

SCREEN PRINTED THICK FILM METALLIZATION OF SILICON SOLAR CELLS - RECENT DEVELOPMENTS AND FUTURE PERSPECTIVES

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ABSTRACT: Within this work, we present actual results in the field of screen printing front side metallization for Silicon solar cells using standard and knotless screen technology. We show that knotless screens have the potential to improve the printed finger geometry and reduce silver consumption. A fine line front side metallization for PERC (passivated emitter and rear) with a mean finger width of $w_f = 27 \mu\text{m}$ is realized using a fine line screen printing process at Fraunhofer ISE. The PERC solar cells obtain a mean conversion efficiency of $\eta = 21.6 \%$. Furthermore, we present actual results regarding rotary screen printed front side metallization – a highly promising approach to increase throughput significantly. Using this technology, PERC solar cells are metallized at a printing speed of $v = 333 \text{ mm/s}$. A mean finger width $w_f = 47 \mu\text{m}$ and a mean finger height of $h_f = 13 \mu\text{m}$ is obtained.

Keywords: Solar cell metallization, flatbed screen printing, knotless screens, rotary screen printing

1 INTRODUCTION

1.1 Flatbed screen printing - status and current challenges

Since the first published application for solar cells in 1975 [1], flatbed screen printing (FSP) has been established as the leading production technology for front and rear side metallization of crystalline Silicon (c-Si) solar cells. Today, more than 95 % of all c-Si solar cells worldwide are metallized using FSP [2]. The ongoing success of FSP is based on a number of factors: FSP is comparatively easy to handle, reliable and cost-efficient compared to much more elaborate alternatives like photolithography, plating or other printing technologies. On the other hand, increasing the throughput of the flatbed screen printing process further (currently up to 4000 wafers/h on a single line) is one major challenge which makes alternative technologies with significantly higher throughput more and more interesting. If one considers the technological challenge of solar cell metallization from a printer's point of view, the main challenge is the front side metallization of the solar cell. On the one hand, the mean finger width w_f of the grid should be as low as possible to minimize shading losses. Fig. 1 illustrates the progress in reducing the screen printed finger width w_f since 2005 on the basis of published results.

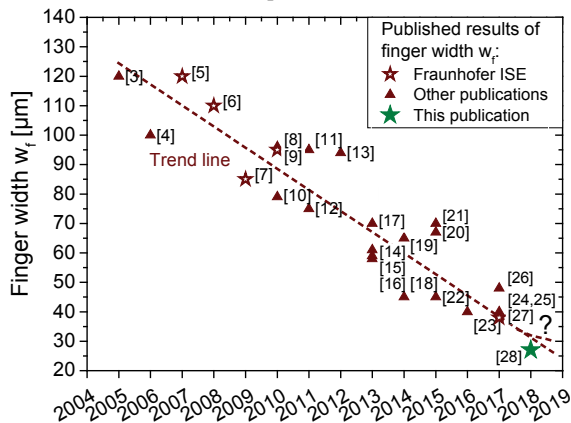


Figure 1: Learning curve of the flatbed screen printing process (2005-2017) regarding finger width w_f based on published results [3–28].

The steep learning curve is the result of intense industrial efforts to optimize paste, screen and machine technology. This impressive development underlines the ongoing potential of screen printing technology for the metallization of solar cells. Beside a narrow finger width w_f , the mean lateral finger resistance R_L or respectively the so-called Grid Resistance R_{grid} has to be sufficiently low to ensure a low series resistance contribution and in consequence a high Fill factor FF of the solar cell. Thus, the ideal contact finger geometry is characterized by a narrow mean finger width w_f and a large contact finger cross-section area A_f (provided that the specific contact resistance ρ_c of the sintered silver paste is sufficiently low). In other words, the electrical aspect ratio AR_{el} as introduced by Pospischil et al. [29] has to be maximized:

$$AR_{\text{el}} = \frac{A_{f,0}}{w_{f,0}^2} \quad (1)$$

Furthermore, significant variations of the finger height, width and cross-section area along the finger have to be minimized. These variations (commonly known as “mesh marks”) are caused by the deformation of the printed finger profile by wire intersections within the screen mesh (Fig. 2) on the one hand and an insufficient sealing (known as “gasket seal effect”) between the emulsion along the finger channels in the screen and the rough surface texture of the silicon wafer [30]. Both effects lead to a deformation of the finger profile.

