COMPREHENSIVE COMPARISON OF DIFFERENT FINE LINE PRINTING TECHNOLOGIES ADDRESSING THE SEED AND PLATE APPROACH WITH NI-CU-PLATING

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ABSTRACT: The seed and plate approach with subsequent Ni-Cu-Ag light-induced plating is still of high interest for the front side metallization of silicon solar cells. From a technical point of view (shape of the contact fingers, lateral conductivity), the quality of the plated front contacts is considerably higher compared to screen printed contacts. From an economical point of view, this approach offers the potential to reduce silver consumption significantly. Within this work, a fine line seed layer front side grid has been applied using two innovative fine line printing technologies – rotational flexographic printing and inkjet printing. Both technologies achieved an average seed layer finger width < 40 μm, in case of flexographic printing even < 30 μm. The electrical results of the solar cells with inkjet and flexo printed seed layer after Ni-Cu-Ag plating have been compared to state-of-the-art screen printed solar cells. The total silver consumption of the seed and plate cells of 15 to 17 mg on the front side is considerably smaller than the screen printed reference cells with approx. 100 mg. Both groups achieved an average conversion efficiency of $\eta_\varnothing = 19.1$ % which is comparable to screen printed solar cells on the same material.

KEYWORDS: Silicon Solar Cell, Flexographic Printing, Inkjet Printing, Seed and Plate, Copper Plating

1 INTRODUCTION

Screen printing is the state-of-the-art technology for solar cell front side metallization. However, front side metallization using a seed and plate approach is still of high interest, as the partial substitution of silver by copper offers the potential for a considerable cost reduction [1]. Furthermore, electrical and optical quality of the contacts is usually higher [2,3]. In the first step, a narrow silver seed-layer with as little silver consumption as possible is applied by fine line printing techniques to form the contact to the emitter. In the second step, the seed layer is reinforced with a dense, ~ 1 μm thick nickel layer as diffusion barrier, a highly conductive ~ 8-10 μm thick copper layer and a ~ 0.5 μm thin silver capping layer. This sequence involves only minor modifications to existing production lines. Considerable progress has been made recently to overcome the technical challenges of this approach [4,5]. The aspect ratio and the electrical parameters of this seed and plate front side contacts depend strongly on the properties of the applied seed layers. Several highly interesting fine line printing technologies like inkjet [6,7], flexographic printing [8], aerosol printing [9] or seed layer screen printing [10] are able to form narrow seed layer contacts with a very low silver consumption. Flexographic printing is able to print ultrafine seed layer contact fingers down to 25 μm in with. Furthermore, a considerable cost-saving potential due to a considerably higher throughput and a significantly lower silver consumption has been demonstrated for this approach [11]. Inkjet printing is known to generate very uniform and narrow contact fingers with low silver consumption. Within this work, both printing technologies are used to produce full scale solar cells (area A = 156 x 156 mm²) with plated Ni-Cu-Ag front side metallization. It will be demonstrated that both technologies generate seed layer front side grids with very low silver consumption and very narrow seed layer contact fingers. The electrical performance of solar cells fabricated with both technologies are compared to typical screen printed cells on the same material.

2 FLEXOGRAPHIC PRINTING

Flexographic printing is a usually roll-to-roll based printing method utilizing flexible relief printing plates. A steel cylinder with a finely textured chromium or ceramic surface, known as anilox roller, transfers a specific amount of ink from the ink reservoir onto elevated areas of the printing plate. This characteristic amount of ink is specified as dip volume and is defined by the angle, volume and line screening of the engraved cells on the roller surface. The dip volume is denoted in ml/m². Excessive ink is removed by a doctor blade before the anilox roller wets the printing plate with a uniform layer thickness. Finally, the ink is transferred from the printing plate onto the substrate. Flexography is well suited for high quality printing of small ink amounts on rough surfaces. As the printing process requires only low printing pressure, it is also well applicable for fragile substrates like silicon wafers. Flexographic printing platforms are usually roll-to-roll based. In order to use this technology for the metallization of silicon solar cells, a roll-to-flat machine with a vacuum substrate holder for the silicon wafers is required (Fig. 1).
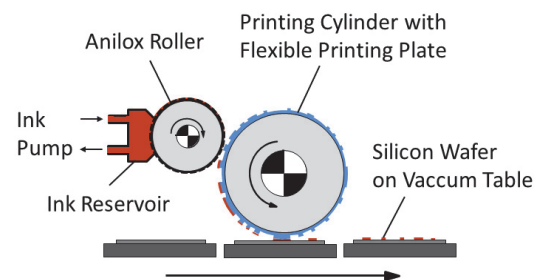

