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Towards a high-throughput metallization for silicon solar cells using rotary-printing methods

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ABSTRACT

Today, flatbed screen printing is the state-of-the-art technology for solar cell metallization; however, the throughput of a single flatbed screen-printed metallization line is currently limited to approximately 2,000 wafers/h. A highly promising route to significantly increasing throughput is the use of rotary-printing methods, with an expected throughput of at least 6,000 wafers/h. This paper presents two innovative rotary-printing technologies: flexographic printing and rotary screen printing. *Flexographic printing* is a high-speed method that is capable of realizing narrow contact fingers for front-side metallization. *Rotary screen printing* is particularly suited to rear-side metallization, as it combines the advantages of thick-film metallization with a very high printing speed. The actual achievements and challenges of these highly promising approaches will be discussed, and the path of future research activities will be outlined.

Introduction

Modern single metallization lines using flatbed screen printing (FSP) can realize a maximum output of approximately 2,000 wafers/h [1]. For several reasons, achieving a significant further increase in throughput of the FSP process is technically challenging. First, the usage of high-viscous silver and aluminium pastes requires a separate, and hence time-consuming, flooding and printing step. Second, the speed of the FSP process is limited by the rheological properties of the pastes, and is therefore highly dependent on the development and availability of suitable pastes.

Elevating the solar cell metallization process to a new level of productivity thus requires new concepts in the future. One such, highly promising, concept is the use of high-speed rotational printing methods for the front- and rear-side metallization of silicon (Si) solar cells. The vision for a future high-throughput back-end metallization line combines different rotary-printing methods (Fig. 1), among which rotary screen printing (RSP) and flexographic (or flexo) printing (FXP) are particularly promising techniques. RSP is closely related to FXP and primarily suited to the rear-side metallization of aluminium back-surface field (Al BSF) or passivated emitter and rear contact (PERC) solar cells. Other possible fields of application are the structured rear-side metallization for bifacial solar cells [2], or the separate imprinting of busbars within a dual-

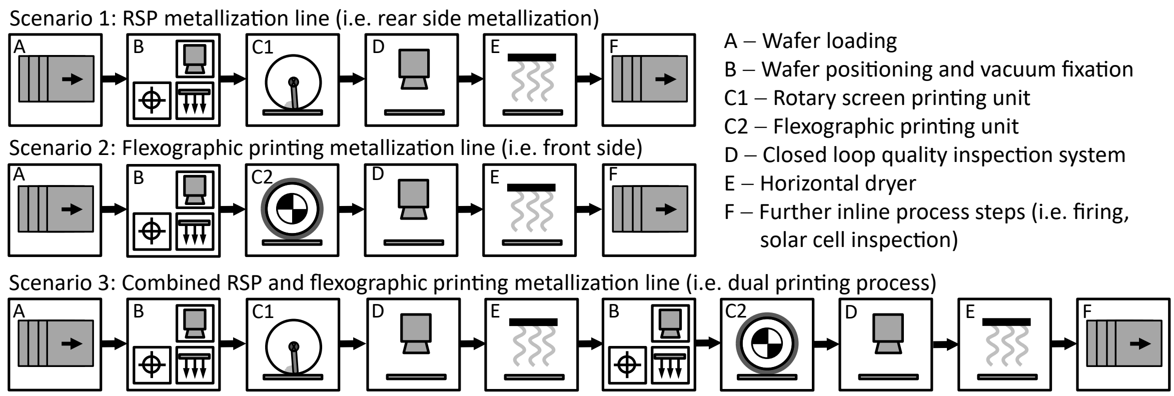

Figure 1. Illustrative presentation of different configurations for a back-end metallization line using rotary-printing methods. Scenarios 1 and 2 represent concepts for a rear-side metallization line using RSP and a front-side metallization line using FXP respectively. Scenario 3 combines both technologies in one metallization line (i.e. for a dual-printing process of busbars and contact fingers).

printing process. FXP technology [3] is a high-speed letterpress printing method using flexible photopolymer or rubber printing plates. With this technology it is possible to apply very narrow contact fingers, and it is thus primarily suited to front-side metallization using either a seed-and-plate approach [4–6] or a direct metallization process for solar cells with wire interconnection [7].

