Screen pattern simulation for an improved front-side Ag-electrode metallization of Si-solar cells

Sebastian Tepner1 | Linda Ney1 | Michael Linse1 | Andreas Lorenz1 | Maximilian Pospischil1 | Kenji Masuri2 | Florian Clement1

1Department for Production Technology: Structuring and Metallization (PSM), Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, Freiburg im Breisgau, 79110, Germany
2Murakami Co., Ltd., Yokokawa, Sumida-ku, Tokyo, 130-0003, Japan

Correspondence
Sebastian Tepner, Department for Production Technology: Structuring and Metallization (PSM), Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, Freiburg im Breisgau 79110, Germany.
Email: sebastian.tepner@ise.fraunhofer.de

Abstract
Flatbed screen printing proves to be the dominant metallization approach for mass production of silicon (Si)-solar cells because of its robust and cost-effective production capability. However, the ongoing demand of the PV industry to further decrease the width of printed Ag-electrodes (contact fingers) requires new optimizations. This study presents the latest results on Si-solar cell metallization using fine-line screens down to screen opening widths of \( w_n = 15 \mu m \). The best experimental group achieved a record finger geometry with a mean finger width of \( w_f = 19 \mu m \) and a mean finger height of \( h_f = 18 \mu m \). Furthermore, solar cell performance using a front-side grid with a screen opening width of \( w_n = 24 \mu m \) is investigated, reporting cell efficiencies up to 22.1% for Passivated Emitter and Rear Contact (PERC) solar cells. Finally, a novel screen pattern simulation is presented, revealing a correlation between the measured lateral finger resistance and the novel dimensionless parameter screen utility index (SUI). It describes the ratio between the average size of individual openings defined by the screen mesh angle and the chosen underlying mesh type. For SUI < 1, the printing result will strongly depend on the screen configuration, whereas for values of SUI > 1, the impact of the screen on the overall printability diminishes.

KEYWORDS
screen printing, knotless screens, Si-solar cells, metallization, screen simulation

1 | INTRODUCTION

The metallization process of silicon (Si)-solar cells in today’s market is dominated by flatbed screen printing because of its cost-effective production capabilities and its numerous optimizations throughout the years. Within the last decade, flatbed screen printing has made tremendous progress in reducing the printed width of the electrodes (contact fingers) from approx. 120–100 \( \mu m \) in 2005 to published results of 26 \( \mu m \) in 2019.1–3 Figure 1 shows the evolution of published results for printed finger widths on a scientific level. The International Technology Roadmap for Photovoltaic (ITRPV) prediction from 2011 is in excellent agreement with this trend for achievable finger width on an industrial level.4 The current ITRPV from 2019 is predicting that the pace at which the reduction is likely to continue will slow down in the upcoming years.5 However, recent results on scientific scale do outperform this prediction significantly, indicating that the old reduction rate can be continued up to this date. However, when optimizing the finger geometry, one must always consider the impact on the solar cell as an optimal trade-off between the total shading of contact fingers (the product of the average finger width and the total number of contact fingers), the series resistance contribution (the lateral grid resistance and the contact resistance), and...
overall Ag-consumption (optimized by the uniformity of contact fingers). Therefore, further optimization of screen-printed finger widths is becoming increasingly challenging as all of these aspects have to be considered. Additionally, when a sufficient printability of front-side Ag paste at high flooding and printing speeds is desired, a low viscosity in the high shear regime seems to be necessary. The printability in terms of sufficient paste transfer usually comes at the cost of inducing high shearing forces into the paste sample, resulting in significant spreading and the loss of high aspect ratios. Xu et al. showed in separate studies that an improved slip behavior of the paste during flooding could help to optimize this trade-off further because slip between the paste and emulsion surface allows for relative movement without the induction of unnecessary shearing forces. The question arises if only further development of the metallization paste can push the limits of fine-line screen printing.