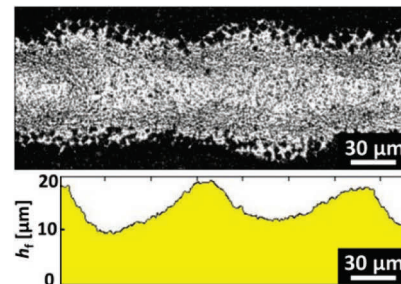


Figure 2: Microscopic image and height profile of a screen-printed contact finger with typical width and height variations (“mesh marks”).

1.2 Knotless screens

In recent years, several approaches have been introduced to address the challenge to optimize the finger geometry with respect to uniformity and high AR_{el} . Examples of such approaches which have found their way to an industrial application in the past are stencil printing [31], parallel dispensing [32], screen printing of hotmelt pastes [33] and the application of a double printing sequence [34]. Recently, so-called knotless screens (also called knot-free or super screens) have gained increasing attention [35]. This type of screen is characterized by a 0° mesh angle (orientation of the mesh to the screen frame). Compared to conventional screen meshes with a 22.5° mesh angle, knotless screens have no wire intersections in the open channels for contact fingers. This can be realized by omitting selected threads within the production process of the mesh (Fig. 3). Compared to standard screens, knotless screens have an increased open area ratio of the mesh (open area in proportion to covered area by the wires) and should thus enable a higher amount of paste transfer within the finger channels. Furthermore, one can expect less mesh marks along the contact fingers and thus a better uniformity of the contact fingers. In consequence, a better lateral conductivity of the printed and fired contact fingers as well as a reduction of paste consumption due to the reduction of finger height and width variations can be expected.

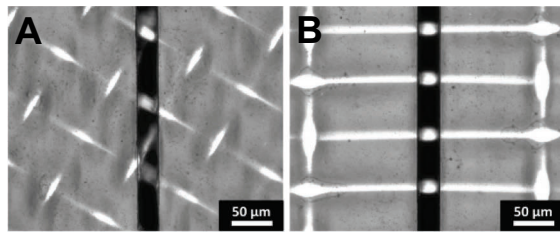


Figure 3: Microscopic images of contact finger channels within the standard screen with mesh angle 22.5° (A) and a Frintrup knotless screen with mesh angle 0° (B). The knotless screen is fabricated by omitting selected threads in the intended finger opening areas during the production process. As a consequence, wire intersections within the finger openings can be avoided.

1.3 Boosting throughput with rotary screen printing

Rotary screen printing (RSP) – a closely related technology to flatbed screen printing – has the potential to combine the technological advantages of thick film metallization with the potential high throughput of rotary printing methods. To date, this technology is primarily used on web-based materials (i.e. label or textile printing) with a printing speed of up to 100 m/min. First attempts to use this technology for solar cell metallization date back to the year 1999 [36]. In the last years, this promising technology has been intensively investigated [37–39] and gained increasing attention within the metallization community [35,40].

Similar to flatbed screen printing, a woven screen mesh covered with a partly open emulsion layer is used as printing form. However, in contrary to the flat screen used in FSP, cylinder-shaped screens are used for RSP. The meshes of such screens can consist of up to 400 threads per inch (mesh count). However, due to stability reasons of the cylinder screen, thread thickness is increased (minimum 25 to 30 μm) compared to flat screens. FSP requires two printing sequences. Firstly, the

open areas of the screen are filled using a metal flood bar. Secondly, the paste is pressed through the openings of the flat screen using a flexible squeegee. Using RSP, the paste is constantly pressed through the screen openings by a fixed squeegee within the rotating screen cylinder (Fig. 4). A pre-filling of the screen is thus not required. RSP requires a lower paste viscosity compared to FSP pastes to ensure a good paste transfer through the screen openings. The ability to transfer thick film metallization patterns makes RSP interesting for both – front and rear side metallization of c-Si solar cells.

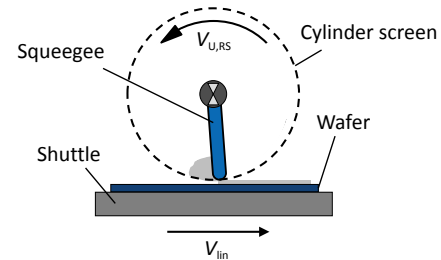


Figure 4: Schematic drawing of a rotary screen printing unit for the metallization of c-Si solar cells. The paste is pressed through the openings of the rotating cylinder screen onto the wafer substrate. The wafer can be transported i.e. by a shuttle system through the printing unit.