"One of the main goals is the development of a prototype demonstrator using RSP and FXP units to realize the front- and rear-side metallization of Si solar cells with a throughput of 6,000–8,000 wafer/h."

In 2015 a project consortium of several industry partners led by ASYS Group and Fraunhofer ISE initiated the ambitious Rock-Star project (contract number 13N13512 [8]) with the aim of evaluating the potential of RSP and FXP technologies [7,9] for the metallization of Si solar cells. The joint project is partly supported by the German Federal Ministry of Education and Research (BMBF) within the Photonics Research Germany funding programme. One of the main goals of the project is the development of a prototype demonstrator using RSP and FXP units to realize the front- and rear-side metallization of Si solar cells with a throughput of 6,000–8,000 wafer/h. To cope with this ambitious challenge, a close cooperation in the field of automation and wafer handling (ASYS Group), printing technology and machine manufacturing (Gallus Ferd. Ruesch AG), and material/process optimization (ContiTech Elastomer Coatings, Fraunhofer ISE, TU Darmstadt IDD) is essential. This paper presents the current state of the art and discusses the existing challenges with regard to solar cell front- and rear-side metallization using both technologies.

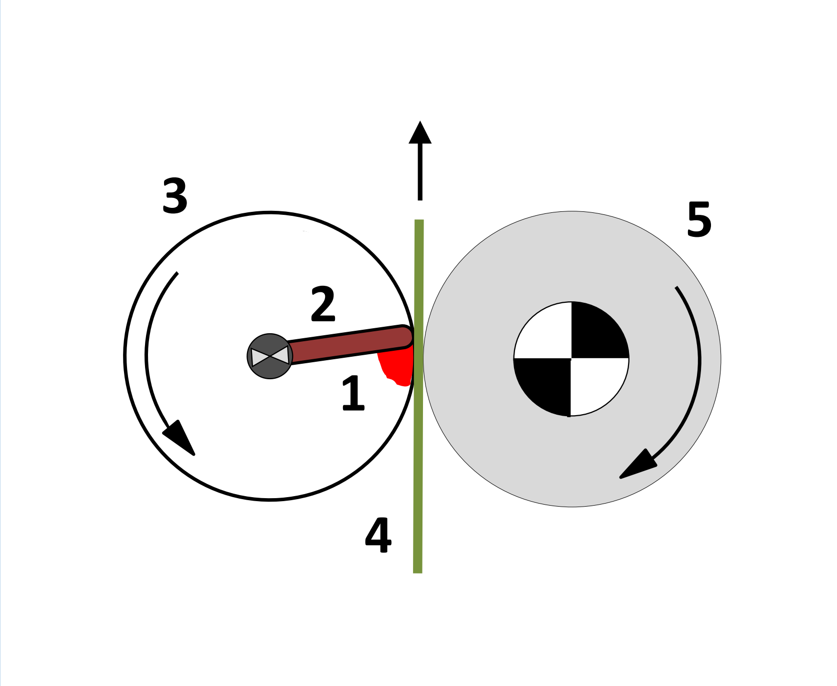

Figure 2. Schematic of an RSP unit for web-based materials. The paste (1) is pressed by a fixed squeegee (2) through the openings of the rotating cylinder screen (3). The web-based substrate (4) is guided by an impression cylinder (5) opposite the cylinder screen.

Figure 3. The RSP unit of the Gallus EM 280 label printing machine, which was used for the experiments. This printing machine allows a printing speed of up to v = 100m/min. (1.7m/s).