Figure 1: Schematic drawing of the flexographic printing process for the metallization of silicon solar cells: the ink is transferred by an anilox roller from the ink reservoir onto elevated elements of the printing plate and from there onto the silicon wafer

3 EXPERIMENTAL APPROACH

3.1 Material

Industrially preproduced alkaline textured p-type Czochralski-grown silicon (Cz-Si) precursors with an edge length of 156 mm habe been used for the experiment. On the front side, these precursors have a n-type emitter with a mean sheet resistivity of R_{SH} = 90-100 Ω/sq (emitter depth x =200 - 300 nm). The base resistivity is ρ_{base} = 1-3 Ωcm. The front side has further been coated with a 70 nm thick silicon nitride anti-reflection coating (ARC) on the front side. The rear side metallization, consisting of silver solder pads and aluminum back surface field (Al BSF), has been applied using standard screen printing technology using commercially available Ag- and Al-paste.

3.2 Flexo printed seed layer

For the front side metallization, a front side grid layout with 100 contact fingers has been chosen, based on a previous simulation of the optimum grid layout. Using this layout, a flexographic printing plate type *Flint Nyloflex® ACE* with a shore hardness of 62° Shore A has been fabricated by UV-exposure with a resolution of 4000 dpi. The nominal finger width of the contact fingers in the digital layout was w_n = 25 μm. A roll-to-flat flexo-graphic printing machine type *Nissha Angstromer S15* has been used for the front side metallization (fig. 2A). This machine has a square shaped vacuum table to hold a wafer with 156 mm edge length during the printing process. The vertical position of the vacuum table can be adjusted continuously by a micrometer screw. Anilox roller, printing cylinder and vacuum table have been carefully levelled out before the printing test to ensure as identical pressure conditions as possible and thus an homogeneous ink transfer over the entire wafer surface. The fine line printing plate (fig. 2B) has been mounted on the printing cylinder on top of a defined stack of soft and hard mounting foam tape. The wafers were positioned manually on the vacuum table before each printing step.
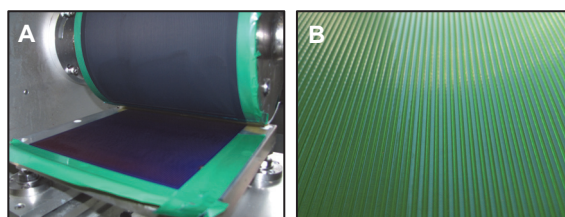

Figure 2: Flexographic printing platform used to carry out the roll-to-wafer printing experiments (A) / Flexo printing plate for seed layer front side metallization (B)

A silver-based seed layer ink, especially adapted for flexographic printing, has been prepared for the experiment. This ink is based on an aerosol jet ink recipe which has been developed at Fraunhofer ISE previously [12]. The ink contains solvents, binders, silver particles, glass frit for contact formation and several additives to enhance printability, adjust the ink viscosity and enhance the contacting behavior. All wafers have been printed in one run at the same printing conditions and dried in a cabinet drier at T = 200-220°C. Subsequently, three segmented busbars (max. width 1.2 mm) have been printed on top of the flexo printed front side grid using a standard screen printing process with a non-contacting silver paste. Usually, it would be possible to print busbars and fingers in one run using one flexo printing plate. However, fingers and busbars have been printed separately within this experiment to ensure comparability to the inkjet group. Finally, a firing variation with three peak set temperatures (T_1 = 880°C, T_2 = 900°C, T_3 = 920°C) has been carried out to evaluate the optimum peak set temperature. T_1 has been identified as the optimum firing peak set temperature for the flexo printed seed layer.