In recent years, screen manufacturers have started to contribute significant improvements to this problem by adjusting the screen architecture to enhance the paste transfer during flooding and screen snap-off. Figure 2 illustrates how the underlying mesh and partially opened emulsion define the screen architecture. The mesh consists of woven metal wires with a diameter \( d \), separated by the distance \( d_0 \). On top of this mesh, an emulsion is applied and partially opened to create a rectangular channel with a width \( w_n \). Further, this screen opening is placed at a specific angle \( \varphi \) in reference to the quadratic woven mesh. State-of-the-art screens are usually made with an angle of \( \varphi = 22.5^\circ \). Because of this choice, wire crossings always exist within each screen opening, limiting the printability and reducing the local finger height, respectively. In recent years, so-called "knotless screens" emerged, where the mesh is aligned at a 0° angle, avoiding any wire crossings within the screen opening, thus increasing the potential paste transfer. In order to establish a comprehensive understanding of the significance of the presented screen parameters, Ney et al. published a method to model the screen opening based on those parameters. Later, Tepner et al. expanded this simulation model to derive specific conclusions by simulating and studying the dependency of the wire crossings on such screen parameters. They were able to show that the state-of-the-art method of describing a screen channel by the established parameter open area \( OA_{\%} \) is not sufficient when fine-line screen printing below 30 \( \mu m \) is desired. They concluded that the rate at which the open area \( OA_{\%} \) changes across the screen opening is crucial to the screen performance. Therefore, they introduced a new parameter \( \sigma_{OA} \) describing the average deviation of \( OA_{\%} \) across the screen opening length. In this study, we will elaborate on these results by running a full simulation of different screen architectures and then perform solar cell metallization experiments for five different screen architectures at four different screen opening widths \( w_n \). Afterwards, the simulation results are directly correlated to the printing performance to create a complete understanding of how changes to the screen architecture are influencing fine-line screen printing.

2 | METHODS

2.1 | Screen simulation approach

In this study, we utilize the simulation approach first published by Ney et al. and then extended by Tepner et al. to perform a complete
screen pattern analysis on different screen openings to derive conclusions about their expected screen printing performance for solar cell metallization. The simulation approach is based on a mathematical model that calculates all intersection points between an arbitrary quadratic grid and a rectangle with the width \( w_n \) and the length \( l \), which is placed at an angle \( \varphi \) on that grid. A Boolean calculation was set up in MATLAB MathWorks©, which finds all existing intersection points, further calculates their exact coordinates, and connects the intersection points to polygons. Afterwards, the shape and exact size of all polygons are calculated, creating a full mathematical description of any screen opening defined by its wire diameter \( d \), the mesh count MC (or wire-to-wire distance \( d_0 \)), the screen opening width \( w_n \), and the screen angle \( \varphi \) (illustrated in Figure 2).\(^{22}\) The simulation approach was experimentally verified in both previous publications. Table 1 shows the range and increment of the sweep for the screen parameters and the alignment on the screen perpendicular to the screen opening direction. This alignment \( k_0 \) defines the position of the screen opening (see Figure 2) in reference to the underlying mesh.

In this study, all simulation results are presented as average values for a full sweep of \( k_0 \) because any conclusion derived needs to be true for all 120 screen openings on the entire screen. The simulation approach is repeated for three types of mesh with a mesh count and wire diameter of 380 inch\(^{-1}/0.014\) mm, 440 inch\(^{-1}/0.013\) mm, and 480 inch\(^{-1}/0.011\) mm. The simulation output data include the area of all individual openings and the average frequency of occurrence for each type of shape.

### 2.2 Experimental screen evaluation

In order to evaluate the printability of different screen opening patterns, four different fine-line screens (delivered by Murakami Ltd., Japan) and one reference screen from a different supplier are investigated in two separate experimental steps. In the first run, a test layout with four solar cell grid segments with 120 contact fingers of different screen opening width \( w_n \) (15, 18, 21, and 24 \( \mu \)m) separated by five busbars is used. The design of the test layout is presented in Figure 3. It allows a standard measurement of the busbar-to-busbar grid resistance \( R_{BB-BB} \) using an industrial cell tester and thus a statistical determination of the mean lateral resistance \( R_L \) of the contact fingers (also commonly known as grid line resistance \( R_L \)) for each segment.

