pattern types with fingers and busbars in one print stroke [2]. The use of single layer stencils with only the fingers needs an extra drying step and subsequent printing of the busbars with a traditional screen [3]. A different approach for single layer stencil printing of the full pattern of fingers and busbars in one stroke is introduced at this conference [4].

This paper summarizes recent testing with single and double layer stencil printing in comparison with screen-printing. A further comparison of the stencil and screen printing performance of different pastes is described. In this study electroformed hard nickel stencils manufactured by Stork Veco have been used [5]. ECN and Stork Veco have been developing the stencil approach and specifically the double layer stencil for solar cell applications.

2. PRINTING WITH STENCILS AND SCREENS

Under production conditions screens allow for printing fingers with fired dimensions of about 110 to 130 μm width and relatively moderate heights from 5 to 10 μm. The consequent number of prints per screen ranges from 10,000 to 30,000, although in the latter case print definition will be diminished, and fingers will be wider. The wider the fingers to be printed, the less difficult it is to achieve higher prints. The finer the finger dimensions one attempts to print, the more sensitive the printing process becomes with the result of a diminishing finger quality over time. In practice, wiping and cleaning of the screen is frequently required to keep the quality acceptable.

The major constraint limiting performance is the quality and durability of the screen. The quality of the screen is pushed to the limit because of the lack of pastes optimized for the demands of printing finer lines with a proper aspect ratio [reologie 5]. Finer lines are necessary to fulfill the cell efficiency demands in decreasing the shadow loss factor. Higher fingers are then needed to accomplish an equivalent low line resistance. For fine and high line screens the open area available for transferring the paste to the silicon substrate and the available theoretical print volume are limited. Other limitations concern the quality of the open area in the polymer emulsion layer, and the durability of the layer.

For electroformed nickel stencils these disadvantages are not present. The open area and theoretical print volume for a comparable single and double layer stencil are larger than for a screen, allowing the printing of fingers with improved aspect ratios. For the screen types generally used for front side metallisation the open area is in the range of 40%. In practice this value will even be smaller as a result of blocked mesh openings by polymer residues that are not properly washed out. For a double layer stencil the open area can be up to 85% and it is even 100% for a single layer stencil with only fingers. For a comparison of screen and double layer stencil see figures 1 and 2.

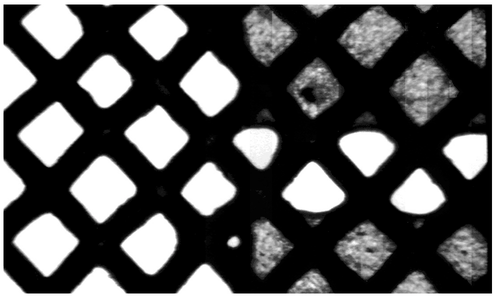

Figure 1. Back light photograph of emulsion type screen with part of the busbar (to the left) and finger (pointing to the right), showing the available open area for printing. Finger width in screen is 90 μm.

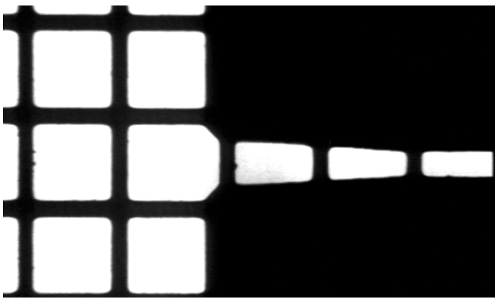

Figure 2. Photograph as in figure 1 of double layer stencil with part of the busbar (to the left) and finger (pointing to the right), showing the available open area for printing. Finger width in stencil 70 μm.

The theoretical print volume dictates the amount of paste to be transferred to the substrate. For a screen it is the volume enclosed by the mesh and bounded by the emulsion layer. For a screen the angle of the opening in the emulsion layer is smaller than 90°, because of the constraints in the photographic process. This means that the width of opening in the emulsion near to the mesh is smaller than at the underside of the emulsion layer. For a screen this means a reduction in theoretical print volume. The influence becomes more prominent if one wants to produce a screen for fine and high lines. An electroformed stencil does not suffer from this artifact and consequently allows printing a larger print volume with the same basic specifications.