Rotary screen printing

While FSP is widely known as a state-of-the-art technology for thick-film metallization, RSP is a fairly unknown printing technology. However, RSP is a well-established and highly developed high-speed printing technology commonly used for specific applications such as textile or label printing [10]. Similar to FSP, RSP can print thick films on various substrates. To date, RSP has almost exclusively been used for web-based materials, such as foil, paper, textile fabrics and cardboard; such web-fed machines with RSP units can realize a printing speed of up to 160m/min. (2.7m/s) [11]. The high metallization quality of screen-printed thick-film metallization in combination with the rotary-printing principle of RSP could therefore be a highly promising

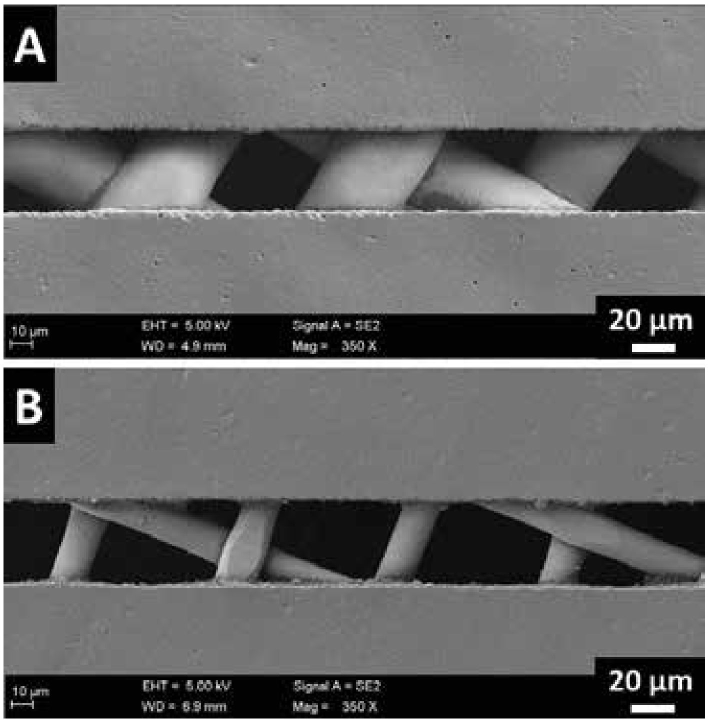

Figure 4. SEM images of a fine-line opening in an RSP cylinder screen (A) and in an FSP flatbed screen (B). The significantly greater wire thickness of the RSP screen mesh is clearly visible.

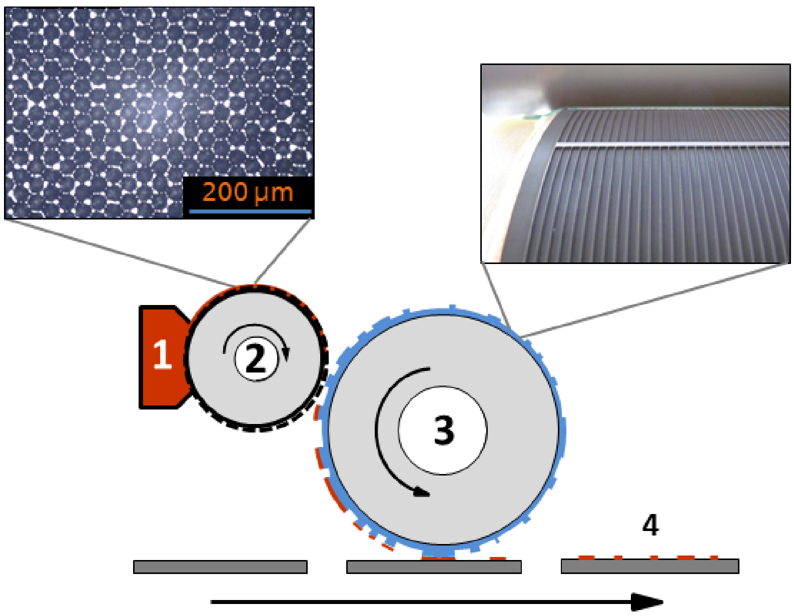

Figure 5. Schematic of a (theoretical) FXP unit for the metallization of silicon solar cells: from the ink reservoir (1), a defined amount of ink is transferred by the anilox roll (2) onto fine finger elements on the printing plate (3), and subsequently onto the silicon wafer (4).

path for a future high-throughput metallization line. The first attempts to use this technology for solar cell metallization date back as far as 1999; however, there are no known published results from these activities [12].