**TABLE 1** Parameter sweep for the presented simulation approach

| Screen parameter                      | Start | End | Increment |
|---------------------------------------|-------|-----|-----------|
| Mesh angle \( \varphi \) [°]           | 0     | 45  | 0.001     |
| Emulsion alignment \( k_0 \) [μm]     | 0     | 84.67 | 0.002    |
| Screen opening \( w_n \) [μm]         | 15    | 30  | 3         |

Note: Simulation is run for 380/0.014, 440/0.013, and 480/0.011 meshes. The screen mesh angle is simulated from 0° to 45° in 0.001° increments. The screen opening is changed according to the used test layout and extended to 27 and 30 \( \mu \)m to obtain data for the printing experiments carried out in Tepner et al.\(^{2} \) Finally, the emulsion alignment \( k_0 \) is varied to determine the average output for any finger number on the layout.

The geometry of the contact fingers is statistically analyzed by confocal microscopy and image analysis using an algorithm developed at Fraunhofer ISE.\(^{23} \) To get statistically significant data on the printed finger geometry, the finger width \( w_h \), the finger height \( h_n \), and the cross-sectional area \( A_n \) is measured for each screen opening width \( w_n \) at three different fingers (#30, #60, #90) in the middle between corresponding busbars on five different wafers. Finally, a scanning electron microscopy (SEM) analysis of selected finger cross-sections is carried out.

In the second experimental step, solar cells are fabricated by applying a fine-line metallization and contact firing step on industrially prefabricated p-type Czochalski-grown (Cz) Si Passivated Emitter and Rear Contact (PERC) solar cells (precursors) including SiNx-anti-reflection coating, rear side passivation, and local contact opening (LCO). For the front-side metallization step, the most promising screen configurations from the first experimental step are used to evaluate the result on cell level. Additionally, for the best screen configuration, a paste variation is carried out. In Figure 3, the detailed process flow of both experimental steps is shown. The type of mesh (mesh count MC and wire diameter \( d \)) is the same as for the simulation approach. The presented knotless (0°) and 30° screen mesh angle are chosen based on the simulation results.

### 3 RESULTS AND DISCUSSION

#### 3.1 Simulation results

A systematic screen pattern simulation approach was carried out to determine the shape, size, and exact location of all individual opened areas that can occur within a screen opening. The method is well described in literature.\(^{19,22} \) We have found that only seven different types of opening shapes can mathematically exist within a screen opening defined by two straight parallel edges superimposed onto a quadratic mesh. If the screen opening width \( w_n \) is smaller than the wire-to-wire distance \( d_0 \), the quadratic shape can be removed from the investigation, resulting in six remaining different types of shapes presented in Figure 4.

Figure 5 shows the screen angle dependency of the mean area (left) of different opening shapes and their relative frequency of occurrence (right). On the top, the screen opening width \( w_n \) is set to 24 \( \mu \)m and on the bottom to \( w_n = 15 \) \( \mu \)m, respectively. In both simulations, a 440/0.013 mesh has been chosen. The simulated data indicate that different types of openings show a completely different dependency on the screen angle \( \varphi \). The simplest example is the typical 0° knotless screen, where all existing individual openings consist of rectangles at a well-defined size, calculated by the product of the wire-to-wire distance \( d_0 \) and the nominal screen opening width \( w_n \). Once an angle above \( \varphi > 0° \) is introduced, trapezoidal-shaped openings show the most frequent occurrence because at these small angles, there is always a wire that slowly creeps into the channel, transforming rectangular-shaped openings into trapezoids. For these small screen angles, trapezoids most frequently come in pairs on each side of the
corresponding wires. This circumstance changes at a certain angle, where trapezoids are companied by triangles on the other side of the wire. Finally, the data suggest that at a specific angle, trapezoidal-shaped openings vanish entirely. This angle is depending on the screen parameters as given by Equation 1.22 Another interesting part is the parallelogram–hexagon relationship. The frequency of occurrence for parallelograms will drop when increasing the screen angle until no parallelograms remain. At that particular angle, hexagons start to emerge, revealing that this angle marks a transition point between parallelograms and hexagon-shaped openings. Further, this angle can be calculated by solving the function presented in Equation 2.22

\[ w_d = d_0 \cdot \sin \phi. \]  

(1)

\[ w_d = d_0 \cdot (\cos \phi - \sin \phi). \]  