Within this work, we compare the results of a state-of-the-art fine line screen and a knotless screen with respect to finger geometry, electric results of the front side metallization and silver consumption. Furthermore, we present recent achievements in the field of rotary screen printing and give an outlook to further research activities.

2 EXPERIMENTAL SETUP

2.1 Outline and parameters of the experiment

Fig. 5 shows the process plan of the experiment. We use state-of-the-art industrially pre-fabricated p-type Cz-Si PERC solar cells (precursors) with SiN_x anti reflection coating and rear-side LCO without metallization on the front and rear side.

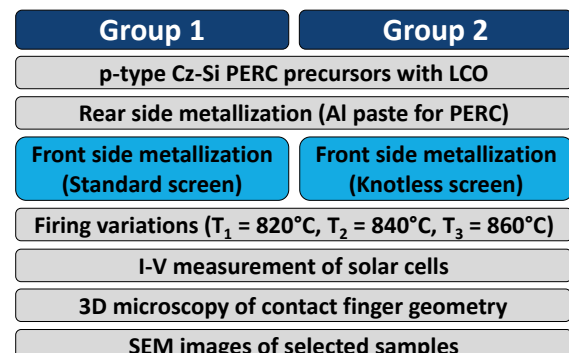


Figure 5: Experimental setup

The front and rear side metallization is carried out on an industrial ASYS screen printing line with Ekra XH-2 screen printing units using a newly developed Heraeus Ag paste and a commercially available Al paste for PERC solar cells. Two experimental groups are metallized using two types of screens. Group 1 is metallized on the front side using a state-of-the-art reference screen A

(380 mesh, mesh angle: 22.5°). Screen A has a grid layout with 5 segmented busbars and 120 contact fingers (nominal finger width $w_n = 30 \mu\text{m}$, measured finger channel width $w_{ch} = 31 \mu\text{m}$). Screen B is a knotless screen fabricated by Hans Frintrup GmbH. This screen has a 400 mesh and a grid layout with 5 segmented busbars and 111 contact fingers (nominal finger width $w_n = 25 \mu\text{m}$, measured finger channel width $w_{ch} = 28 \mu\text{m}$). For organizational reasons, the number of contact fingers within the grid layout of both screens is different. This leads to different results with respect to j_{sc} , V_{oc} and FF of the fabricated solar cells and has to be considered when comparing the I-V-results of both groups. During the printing step, the applied mass of Ag paste for the front side metallization is measured inline using precision inline scales. 30 solar cells of each group are metallized, cured in an inline drier and subsequently fired using an industrial fast firing oven (FFO) with 3 peak set temperatures á 10 cells per temperature ($T_1 = 820^\circ\text{C}$, $T_2 = 840^\circ\text{C}$, $T_3 = 860^\circ\text{C}$).

2.2 Characterization of the experimental results

I-V-results of the solar cells are measured using an industrial HALM cell tester with standard conditions. The measurement data includes the total busbar-to-busbar resistance (Grid resistance) R_{BB-BB} from which the mean lateral finger resistance $R_{L\phi}$ can be calculated with known number of contact fingers n_f and finger segment length l_f :

$$R_{L\phi} = \frac{n_f R_{BB-BB}}{l_f} \quad \text{for } r_{BB} \ll r_f \quad (2)$$

To analyze the three-dimensional geometry of the contact fingers with an adequate statistic, 25-30 microscopic measurements per group are carried out (5 measuring positions on 5 cells per group) using an Olympus LEXT confocal laser-scanning microscope (CLSM) with 500x magnification. The finger geometry (mean finger width $w_{f\phi}$, mean finger height $h_{f\phi}$ and mean finger cross-section area $A_{f\phi}$) are analyzed using an image analyze algorithm (FineUp) developed at Fraunhofer ISE [39]. This algorithm allows a reproducible and statistically sufficient analysis of the mean finger geometry.

3 RESULTS AND DISCUSSION

3.1 Three-dimensional contact finger geometry

Group 1 using the reference screen A could be printed using typical printing parameters. However, realizing the front side metallization of group 2 using the knotless screen B turned out to be more challenging. The printing quality reacted sensitively to the printing parameters. This might be possibly caused by the smaller width of the finger channels and another emulsion with different surface properties compared to the reference screen A. However, optimal printing parameters could be identified to print the front side metallization with good quality.