If one compares FSP and RSP technology, one fundamental difference becomes apparent: FSP requires two printing steps for the metallization of one solar cell. In the *flooding step*, the open areas of the flatbed screen are filled with paste using a metal flood bar. In the second stage – the *printing step* – the paste is pressed through the openings of the flat screen by a flexible squeegee. RSP, on the other hand, is a continuous process, meaning that the paste is constantly pressed through the openings of the rotating cylinder screen by a fixed squeegee (Figs. 2 and 3). The time-consuming two-step printing process associated with FSP can thus be avoided.

While the continuous printing process of RSP is a clear advantage with respect to throughput, RSP also experiences some drawbacks compared with FSP. First, the RSP cylinder screens require a considerably higher stability of the mesh than in the case of FSP flatbed screens. To ensure this stability, the meshes in rotary screens have significantly thicker wires ($d_{wire} \approx 30–50\mu m$) than in flatbed screens ($d_{wire} \approx 14–25\mu m$), as illustrated in Fig. 4.

Thicker wires obviously reduce the open area of the mesh, and hence the paste transfer capacity per unit area; they could also increase the impact of so-called *mesh marks* on the printed finger geometry. A second characteristic of RSP is the necessity of a lower paste viscosity compared with FSP pastes, which can be explained by the continuous printing process and the absent pre-filling of the screen. Reducing the paste viscosity usually has an impact on effects such as paste spreading on the wafer surface, and could thus negatively affect the resulting finger geometry. A lower paste viscosity could also affect other important rheology parameters of the paste, such as yield stress and wall slipping [13]. The rheological requirements of RSP metallization have not yet been sufficiently examined to categorically assess these effects on finger geometry.

Flexographic printing

FXP technology is a well-known and widely used printing technology, usually for graphic arts printing on substrates such as cardboard, paper and foil. Roll-to-roll FXP machines can realize a printing speed of up to 800m/min. on web-based materials. While this throughput is obviously unrealistic for the non-continuous metallization of Si solar cells, FXP technology nevertheless offers the potential to increase throughput considerably in cell metallization. Fig. 5 illustrates the working principle of a (theoretical) FXP unit for solar cell metallization.

> "FXP technology offers the potential to increase throughput considerably in cell metallization."

FXP uses a flexible relief printing plate or sleeve [14] as the image carrier. Compressible foam tape is applied below the printing plate in order to compensate for unevenness and to assure a homogeneous ink transfer. The ink is transferred from the ink chamber onto the so-called *anilox roll*, a steel cylinder with a finely textured chromium or ceramic surface. Inks with a low to medium viscosity can be used, depending on the properties of the anilox roll and on the requirements of the printing subject. Excessive ink is removed from the surface of the anilox roll by a doctor blade. The anilox roll continuously wets the elevated areas of the printing plate with a uniform layer thickness. The printing layout (elevated areas on the printing plate) is continuously printed on the substrate by the rotating cylinder.

The relatively low printing pressure and the flexibility of the plate enable fine structures to be printed, even on very rough substrates such as textured silicon wafers. The critical parameters in the FXP process are the printing pressure, anilox roller properties, ink properties and material tolerances. The applicable layer thickness with FXP is usually limited to $d_{layer} \leq 10\mu m$, which represents a challenge for high-aspect-ratio (height-to-width ratio) contact fingers. FXP has proved its ability to print ultrafine conductive structures in many printed electronics applications, such as micro-scale conductive networks [15,16], roll-to-roll polymer solar cell modules [17], cathode layers for batteries [18], and conductive lines [19].

In respect of the front-side metallization of Si solar cells, two different approaches are of interest. The idea behind the seed-and-plate approach is to print a fine-line seed-layer grid on Si wafers; this layer can subsequently be enhanced by light-induced plating (LIP) using silver (Ag) or a stack of nickel (Ni) as a diffusion barrier, copper (Cu) as a conducting layer, and Ag or tin (Sn) as an anti-oxidation capping layer. The second approach is the direct front-side metallization of Si solar cells without subsequent plating; the most critical aspect of this approach is the realization of the grid with a sufficiently low lateral finger resistance R_L.