(2)
Finally, the most critical opening shape is the triangle because it is the smallest in size and the most frequent one for higher angles. Small individual openings need to be avoided at all costs when a sufficient paste transfer during printing is desired. Therefore, a screen angle of $\phi = 30^\circ$ could be chosen as it offers the maximum opening size of triangles. If the screen opening width is now reduced from 24 down to 15 $\mu$m, the overall average size of all opening shapes is decreased significantly, and the frequency of occurrence becomes more evenly distributed at a decreased overall level. When a $30^\circ$ angle is chosen, the 15-$\mu$m screen opening will have a completely different opening pattern as almost no hexagons or parallelograms are involved. On the other hand, the pattern is dominated by pentagon–triangle pairs that show a plateau in their frequency of occurrence from approximately $20^\circ$–$30^\circ$. This type of behavior was not present for the 24-$\mu$m screen opening because at that corresponding screen angle, hexagons have already started to emerge within the screen opening, creating triangle pairs in adjacent mesh units (see Figure 5). With the knowledge of the average size of each opening pattern and their frequency of occurrence, the overall average opening size in a screen can be calculated by their weighted arithmetic mean. This value is going to be utilized in Section 3.3 to establish a correlation between screen design and related performance during screen printing.

### 3.2 Printing results

Figure 6 presents the corresponding measurement of the lateral finger resistance $R_L$ for each group, revealing that a 440/0.013 knotless screen configuration enables a sufficient paste transfer even through screen openings with a nominal width of only $w_n = 15 \mu$m. For this
configuration, we have calculated theoretical series resistance contribution of a solar cell front-side grid (e.g., 120 fingers and 18 wires for interconnection) with the presented measured lateral finger resistance of $R_L = 270 \, \Omega/m$, resulting in an induced series resistance contribution of $R_{s,Grid} = 0.022 \, W/cm^2$. Therefore, we can conclude that this screen–paste combination could easily be suitable for a busbarless application.

Comparing different meshes for the 30° angled screen of Groups 1, 2, and 4 shows a slight decrease in the lateral finger resistance $R_L$ with increasing mesh fineness, starting from a 380/0.014 standard mesh to a 480/0.011 fine mesh. The printed finger width for the biggest screen opening $w_n = 24 \, \mu m$ does not show significant differences, resulting in an average printed finger width of $w_f = 27 \pm 1 \, \mu m$ for all screen types. This comes because of the fact that spreading is mainly depending on the paste–rheology and paste–emulsion interaction during screen snap-off, thus depending on emulsion surface properties as well as process speed.\(^1\) When only the finger width $w_n$ is considered, this conclusion holds even for smaller screen openings down to $w_n = 15 \, \mu m$. However, the average finger height $h_f$ and more importantly its deviation $\sigma_h$ changes dramatically between groups, resulting in the presented changes in lateral finger resistance $R_L$. For all groups, the same emulsion height $EOM = 15 \, \mu m$ and the same process parameters were chosen.

Therefore, the paste transfer during flooding is strongly influenced by the opening pattern of each screen configuration.

The advantage of increasing the screen angle is revealed when the 30° angled screen is compared with the 22.5° reference screen in Group 5. The data reveal a reduction of the lateral finger resistance $R_L$ for screen openings $w_n = 24 \, \mu m$ of approx. 10% from $R_{L,22.5} = 128 \, \Omega/m$ for the 480/0.011/22.5° screen to $R_{L,30} = 115 \, \Omega/m$ for the 480/0.011/30° screen. For the screen opening $w_n = 21 \, \mu m$, this effect is increased to a reduction of approx. 50% from $R_{L,22.5} = 390 \, \Omega/m$ for the 480/0.011/22.5° to $R_{L,30} = 182 \, \Omega/m$ for the 480/0.011/30° screen. However, this result might overestimate the true effect due to limited sample size. In Figure 7, an SEM image of a printed finger using the knotless 440/0.013 screen at $w_n = 15 \, \mu m$ is shown, demonstrating that it was possible to achieve an average finger width of $w_f = 19 \pm 1 \, \mu m$ at an average finger height of $h_f = 18 \pm 1 \, \mu m$. On the right of Figure 7, the homogeneity of the finger geometry is shown, indicating that only minor mesh marks do exist, which are not significantly increasing the lateral finger resistance $R_L$.