During printing under cell production conditions the emulsion layer is subjected to wear and tear. Specifically, the corner of the finger opening becomes rounded after some time. This introduces paste bleeding and consequently the fingers become wider and less well defined. This wear aspect leads to increased shadow losses causing the efficiency of the cells to decrease. The electroformed stencils used for this project are produced from hard nickel and have excellent spatial specifications. Wear is minimal, thereby keeping the print quality constant over time.

If the theoretical print volume and also the open area can be improved, it is clear that the influence of the paste rheology becomes more noticeable. If, with a high aspect ratio, more paste can be transferred to the substrate, then any tendency to spread out more becomes evident. This means that for printing fine lines with a high aspect ratio the rheology of the paste must be adequately adapted. In a previous paper [6] several pastes were compared for their printing behavior. Only one or two were found to comply with the requirements to print easily and allow for a high aspect ratio. In this study again different pastes are being used for comparison of the print performance. The previously used term slumping, however, seems not to cover the behavior of the deposited paste properly. Since gravitational forces can be neglected in the fine line deposit, and surface tension effects together with the polymer chain molecular binding dictate the form, the term spreading is more appropriate for the observed line broadening.

For the demands of printing the front side metallization on silicon solar cells it is obvious that multiple performance requirements relating to the screen or stencil, the conductor paste, the printing apparatus and the operational possibilities must all be satisfied.

3. MEASUREMENTS AND RESULTS

Several experimental stencils and standard screens have been tested under laboratory as well as different production conditions and evaluated for capabilities and performances. The aim was to accumulate more experience with the stencil printing and to evaluate the performance of the double and single layer stencil in comparison with the screen. In the laboratory also a single and a double stencil, together with a screen were tested for their paste release capabilities. A series of commercial and development pastes have been tested for the ability to easily print fine and high lines.

In this paper the following tests are summarized.

3.1 - a comparison of screen and single layer stencil printing of 2000 cells
3.2 - a comparison of screen and double layer stencil printing of 3000 cells
3.3 - a comparison of single layer stencil with screen printing on laboratory scale
3.4 - influence of screen and stencil specifications on printed line definition
3.5 - a comparative study of the paste rheology influence for screen and stencil printed line definition

Note: in each test different stencil and or screen specifications are used.

3.1. Screen and single layer stencil printing of 2000 cells

Cells were produced using screen printing and single layer stencil printing. The single layer stencil printing was used to produce the fingers. After drying the busbars were screen printed. In this study a modified screen print paste was used to improve printing and results.

The goal of the experiment was to compare screen and stencil printing by aiming at printing fingers with a maximum width of 100 microns and a minimum height of 10 microns after firing. The experiment was not meant to determine optimum stencil parameters.

- A stable average finger width after firing of 90 microns with height of 16 microns was measured with the optical microscope for the 2000 stencil printed cells.
- For 500 cells, an increase in efficiency of about 1% relative is measured versus the 100 reference screen printed cells. The increase can be fully attributed to an improved short circuit current.
- For the stencil pinting as compared to the screen printing a more constant FF was reached through an improved line definition in time and leading to a reduction in the standard deviation of the efficiency by 12%.

3.2 Screen and double layer stencil printing of 3000 cells

Cells were produced by double layer stencil printing and compared with screen printed cells. A standard screen print paste and a paste with improved rheology were used in this study for screen and double layer stencil printing of 100 cells and double layer stencil printing of 3000 cells. A goal was to evaluate the performance of stencil printing on production scale. For this testing the line definition in the stencil was conservatively chosen.

- For the 100 cell comparison, the use of the double layer stencil together with the improved paste resulted in an efficiency increase of 0.4%. The fired finger width decreased with 11% and the height improved 33%. The standard deviation of the efficiency was reduced by more than 64%.
- In a comparison of the improved paste with the standard paste using screens an efficiency gain was reached of 1%, attributed to a 1.5% increase in short circuit current.
- The application of the double layer stencil together with the improved paste proved to be reliable for the printing of 3000 cells produced at full production speed. The cell results were more than sufficient, but since a different batch of wafers was used the cell results could not be compared.