3.2 Inkjet printed seed layer

The inkjet seed layer metallization has been printed using a *X-Jet Minijet* printer with and experimental silver seed layer ink (figs. 3A and B). A front side grid layout with 100 contact fingers has been printed on 50 of the same precursors using this device. Due to a heated substrate holder, the ink is dried immediately after printing. In a separate step, three segmented busbars have been printed on top of the inkjet finger grid using screen printing technology. A firing variation at three peak set temperatures (T_1 = 880°C, T_2 = 900°C, T_3 = 920°C) has been carried out and T_3 has been identified as the optimum peak set temperature. I-V-measurements of the fired and plated solar cells have been carried out on the same industrial solar cell tester which has been used for the flexo printed solar cells. Yet, it should be considered that the measurements have not been carried out at the same date. The results of this experiment have already been published within another work [13].
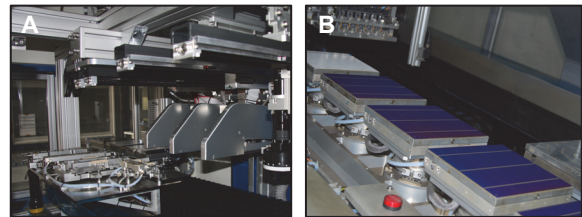

Figure 3: Inkjet printing platform used for the printing experiments

3.3 Ni-Cu light-induced plating

The fired seed layers of both groups (flexography and inkjet) have been reinforced with Ni-Cu-Ag light induced plating (Ni-Cu-Ag-LIP). An amount of approx. 10-15 mg Ni has been deposited on the fired seed layer grid as diffusion barrier. On top, approx. 65-70 mg Cu has been plated as conducting layer and finally 5-10 mg Ag as capping layer. In total, an average mass of m_{LIP} = 83 mg has been plated on top of the seed layers.

3.4 Optical and electrical characterization

The seed layer width of the printed and fired contact fingers has been determined using a Leica microscope at 100x magnification. To ensure a precise and reproducible quantification of the finger widths, an image analysis algorithm developed at Fraunhofer ISE has been used to determine the width. Shading-relevant contact finger width w_p has been determined after Ni-Cu-Ag-LIP using the same method. Selected contact fingers before and after Ni-Cu-LIP have been deeper analyzed using a *Zeiss Auriga 60* SEM. Electrical solar cell parameters of all fabricated solar cells have been measured using an industrial cell tester. Finally, specific contact resistance ρ_c has been determined on selected samples of both groups using transfer length method (TLM) [14].

3.5 Measurement of total silver consumption

To determine the wet ink/paste consumption, solar cells of both experimental groups have been weighed before and after seed layer printing and again before and after the subsequent busbar imprint using presicion scales. The silver consumption of the printed (seed layer) front side metallization has been calculated with the known Ag percentage of the inks/paste. The silver consumption of the Ag-capping during LIP has been added to this value to calculate the total silver consumption.

3.6 Comparison to typical screen printed solar cells

The achieved solar cell results of both groups have been compared to typical results of screen printed solar cells on the same wafer material. Yet, it should be considered that the front side metallization of the screen printed solar cells has been printed in one run with the same paste as the contact fingers. Also, the design of the busbars differed slightly from the busbars of the experimental seed and plate groups. Thus, the experimental results are compared to a typical range of screen printed solar cells on this material.

4 RESULTS AND DISCUSSION

4.1 Flexo printed seed layer

Using flexographic printing, an average seed layer finger width of $w_{s,\varnothing} = 23$ μm with a standard deviation of $\sigma = 2$ μm (50 measurements in total, 5 positions on 10 cells) could be achieved. The SEM analysis confirmed the presence of ultrafine contact fingers with a uniform edge definition (fig. 4A).
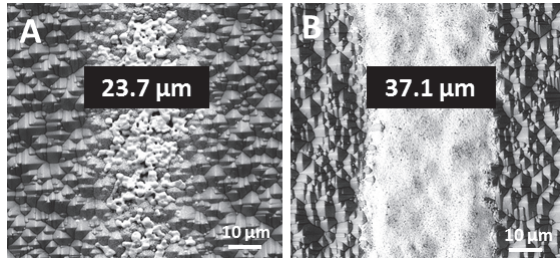

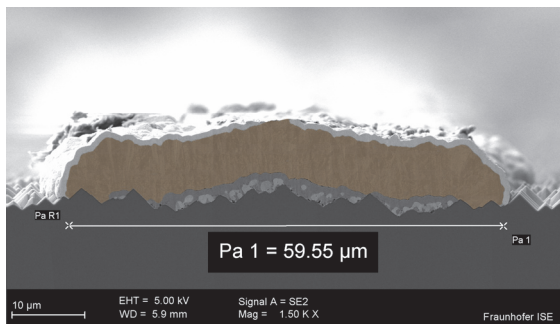**Figure 4:** SEM image of flexo printed (A) and inkjet printed (B) fine line seed layer fingers