The I-V measurements for the second experiment are presented in Figure 8 and reveal that the knotless 440/0.013 screen offers a substantial increase in cell efficiency. This comes from a significant

---

**Figure 6** Lateral finger resistance $R_L$ for all investigated groups is presented. All nominal screen openings are shown and highlighted above the corresponding group [Colour figure can be viewed at wileyonlinelibrary.com]

**Figure 7** SEM image of an Ag-electrode printed with a 440/0.013/0° screen and a screen opening of $w_n = 15 \, \mu m$. An average aspect ratio of 0.9 at an average finger width of 19 \, \mu m can be reported. This SEM image was previously published by the authors.\(^2,25\) On the right, an angled tilted 3D microscope image of the printed finger is shown to illustrate the uniformity of the finger shape along the contacts by using this screen configuration [Colour figure can be viewed at wileyonlinelibrary.com]
increase in Fill Factor (FF), mainly contributed by the reduction in finger and thus total grid resistance. For the screen of Group 6, a grid line resistance $R_{L, 30}/C_{14} = 110 \, \Omega/m$ for a screen opening width $w_n = 24 \, \mu m$ has been achieved, whereas using the knotless 440/0.013 screen with the same screen opening width yielded an $R_{L, 30} = 72 \, \Omega/m$. This reduction of 35% between screens of Group 6 and Group 8 could explain the increase in FF by $\Delta_{FF} = 0.3 \%$ abs. However, to verify this statement experimentally, a full analysis of the contact resistance between the metal grid and emitter has to be conducted. Additional contributions beyond the contact resistance and grid line resistance to the total series resistance $r_s$, thus influencing the FF further, are assumed to be constant throughout this study as only the screen for front-side metallization has been varied. Additionally, a minor increase of $J_{sc}$ due to a small reduction in shading losses can be observed. Furthermore, the $V_{oc}$ is increased for the knotless screen configuration by 0.6% from 664.0 mV for Group 6 to 667.4 mV for the corresponding Group 8. At this point, further studies on contact formation with this type of paste need to be conducted to explain this increase in $V_{oc}$ completely. The result for Group 8 is furthermore repeated on a different precursor material from another cell supplier, increasing the $V_{oc}$ to 679.7 mV for the best individual cell. This cell achieved a cell efficiency of $\eta = 22.1 \%$, which has been verified by Fraunhofer ISE CalLab PV Cells (Figure 8).

### 3.3 | Correlation of screen simulation results and printing performance

In Figure 5, we have presented the average size and frequency of occurrence for all possible individual openings shapes, which can occur within a screen opening. With the knowledge of the average size and frequency of occurrence, the overall average area of individual openings $A_{ind, opening}$ for all screen configurations can be obtained by calculating the average across all opening shapes, weighted with their frequency of occurrence, as presented in Equation 3.

$$A_{ind, opening}(d_0, d, \phi, w_n) = \sum_{shapes} a_{shape}(d_0, d, \phi, w_n) \cdot f_{shape}(d_0, d, \phi, w_n).$$  \(3\)

The index "shapes" accounts for the iteration between all possible shapes presented in (4). The question arises, how is $A_{ind, opening}$ influencing the paste transfer, that is, the printability for a given paste. In order to address this question, we introduce an empirical nondimensional screen parameter screen utility index (SUI), which can be used to gain additional information on the expected printability of a screen with respect to a given paste.