Rotary screen-printed rear-side metallization

The metallization of the rear side of Al BSF or PERC solar cells requires the transfer of a homogeneous Al layer with a thickness of approximately 20–30µm. Prior to the feasibility study, it was unclear whether RSP technology would be able to meet this challenge with satisfying results. Consequently, an experiment with respect to the rear-side metallization of Al BSF solar cells was conducted using industrially pre-processed p-type Czochralski-grown silicon (Cz-Si) precursors with well-known properties ($R_{sh} \approx 85–90\Omega$/sq.).

A major challenge for the experiment was the availability of an adequate test assembly for the metallization of the Si wafer. The test assembly was realized by fixing the wafers manually on the foil web of a Gallus EM 280 label printing machine with an RSP unit [20] (Fig. 6). This improvised assembly allowed a safe transport of single wafers through the printing unit, with an alignment tolerance of approximately 1–1.5cm between the printing image and the wafer. In order to realize a full solar cell layout on the precursors despite this alignment tolerance, it was decided to print a smaller cell layout (125mm × 125mm) on 6" precursors (156mm edge length).

For the RSP rear-side metallization, three different cylinder screens with varying screen-mesh properties (mesh count and theoretical paste transfer volume V_{th}) were used. A commercially available Al paste for Al BSF solar cells was iteratively diluted to an adequate viscosity. Subsequently, all cells were cut out along the position of the printed image by laser cutting. In a second step, the front-side grid

Figure 6. Transport of a Si wafer through the RSP printing unit by fixing it on a foil web.

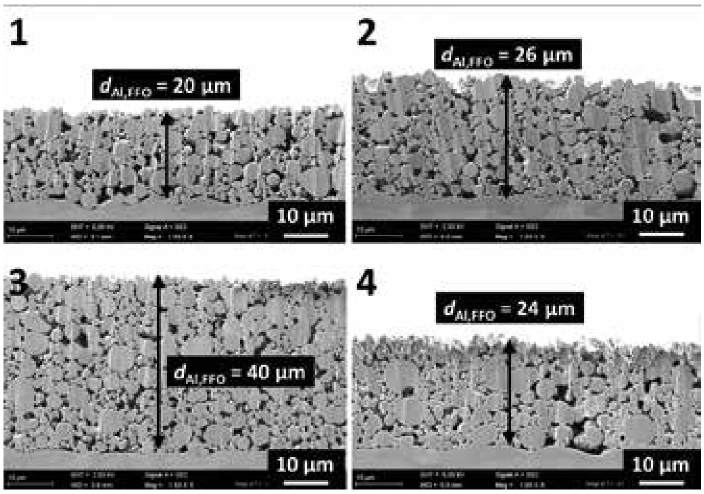

Figure 7. SEM cross-sectional images of the Al rear-side metallization after contact firing. Images 1 to 3 represent samples with RSP rear-side metallization and different cylinder screens. Image 4 is the reference sample with FSP rear-side metallization.

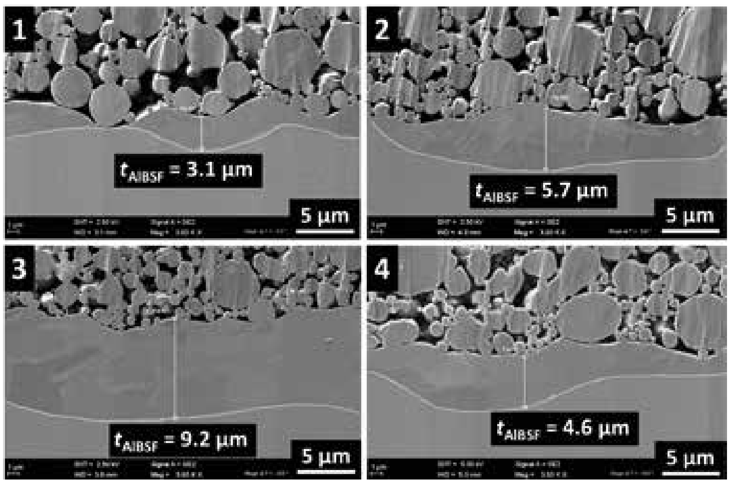

Figure 8. SEM cross-sectional images and local measurement of the resulting Al BSF depth after contact firing. Images 1 to 3 represent samples with RSP rear-side metallization and different cylinder screens. Image 4 is the reference sample with FSP rear-side metallization.