Figure 5: Colorized SEM image of flexo printed seed layer finger with Ni-Cu-Ag-LIP

These achieved finger widths were significantly narrower than results of previous studies using flexographic printing [8,11]. The question arises about the reasons for this considerable reduction of the average finger width by nearly 50 %. Several reasons are presumably responsible for these remarkably better results. In contrast to previous experiments, a stack of softer foam mounting tape has been used as substructure. It is likely that the soft substructure supports narrower line widths as the deformation of the finger elements on the plate under pressure is probably lower. Secondly, a new ink formulation has been used which revealed a lower spreading behavior on the alkaline textured wafer surface. Thirdly, the three-dimensional shape of the contact fingers on the (elastomeric) plate has been optimized based on previous compression experiments. And most important, the anilox roll, printing cylinder and vacuum substrate holder have been levelled out with high precision using a new adjustment method. The results demonstrate the ability of flexographic printing to generate stable seed layer contact fingers < 30 μm if the process is optimized adequately.

4.2 Inkjet printed seed layer

The inkjet printed seed layer contact fingers achieved an average width of $w_{s,\varnothing} = 36$ μm with a standard deviation of $\sigma = 3$ μm. SEM images show a well-defined finger shape which is typical for inkjet printing (fig. 4B). Also, the seed layer was very homogeneous with nearly no interruptions.

4.3 Results after light induced plating

The deposition of plated Ni, Cu and Ag considerably increased the shading-relevant width w_p of the flexo printed contact fingers. Table I gives an overview over the obtained seed layer finger width w_s and the plated finger width w_p compared to typical screen printing results. While the width of flexo printed fingers increased by 30 μm to an average width of $w_{p,fx} = 53$ μm during LIP, the inkjet printed contact fingers showed only slight increase to an average width of $w_{p,ink} = 38$ μm.

Table I: Contact finger width of the different groups

	$\varnothing$ Seed layer width w_s [μm]	$\varnothing$ Plated/printed width w_p [μm]
Flexo	23	53
Inkjet	36	38
Screen Printing (SP)*	-	~50-60

typical results of screen printed solar cells on the same wafer material

4.3 Solar cell results

Both groups obtained comparable solar cell results after Ni-Cu-Ag-LIP (Table II). Taking a closer look at the solar cell parameters, the inkjet group showed a slightly better open circuit voltage V_{oc}. A lower surface recombination of the inkjet printed front side metallization due to a less aggressive ink might be a reason for this.

Table II: Solar cell results (as processed) after LIP

		V_{oc} [mV]	J_{sc} [mA/cm²]	FF [%]	η [%]
Flexo	Avg.	638.7	37.8	79.1	19.1
	Best	639.6	37.9	79.3	19.2
Inkjet	Avg.	640.6	37.9	78.6	19.1
	Best	641.6	38.0	79.0	19.2
SP*		638-640	37.8-38.1	78.5-79.2	19.0-19.3

typical results of screen printed solar cells on the same wafer material

Measurements of the mean grid resistance R_{Grid} between the busbars revealed a sufficiently low lateral resistance of the contact fingers (Table III). This indicates that an adequate amount of Ni, Cu and Ag has been plated via LIP. Yet, the metal amount and distribution might be optimized further to minimize shading and thus increase cell current. Measurements of the specific contact resistance between the seed layer and the emitter using TLM revealed a sufficiently low mean specific contact resistance of $\rho_c = 4$ mΩcm² for the flexo seed layer. This indicates a good ohmic contact to the emitter. The inkjet seed layer obtained a higher mean specific contact resistance of $\rho_c = 8$ mΩcm². Both groups obtained satisfying fill factors FF, indicating that the fill factor of is neither limited by the grid resistance nor by the specific contact resistance of the seed layers.