**FIGURE 8**  I-V measurements for Groups 6–8. Metallization with the 440/0.013/0° knotless screen configuration yields the highest cell efficiency due to increases in FF, $J_{sc}$, and even $V_{oc}$. *Group 8b is printed on a different precursor, verified by Fraunhofer ISE CalLab PV Cells [Colour figure can be viewed at wileyonlinelibrary.com]*
In Equation 4, we calculate the ratio of the average area of individual openings across the screen channel $A_{\text{ind\,opening}}$ and the product of $\cos \phi$, the wire diameter $d$, and the wire-to-wire distance $d_0$. This ratio describes how big the average individual opening for a given mesh pattern can become without limiting the paste transfer substantially. The term $\cos \phi$ is added to account for the angle dependency of the total amount of mesh units, which exist within a screen opening. As seen in Figure 2, the introduction of an angle will tilt the pattern of individual openings across the screen channel $A_{\text{ind\,opening}}$ and increases its number. Furthermore, the SUI will increase with a finer mesh (decreasing $d$ and $d_0$) and decreases with a reduction of the screen opening width $w_n$ ($A_{\text{ind\,opening}}$ depends on $w_n$ as seen in Figure 5). We cannot state an equation that describes the full dependency of the SUI on the screen angle $\phi$ for any angle above $0^\circ$ because $A_{\text{ind\,opening}}$ depends on the screen angle $\phi$ itself. Therefore, the calculation of the SUI requires the presented simulation model. In Figure 9, the relationship between the lateral finger resistance $R_L$ for each group and the SUI value is shown. In order to get a more complete picture, published data from Tepner et al. have also been included. The comparison is suitable because the same paste and very similar printing process parameters have been chosen in that study, making the screen architecture the only variable between studies. The data indicate that at SUI = 1, the relationship between the printability and the screen architecture changes. In the regime where SUI < 1 applies, there is a strong increase in lateral finger resistance $R_L$ which indicates that screen parameter choices will significantly influence the expected printing performance. For SUI > 1 values, the average size of individual openings is wide enough to guarantee a stable and sufficient paste transfer indicating that the screen architecture is not the limiting factor. In order to make the right screen parameter choices, one has to run a full simulation on all potential combinations of screen opening widths $w_n$ and screen angles $\phi$ for all available mesh types. Afterwards, all screen candidates can be ranked relative to each other by comparison of the SUI.

For today’s mass production of Si-solar cells, a SUI < 1 should be avoided at all costs, as small deviations of screen configurations due to manufacturing tolerances might significantly influence the expected printing result. If manufacturing tolerances for screen angle alignment and the wire-to-wire distance on meshes decrease in the future, smaller SUI values might become suitable for mass production. At this point, the interaction with an arbitrary paste is completely neglected as any highly filled suspension with a certain average particle size will cause significant clogging of a portion of these individual openings. This would cause an increase of the measured lateral finger resistance $R_L$ eventually. In future studies, the determination of the nominator of Equation 3 needs to account for certain clogging probabilities of highly filled suspensions like metal pastes. Finally, the SUI can only be used to compare screens if the emulsion height and all printing parameters are kept constant. However, even with these limitations, the SUI value offers a potential explanation of why the evolution of published results for printed finger width over the last 15 years (Figure 1) was achieved at an outstanding reduction rate of more than 7 μm per year.

Further paste development was enough to drive this evolution as SUI values for screens during that time were far beyond SUI > 1, revealing that the screen was not the limiting factor when it comes to printability. With the ongoing reduction of screen opening widths, this will change dramatically in the upcoming years. Improvements on screen manufacturing tolerances will likely become a major driver for continuing the presented evolution to maintain a controllable and sufficient mass production environment.

### CONCLUSIONS

In this work, a screen pattern analysis by a novel simulation approach was conducted and revealed that the screen angle has a significant influence on the expected printing result. A full PERC metallization has been carried out for a total of 20 different screen configurations, revealing that a $0^\circ$ knotless screen with a 440/0.013 mesh shows substantial advantages in paste transfer and homogeneity of printed finger geometries down to only $w_n = 15$-μm screen opening widths. It was possible to achieve printed finger width of $w_f = 19$ μm at an average finger height of $h_f = 18$ μm with an average lateral finger resistance of $R_L = 270$ Ω/m. For solar cell metallization, a 24-μm screen opening width for the 440/0.013 knotless screen was chosen and resulted in a cell efficiency of up to 22.1%. Finally, simulation...
results for all screen configurations are correlated with printing results, revealing a relationship that can be explained by a novel dimensionless parameter, the SUI, giving a quantitative value for any screen configuration to describe its impact on printability.