Rear-side metallization	Mesh [wires/inch]	Theoretical paste volume V_{th} [cm³/m²]	Ø Layer thickness [µm]	Ø Depth of Al BSF [µm]	Ø V_{oc} [mV]	Ø j_{sc} [mA/cm²]	Ø *FF* [%]	Ø η [%]
RSP	200	22	20	2.5	639.0 ± 3.0	37.5 ± 0.2	80.4 ± 0.1	19.2 ± 0.2
RSP	145	32	26	3.6	641.7 ± 0.7	37.5 ± 0.1	80.6 ± 0.2	19.4 ± 0.1
RSP	88	67	40	7.8	642.7 ± 0.4	37.5 ± 0.1	80.2 ± 0.3	19.4 ± 0.1
FSP	280	27	24	4.0	642.2 ± 0.5	37.6 ± 0.1	80.0 ± 0.2	19.3 ± 0.1

Table 1. Properties of rotary and flatbed screens, layer thickness after contact firing, depth of Al BSF, open-circuit voltage V_{oc}, short-circuit current density j_{sc}, fill factor *FF*, and energy conversion efficiency η for various solar cell groups.

(85 contact fingers, three busbars with w_b = 1.0mm) was printed using FSP with a standard screen (400 wires/inch, nominal finger width w_n = 45µm). Finally, a contact firing step, *I–V* measurements and an SEM analysis of the rear-side metallization were carried out. In parallel, a reference group with FSP front and rear-side metallization was fabricated on identical cut-down precursors, using the same pastes and layouts.

The experiment revealed several important aspects. A significant finding was the fact that commercially available Al pastes can be used for RSP after slight modification (dilution) in order to adjust the viscosity. The layer thickness of the rear-side metallization could be easily controlled by choosing a cylinder screen with an adequate paste transfer capacity (Fig. 7 and Table 1). Optimal results were achieved using a cylinder screen with a mesh count of 145 wires/inch. The resulting mean layer thickness of d_{Al} = 26µm after contact firing was close to the layer thickness of the reference cells with FSP rear-side metallization (d_{Al} = 24µm). The use of a cylinder screen with 88 wires/inch led to a significantly thicker Al layer of d_{Al} = 40µm, which induced a strong bowing of the solar cells due to thermal expansion in the contact firing process. This bowing needs to be minimized, as it negatively affects, or even prevents, the automation of wafer handling in subsequent process steps.

"With RSP it is possible to realize a high-quality rear-side metallization for Al BSF solar cells using a slightly diluted Al paste and an optimal cylinder screen mesh."

An analysis of the BSF using SEM further revealed a clear dependence of the BSF depth t_{ALBSF} on the initial Al layer on the rear side (Fig. 8). This dependency has also been found in previous studies [21–23] and can be explained by a varying concentration gradient between Al and Si during the formation of the Al–Si eutectic in the contact firing process [24]. An inspection of the *I–V* results revealed a visible effect of t_{ALBSF} on open-circuit voltage V_{oc} of the solar cells (Table 1). The optimum balance with regard to the *I–V* results and the minimal bow could be achieved with a cylinder screen having 145 wires/inch. For this screen configuration, the conversion efficiency (η = 19.4%) was similar to that for the FSP reference group (η = 19.3%). To summarize the results, it was found that with RSP it is possible to realize a high-quality rear-side metallization for Al BSF solar cells using a slightly diluted Al paste and an optimal cylinder screen mesh. Transferring the rear-side metallization process from FSP to RSP technology should therefore be a relatively easy task.