Table 1 shows the statistically analyzed results of the three-dimensional finger geometry for both groups.

Table 1: Finger geometry (mean values) of group 1 (screen A) and 2 (screen B).

Group	Finger geometry parameter		
	Ø Width $w_{f\phi}$ [μm]	Ø Height $h_{f\phi}$ [μm]	Ø Cross-section area $A_{f\phi}$ [μm^2]
1	30 ($\sigma = 1.2$)	16 ($\sigma = 1.0$)	324 ($\sigma = 22$)
2	27 ($\sigma = 1.2$)	17 ($\sigma = 0.9$)	320 ($\sigma = 18$)

The results show a slightly smaller mean finger width of group 2 (screen B) compared to group 1 (screen A) while the mean finger height h_f and finger cross section area A_f of both groups are closely comparable. The smaller mean finger width of group 2 can be most likely traced back to the narrower nominal finger width w_n (respectively finger channel width w_{ch}) of screen B and is thus no clear indication for a benefit of the knotless screen. However, if one calculates the electric aspect ratio AR_{el} based on equation (1), contact fingers of group 1 obtained a smaller $AR_{el,1} = 0.36$ compared to group 2 with $AR_{el,2} = 0.44$. This can be demonstrated by a superimposed illustration of an averaged finger profile of selected, representative contact fingers from group 1 and 2 (Fig. 6). The results indicate a benefit for the knotless screen B with respect to the printed finger geometry (aspect ratio). In other words it is possible to print slightly narrower but higher contact fingers with the knotless screen B compared to the standard screen A. The uniformity of the fingers of both groups seems to be comparable according to the measurement data (standard deviation σ of w_f and h_f).

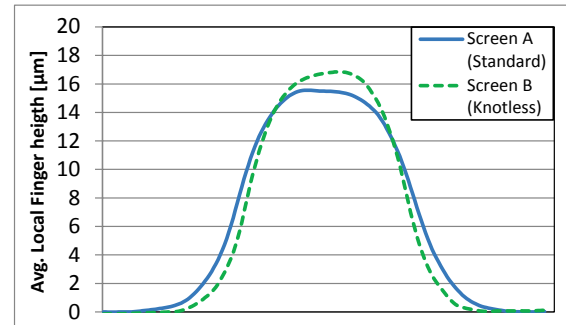


Figure 6: Superimposed mean cross-section profiles of selected, representative contact fingers printed with standard screen A (group 1) and knotless screen B (group 2). An advantage of the knotless screen with respect to the cross-section area A_f , finger aspect ratio and steepness of the flanks is visible.

3.3 Silver consumption

The inline weighing of the applied front side paste revealed that an average mass of $m_1 = (88 \pm 1.8) \text{ mg}$ (group 1) and $m_2 = (69 \pm 1.8) \text{ mg}$ (group 2) wet paste has been applied on the solar cells. However, the total mass of wet paste consumption cannot be directly compared due to the different number of contact fingers in the layout. Yet, if one subtracts the known mass of silver paste applied for the busbars ($m_{BB} = 15 \text{ mg}$) it is possible to calculate the mean paste consumption per finger with the known number of contact fingers in the grid. This calculation gives a mean mass of $m_{f,1} = 0.61 \text{ mg}$ per finger for group 1 and $m_{f,2} = 0.49 \text{ mg}$ per finger for group 2. In consequence, this is an effective wet paste reduction of approx. 20 % of the knotless screen compared to the standard screen. This confirms the ability of knotless screens to reduce the silver consumption und thus generate an economic benefit.

3.2 SEM-Analysis of finger geometry

Fig. 7 shows SEM images of selected, representative contact fingers of both groups. The SEM images also underline the more optimal shape of the contact fingers printed with the knotless screen B. A higher aspect ratio and better uniformity along the finger is visible.

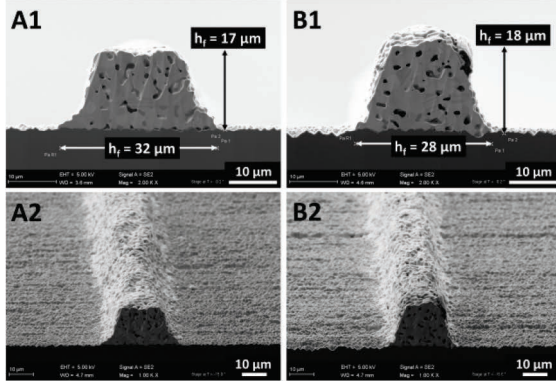


Figure 7: SEM images of selected, representative contact fingers of group 1 (A1 and A2) and group 2 (B1 and B2). This improved finger geometry (higher aspect ratio AR_{cl}) and a better uniformity (less mesh marks) of the finger printed with the knotless screen B (group 2) is clearly visible.