Table III: Solar cell parameters related to the front side metallization after LIP

	$\varnothing\,R_{Grid}$ [Ω/m]	$\varnothing\,R_s$ [Ωcm²]	$\varnothing\,\rho_c$ [mΩ·cm²]
Flexo	41.0	0.5	4
Inkjet	37.7	0.8	8
SP*	~40-60	~0.5	~1.5-3

typical results of screen printed solar cells on the same wafer material

Fig. 6 shows the achieved conversion efficiencies η of the experimental groups after Ni-Cu-LIP. The results are compared to the typical corridor of screen printed solar cells on the same wafer material. The results show that both technologies are able to fabricate solar cells with comparable electrical results to typical screen printed solar cells on the same wafer material.
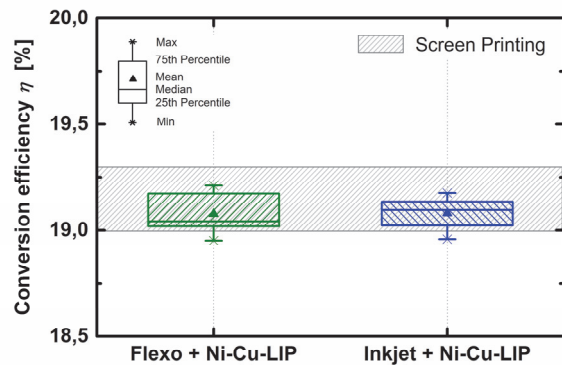

Figure 6: Conversion efficiencies of cell groups with flexo and inkjet seed layer + Ni-Cu-LIP compared to typical results of screen printed solar cells on the same wafer material.

4.4 Silver consumption

The total silver consumption of both seed and plate groups is considerably smaller than the screen printed reference group. A very low total silver mass of $m_{Ag,ink} = 17$ mg/cell (inkjet) and $m_{Ag,fx} = 15$ mg/cell (flexo printing) has been consumed on the front side for the seed and plate approach. However, the total silver consumption of the screen printed cells is significantly higher with $m_{Ag,SP} = 96$ mg/cell (Fig. 7). This comparison underlines the great potential of a seed and plate approach with Ni-Cu-Ag-LIP to reduce the consumption of cost-intensive silver dramatically.
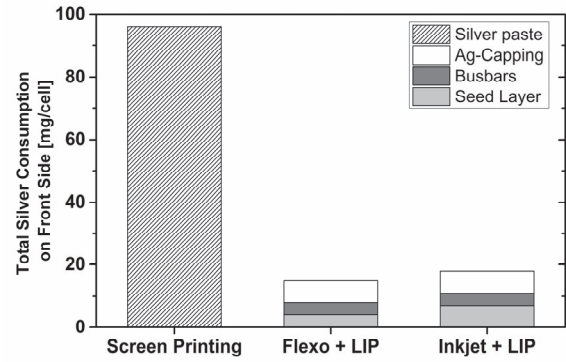

Figure 7: Total silver consumption of all three technologies on the front side of the solar cells (A = 156 x 156 mm²)

6   CONCLUSION

Within the present contribution, ultrafine line seed layer front side grids have been generated on Cz-Si precursors using two innovative technologies – flexographic and inkjet printing. Using inkjet, seed layer contact fingers with an average width of $w_s = 36$ µm could be realized. Flexographic printing was able to print even smaller seed layer contact fingers with an average width of $w_s = 23$ µm. Both types of seed layers were reinforced using Ni-Cu-Ag-LIP. After LIP, the average finger width increased to $w_{p,ink} = 38$ µm in case of inkjet and $w_{p,fx} = 53$ µm in case of flexographic printing. Typical state-of-the-art screen printed contact fingers usually obtain a width of 50 to 60 µm. I-V-measurements showed good fill factors of both groups. A deeper analysis revealed a sufficient lateral grid resistance R_{Grid} of both groups. The specific contact resistance ρ_c of the fired seed layers was different for both groups with a lower contact resistance of the flexo printed seed layers. Both groups achieved an average conversion efficiency of $\eta_\varnothing = 19.1$ %, which is comparable to typical results of screen printed solar cells on the same material. However, the total silver consumption on the front side (after Ni-Cu-Ag-LIP) is considerably smaller for both approaches. The very low amount of silver consumption ($m_{Ag,ink} = 17$ mg/cell of the inkjet group and $m_{Ag,fx} = 15$ mg/cell of the flexo group) compared to screen printed cells (approx. $m_{Ag,ink} = 96$ mg/cell) underlined the great potential of both approaches to reduce cost-intensive silver for the front side metallization.

7   ACKNOWLEDGEMENT

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