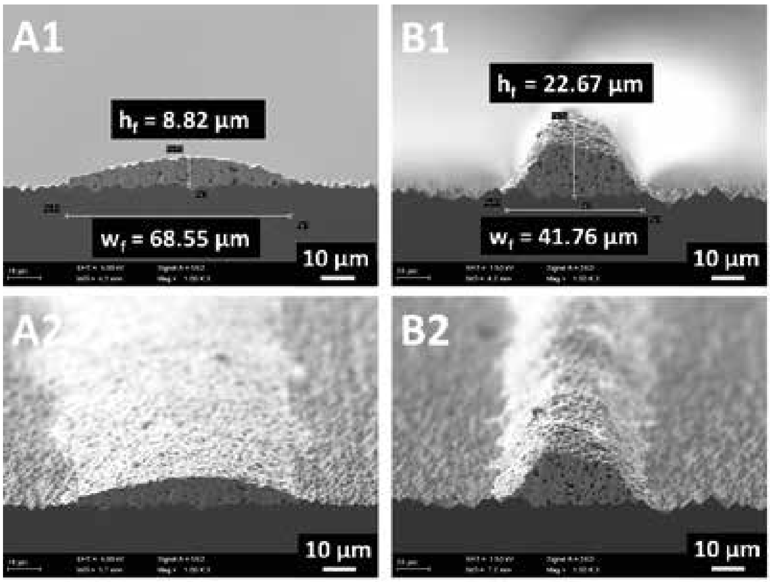

Figure 9. SEM images of a contact finger printed with RSP (A1 and A2) and with FSP (B1 and B2). The much higher aspect ratio of the FSP contact finger is clearly visible.

Rotary screen-printed front-side metallization

The metallization of the front side of Si solar cells is a considerably greater challenge with regard to the printing process. The front-side grid needs to be printed with narrow, uninterrupted contact fingers, and preferably with a small tolerance in finger width and height. Moreover, to minimize the shading losses of the grid and the series resistance losses due to the lateral finger resistance R_L at the same time, the fingers should be printed with a high aspect ratio. To achieve these challenging goals, paste suppliers have put much effort into gradually improving FSP metallization pastes. With the use of RSP for the front-side metallization, one can expect considerable challenges regarding finger geometry, as the thicker wires of the mesh limit the paste transfer capability, and the necessity to adapt the viscosity probably affects the resulting finger geometry.

To evaluate the general feasibility of RSP front-side metallization, an experiment similar to that for rear-side metallization was set up. In this case, the front side was printed using an RSP fine-line cylinder screen with a mesh count of 400 wires/inch and a 4" layout (A = 125mm × 125mm, three busbars with w_b = 1.0mm, 85 fingers with w_n = 35µm) on p-type Cz-Si precursors with an edge length of 156mm. A commercially available Ag paste was used after being slightly diluted with a sufficient thinner. A reference group with FSP front-side metallization was fabricated in parallel. All cells were equipped with a standard FSP rear-side metallization for Al BSF solar cells.

A statistical analysis of the finger geometry using confocal microscopy and SEM analysis revealed significant differences between RSP and FSP (Fig. 9). RSP contact fingers showed, as expected, a significantly broader finger width and a lower finger height compared with FSP contact fingers. This demonstrates that further optimization of paste rheology and cylinder screens is needed in order to enable RSP technology to realize a fine-line front-side metallization of PERC or Al BSF solar cells. Nevertheless, RSP is probably capable of printing less challenging patterns, such as a rear-side grid for bifacial solar cells [2], or busbars in a dual-printing process.

Flexographic-printed front-side metallization

The promising results of feasibility studies using flexography for a seed-and-plate-approach on small-sized solar cell samples [4,5,25] form the basis of the FXP activities at Fraunhofer ISE. A major challenge was the availability of an adequate machine platform to print fine-line grids on non-bendable Si wafers, as FXP machines are usually roll-to-roll based. It was possible to overcome this hurdle by using a laboratory machine of the type Nissha Angstromer S15 with a vacuum table to fix the wafers (Fig. 10).

Initial research activities at Fraunhofer ISE between 2012 and 2015 focused on the seed-and-

Figure 10. Nissha Angstromer S15 flexographic printing machine with a ContiTech Laserline fine-line printing plate and a Cz-Si precursor fixed on the vacuum table.