3.4 Lateral resistance of the front side grid

The mean lateral finger resistance $R_{L\phi}$ of the contact fingers is calculated from the I-V-data with the known number of contact fingers n_f , the segment length of the contact fingers between two busbars l_f and the average busbar-to-busbar resistance R_{BB-BB} using equation (2). For group 1 (screen A), a mean lateral finger resistance of $R_{L\phi} = 0.88 \Omega/\text{cm}$ ($87.9 \Omega/\text{m}$) is calculated. This result corresponds with typical lateral finger resistance values of contact fingers with similar geometry. Group 2 (screen B) obtained a mean lateral finger resistance of $R_{L\phi} = 1.13 \Omega/\text{cm}$ ($112.6 \Omega/\text{m}$) and thus a slightly higher lateral finger resistance. This can be explained by the smaller mean finger cross-section area $A_{f\phi}$ of group 2 which mainly results from the narrower nominal finger width w_n respectively the actual finger channel width w_{ch} in the screen. In a second step, the layout of the front side grid (number of contact fingers) can be optimized with known average R_L in order to realize an optimal tradeoff between j_{sc} (shading losses) and FF (series resistance losses) and thus maximize the conversion efficiency η .

3.5 I-V results of the solar cells

A direct comparison of the I-V results of both groups is due to the different number of contact fingers within the grid layout of both screens not reasonable. The difference regarding the number and nominal finger width w_n of the contact fingers has a significant impact on j_{sc} (shading) and FF (series resistance) and thus prevents a direct comparison of the resulting conversion efficiency η . However, I-V results of both groups are stated for the sake of completeness (table 2 and Fig. 8). In summary, the I-V results of both groups are promising and slightly better than the predicted conversion efficiency of industrial p-type Cz-Si PERC solar cells for 2018 [2]. Group 2 achieved a mean conversion efficiency of $\eta_0 = 21.6 \%$ (best individual cell $\eta_{max} = 21.8 \%$).

Table II: I-V results of the best solar cells of both groups (please note: a direct comparison is not reasonable due to a different number of contact fingers).

I-V Parameter	Unit	Group 1 (Best cell)	Group 2 (Best cell)
j_{sc}	$[\text{mA}/\text{cm}^2]$	39.6	40.0
V_{oc}	$[\text{mV}]$	668.2	669.0
FF	$[\%]$	81.8	81.3
η	$[\%]$	21.7	21.8

j_{sc} = Short-circuit current density, V_{oc} = Open circuit voltage, FF = Fill factor, η = Conversion efficiency

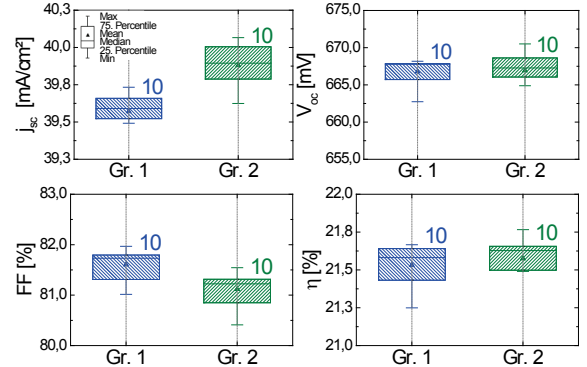


Figure 8: Comparison of the I-V-results of both groups.

4 CURRENT RESULTS OF ROTARY SCREEN PRINTING

The general feasibility of a high throughput front and rear side metallization using rotary screen printing (RSP) has been recently demonstrated in several publications [37,38,40]. While it has been shown that the rear side metallization of Al BSF (aluminium back surface field) solar cells can be realized without FF and η losses compared to FSP metallization [38], front side metallization still represents a bigger challenge due to thicker wires of the cylinder screen mesh and a slightly lower viscosity and yield point of the paste.