3.3 Comparison of single layer stencil with screen printing

One hundred cells were produced from neighbor wafers using single layer stencil printing and compared with the same number of screen printed cells. Both screen and stencil had standard specifications, but assuming a better finger definition would result with the stencil, it was designed with fewer fingers. The goal was to assess the performance of single layer stencil printing. In this test a modified, but non-optimal, screen print paste and a different standard screen print paste have been used for the stencil printing. For the screen printing a standard screen print paste was used.

- The single layer stencil allowed for printing finer and higher fired fingers; on average 20 µm finer and 3 µm higher. This is attributed to the combination of stencil and paste.
- The fill factor increase was about 1.5% and the efficiency increase almost 3%. The short circuit current increased by almost 2% also attributed to the reduced number of fingers in the stencil pattern. Similar improvements were obtained for the modules made of these cells.
- The application of standard screen print paste for the stencil resulted in worse finger dimensions due to spreading of the paste. Compared to results with the screen the finger width was the same, but the height decreased by 33%.

3.4 Influence of screen and stencil specifications on printed line definition

A series of commercially available and development pastes have been used for screen and stencil printing under normal, non-optimized, conditions. The goal was to evaluate the relative printing characteristics by observing the printed line definition. The comparison was supported by rheological measurements.

Eleven pastes have been used in the printing test. The functional specifications of the screen, double layer stencil and single layer stencil are given in table 1. TPH is the theoretical (wet) print height; LW is the measured line width at the ink/substrate interface, and OA the open area of screen and stencils. The values are calculated from results of microscope measurements.

Type	TPH (µm)	LW (µm)	OA (%)
Screen	47	99	44
DL stencil	57	77	85
SL stencil	44	55	100

Table 1: Print specifications for screen and stencils.

Since the goal is to look at the print performance of the paste using normal, state of the art, dimensions of screen and stencils, the specifications are not the same. Having a larger open area for a stencil the finger width can in practice be smaller than for a screen. Also, having a better paste release for the stencil means the height for the double layer stencil can be larger.

After printing and drying at about 150°C the maximum finger height and finger width were measured with the optical microscope. The results are presented as the relative line width RL, calculated as the ratio of the printed line width/ line width in the screen or stencil, and the aspect ratio AR, calculated as the ratio of the printed height/ line width. In table 2 the RL and AR values of (average of 7) typical screen printable pastes are given together with the typical printed and dried line width (PLW in microns).

These data confirm the status of the pastes as in [6]. The relative line width is a measure for the spreading of the paste after printing. A spreading of 10 to 15% is considered acceptable. This controlled spreading is desirable to level the paste and make the impression of the screen disappear.

Typical paste	RL	PLW (µm)	AR
Screen	1.4	140	0.17
DL stencil	1.7	129	0.15
SL stencil	2.0	112	0.16

Table 2: RL, AR and printed line width (PLW) values for typical screen print pastes

Only two of the tested pastes fall in this category. In case of excess spreading the paste performs worse with stencils since these also allow a larger print volume with a higher initial wet AR. The advantage of the stencil, however, lies in the fact that a finer line width (with proper release conditions) is possible. So, even after some spreading, a finer line with a high aspect ratio is achievable. This is visible in table 3, where the RL and (dried) AR values of (average of 4) high aspect ratio pastes are given. One (development) paste was omitted because of poor printing behavior.

High AR paste	RL	PLW (µm)	AR
Screen	1.1	110	0.26
DL stencil	1.2	93	0.26
SL stencil	1.4	78	0.38

Table 3: RL, AR and printed line width (PLW) values for high aspect ratio pastes

If, for an optimum in electrical and shadow losses a fired finger dimension of 80 micron by 15 micron would be required, the dried thickness then would be approximately 30 micron. Then an optimum dried AR of about 0.38 would be required. For optimal fine and high fingers a high aspect ratio together with a low relative line width is required. The single layer stencil used together with a high aspect ratio paste fulfills these demands.