Figure 11. ContiTech Laserline laser-engraved flexographic EPDM printing plate with a fine-line H-pattern layout for seed-layer metallization.

plate approach using p-type Cz-Si-precursors with a 156mm edge length. Ag inks for the seed-layer metallization, based on an existing ink formulation, were developed in-house [6]. High-precision laser-engraved ethylene-propylene-diene rubber (EPDM) plates of the type ContiTech Laserline CSC, with a nominal finger width down to w_n = 5µm, were used to apply the seed-layer front-side grid (Fig. 11).

Extensive trials and significant efforts to optimize materials and machine settings finally led to promising printing and solar cell results. A mean finger width of w_f = 53µm could be obtained after reinforcing the seed-layer grid with Ni-Cu-Ag LIP [26]. The best group of solar cells achieved a mean conversion efficiency of η =19.1%, which was close to the results obtained for reference solar cells with a state-of-the-art FSP front-side metallization (η = 19.3%) [26]. However, total Ag consumption for the front-side metallization of the FXG solar cells (m_{Ag} ≈ 15mg/cell) was considerably reduced compared with the FSP reference cells (m_{Ag} ≈ 96mg/cell). This approach is therefore particularly attractive in the event of sharply rising silver prices.

From 2014 onwards, research activities in the framework of the Rock-Star joint project focused on a direct metallization of Si solar cells using FXP. Extensive printing tests identified the anilox roller and the ink rheology as key parameters in controlling finger geometry and achieving fingers with a higher aspect ratio [9]. The use of an anilox roller with a large ink transfer capacity and a high-viscous Ag ink led to contact fingers with a mean width w_f below 30µm [27] and a finger height up to h_f ≈ 12µm. However, realizing such narrow contact fingers with a sufficiently low lateral finger resistance using FXP technology is still challenging.

FXP, with a mean lateral finger resistance of R_L = 6.1Ω/cm (FSP metallization: R_L ≈ 0.4–0.6Ω/cm), is currently well suited to the front-side metallization of busbarless solar cells with multiwire interconnection (e.g. Meyer Burger's SmartWire concept [28]). In the test runs, busbarless solar cells with FXP front-side metallization achieved a mean conversion efficiency η of up to 19.4% on p-type Cz-Si precursors, and have been successfully interconnected in a working demonstration module [7]. Future R&D activities within the Rock-Star project will focus on further decreasing lateral finger resistance of the FXP direct metallization to make this highly promising concept attractive for H-pattern solar cells with five or more printed busbars.

Summary

Rotary-printing techniques represent a highly promising approach for raising the Si solar cell metallization process to a new level of productivity. A project consortium consisting of several project partners in the fields of automation, machine engineering, material development and research has set itself the ambitious goal, within the framework of the funded Rock-Star joint project, of realizing a demonstrator device with a desired throughput of 6,000–8,000 wafers/h. Development activities within the project focus on two printing technologies: RSP and FXP. The current results show that RSP is capable of realizing the rear-side metallization for Al BSF solar cells with the same quality as that with FSP. Similar results for PERC solar cells have not yet been demonstrated, but can be expected. Using RSP for the front-side metallization of Al BSF or PERC solar cells still represents a challenge and requires further optimization of paste rheology and cylinder screens.

"Future R&D will focus on optimizing the FXP and RSP processes for the front-side metallization of Al BSF and PERC solar cells with five or more busbars."

As regards FXP, the proof of concept has been successfully shown in a multitude of experiments since 2012. With FXP it is possible to realize either a fine-line seed-layer metallization for subsequent reinforcement by LIP, or a direct metallization without LIP. The first approach is highly applicable to the front-side metallization of H-pattern solar cells, and has the benefit of reducing silver consumption per cell by up to 85% compared with FSP. The second approach, direct metallization, is currently limited by the achievable lateral finger resistance, but already works well for the front-side metallization of busbarless solar cells with multiwire interconnection. Future R&D within the Rock-Star project will focus on optimizing the FXP and RSP processes for the front-side metallization of Al BSF and PERC solar cells with five or more busbars.

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