Recently, very promising results have been achieved by applying RSP for the front side metallization of p-type Cz-Si PERC precursors (format 125 mm x 125 mm). The experimental setup is similar to previous test series [38] with the exception of the Ag paste. For the latest test, a state-of-the-art Ag paste for front side metallization has been slightly diluted with a sufficient thinner and used for the test. A fine line Gallus Screeny® cylinder screen with a mesh count of 400 wires/inch and a 4" grid layout (3 busbars with $w_b = 1.0 \text{ mm}$, 85 fingers with $w_n = 35 \mu\text{m}$) has been fabricated and used for the experiment. The metallized precursors have been subsequently fired and the finger geometry has been analyzed by confocal microscopy and SEM.

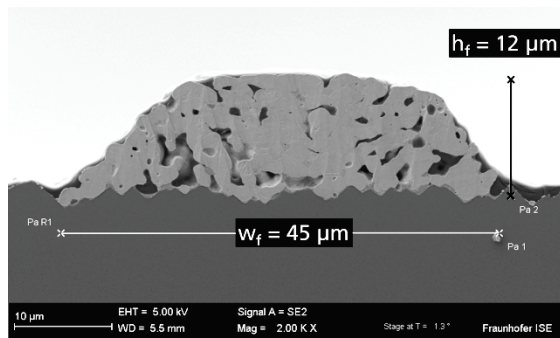


Figure 9: SEM cross section image of an actual rotary screen printed contact finger using slightly diluted commercially available Ag paste and a fine line cylinder screen for rotary screen printing.

Fig. 9 shows a SEM cross section image of a representative contact finger which has been printed within the latest RSP test. The statistical analysis of the finger geometry using confocal microscopy revealed a mean finger width of $w_f = 47 \mu\text{m}$ ($\sigma = 2 \mu\text{m}$) and a mean finger height of $h_f = 13 \mu\text{m}$ ($\sigma = 2 \mu\text{m}$). Four point probe measurements of the lateral finger resistance resulted in a mean lateral resistance of $R_L = 0.9 \Omega/\text{cm}$ ($90 \Omega/\text{m}$) with a standard deviation of $\sigma = 0.07 \mu\text{m}$. In summary, RSP front side metallization has not yet reached the same finger quality as FSP. However, further optimization of screens and pastes will give a realistic chance to achieve closely similar results to the state-of-the-art FSP process. A promising path to achieve this goal might be the development of knotless cylinder screens for rotary screen printing.

5 CONCLUSION

Within this work, a fine line front side metallization using state-of-the-art industrial pastes, screen printing machinery and two types of fine line screens has been realized. Using a standard screen (380-0.014 mesh, mesh angle 22.5° , $w_n = 30 \mu\text{m}$), a mean finger width of $w_f = 30 \mu\text{m}$ with an electric aspect ratio of $AR_{el,1} = 0.36$ could be obtained. Using a specially developed Frintrup knotless screen (400-0.016 mesh, mesh angle 0° , $w_n = 25 \mu\text{m}$), an even narrower mean finger width of $w_f = 27 \mu\text{m}$ and a higher electric aspect ratio of $AR_{el,2} = 0.44$ could be achieved. Image analysis results of the contact finger geometry and SEM images confirmed that the knotless screen is able to realize narrower contact fingers with a comparable cross section area A_f and a better uniformity along the finger (less mesh marks). This underlines the potential of knotless screen technology to realize a more optimal finger geometry and thus increase the overall solar cell efficiency. The best group of p-type Cz-Si PERC solar cells (group 2) which has been metallized with the knotless screen obtained a mean conversion efficiency of $\eta = 21.6 \%$. However, I-V results of both groups cannot be directly compared due the varying number of contact fingers and another nominal finger width w_n of the two screens.

Furthermore, we demonstrated actual research and development results in the field of high-throughput rotary screen printing metallization for Si solar cells. Using slightly diluted commercially available Ag paste and a fine line cylinder screen, a fine line front side metalli-

zation could be successfully printed on p-type Cz-Si PERC precursors. A mean finger width of $w_f = 47 \mu\text{m}$ and a mean lateral finger resistance of $R_L = 0.9 \Omega/\text{cm}$ could be achieved. This results show the fast progress and the potential of this technology with respect to front side metallization.

6 ACKNOWLEDGEMENTS

This work was partly supported by the German Federal Ministry of Education and Research (BMBF) within the funding program Photonics Research Germany under the contract number 13N13512 (Rock-Star) and by the German Federal Ministry of Economic Affairs and Energy under the contract numbers 0325775E (AdmMo) and 0325823 (CUT-A).

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