The favorable paste for stencil printing gives results as presented in table 4.

Favorable paste	RL	PLW (µm)	AR
Screen	1.3	126	0.21
DL stencil	1.2	90	0.27
SL stencil	1.2	63	0.36

Table 4: RL, AR and printed line width (PLW) values the favorable pastes

Since the data are obtained in a comparative test rather than an optimized experiment, better results are achievable per screen, stencil and paste combination. In practice an optimization of the stencil parameters is required for each specific case. This optimization will be dependent on several variables including the particular paste characteristics and the required print parameters.

3.5 Paste rheology influence on printed line definition

The applied oscillation type measurement describes the viscous and elastic behavior of the paste. For the tests a Physica UDS-200 MP51 instrument was used to look at the recovery of the paste after a simulation of the actual print stroke.

In the oscillation mode the complex shear modulus G* is measured, of which the real and imaginary parts, the storage G' and loss G" moduli, represent the elastic and viscous behavior. From the derived loss angle δ, being arc tan G"/G' it was found that now 5 pastes were identified with a fast relaxation behavior after printing (of which 4 were taken along in table 3, high aspect ratio pastes). This is based on G"≤G' and consequently $\delta \leq 45°$. A direct comparison of the previously measured data could not be performed having used a different measurement geometry. Compared to the comparison as presented in [6] now more pastes show an improved aspect ratio. Some of these pastes are developed by ECN.

4. CONCLUSIONS

Cells are produced using single layer and double layer electroformed nickel stencils with various specifications. Up to several thousand cells have been successfully printed using stencils and the goals of improving the print definition and electrical performance have been met. Since the stencil mask differs in characteristics and properties from the screen mask, the stencil specifications for the finger width and finger height are chosen differently from those for the screen. The goal is still to evaluate the performance of stencil printing, while trying to use the benefits of the stencil mask.

It can be concluded that:

- A more consistent and stable cell performance, i.e. constant print quality over several thousands of stencil printed cells is observed.
- Since non optimized stencils (and pastes) are used, the efficiency gain will be at least 1.5% using stencil printing instead of screen printing.
- Improvements of cell characteristics from the stencil approach over screen printing are reached by printing fingers with fired dimensions of 90 μm wide and 16 μm high resulting in significantly less shadowing.
- Even if screen printing is applied to the limit of its performance, stencil printing allows the printing of finer fingers with an improved aspect ratio.
- A very significant influence of the paste rheology on printed line definition for screen and stencils is observed.
- From a comparison of printing behavior, several pastes are identified with improved printing and aspect ratio characteristics.

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REFERENCES

1. H.H.C, de Moor, A.W. Weeber, J. Hoornstra, and W.C. Sinke, “Fine-line Screen Printing For Silicon Solar Cells”, Snowmass Conference Colorado, 6th Workshop on the Role of Impurities and Defects in Silicon Device Processing, Snowmass (CO) (1996), 154-170.
2. J.H. Bultman, M.W. Brieko, A.R. Burgers, J. Hoornstra, A.C. Tip, A.W. Weeber, "Interconnection Through via Holes for Improved Efficiency and Easy Module Manufacturing of Crystalline Silicon Solar Cells", 11th PVSEC Sapporo, 1999. Also to be published in Solar Energy Materials and Solar Cells.
3. H.H.C. de Moor, J. Hoornstra, A.W. Weeber, A.R. Burgers, and W.C. Sinke, “Printing High and Fine Metal Lines Using Stencils”, 14th EPSEC, Barcelona, 1997, 404-407.
4. E. van Kerschaver, P. Choulat, and J. Szlufcik, "Stable and Reliable Metallisation through the Application of Electro-formed Ni Stencil", to be presented at this conference.
5. Stork Veco BV, BU SMT, P.O. Box 10, 6960 AA Eerbeek, The Netherlands.
6. J. Hoornstra, J., A.W. Weeber, H.H.C. de Moor, and W.C. Sinke, “The Importance of Paste Rheology in Improving Fine Line, Thick Film Screen Printing of Front Side Metallisation”, 14th EPSEC, Barcelona, 1997, 823-826.