ORCID

Sebastian Tepner https://orcid.org/0000-0001-8611-5295

REFERENCES

1. Tepner S, Wengenmeyr N, Ney L, Linse M, Pospischil M, Clement F. Improving wall slip behavior of silver pastes on screen emulsions for fine line screen printing. Sol Energy Mater Sol Cells. 2019;200:109969. https://doi.org/10.1016/j.solmat.2019.109969

2. Tepner S, Ney L, Linse M, Lorenz A, Pospischil M. Advances in Screen Printed Metallization for Si-Solar Cells—Towards Ultra-fine Line Contact Fingers Below 20 μm. 29th International PV Science and Engineering Conference, Xi’an, China 2019, DOI: https://doi.org/10.13140/SG.2.2.33088.69126

3. Lorenz A, Linse M, Frintrup H, Jeitler M, Mette A, Lehner M, Greutmann R, Brocker H, König M, Erath D, Clement F. Screen printed thick film metallization of silicon solar cells—recent developments and future perspectives. 35th European Photovoltaic Solar Energy Conference and Exhibition 2018: 819–24. DOI: https://doi.org/10.4229/35THEUPVSEC20182018-2DV.3.65

4. International technology roadmap for photovoltaics. 3rd edition: 2011 Results. ITRPV 2012.

5. International technology roadmap for photovoltaics. 10th edition: 2018 Results. ITRPV 2019.

6. Hong K-K, Cho S-B, You JS, Jeong J-W, Bea S-M, Huh J-Y. Mechanical behavior of Ag crystallites in the Ag thick-film contacts of crystalline Si solar cells. Sol Energy Mater Sol Cells. 2009;93(6):898-904. https://doi.org/10.1016/j.solmat.2008.10.021

7. Thibert S, Jourdan J, Beechvet B, Chaussy D, Reverdy-Brua N, Beneventi D. Influence of silver paste rheology and screen parameters on the front side metallization of silicon solar cell. Mater Sci Semicond Process. 2014;27:790-799. https://doi.org/10.1016/j.mssp.2014.08.023

8. Yüce C, König M, Willenbacher N. Rheology and screen-printing performance of model silver pastes for metallization of Si-solar cells. Coatings. 2018;8(11):423-799. https://doi.org/10.3390/coatings8110406

9. Xu C, Willenbacher N. How rheological properties affect fine-line screen printing of pastes: a combined rheological and high-speed video imaging study. J Coat Technol Res. 2018;15(6):1401-1412. https://doi.org/10.1007/s11998-018-0091-2

10. Durairaj R, Jackson GJ, Ekere NN, Cîlău G, Bailey C. Correlation of solder paste rheology with computational simulations of the stencil printing process. Solder Surf Mount Tech. 2002;14(1):11-17. https://doi.org/10.1108/09540910210416422

11. Hoornstra J, Weeber AW, De Moor, Hugo H. C., Sinke WC. The importance of paste rheology in improving fine line, thick film screen printing of front side metallization. 14th European Photovoltaic Solar Energy Conference and Exhibition 1997.

12. Durairaj R, Man LW, Ekere NN, Mallik S. The effect of wall-slip formation on the rheological behaviour of lead-free solder pastes. Mater Des. 2010;31(3):1056-1062. https://doi.org/10.1016/j.matdes.2009.09.051

13. Xu C, Fies M, Willenbacher N. Impact of wall slip on screen printing of front-side silver pastes for silicon solar cells. IEEE J Photovolt. 2017;7(1):129-135. https://doi.org/10.1109/JPHOTOV.2016.2626147

14. Shannugam V, Wong J, Peters IM, et al. Analysis of fine-line screen and stencil-printed metal contacts for silicon wafer solar cells. IEEE J Photovolt. 2015;5(2):525-533. https://doi.org/10.1109/JPHOTOV.2014.2388073

15. Aoki M, Nakamura K, Tachibana T, Sumita I, Hayashi I, Asada H, Ohshita Y. 30μm fine-line printing for solar cells. IEEE 39th Photovoltaic Specialists 2013: 2162–6. DOI: https://doi.org/10.1109/PVSC.2013.6744903

16. Hahne P. Innovative Druck- und Metallisierungsverfahren für die Solarzellentechnologie. 1st ed. Hagen; 2000.

17. Jewell E, Hamblyn S, Claypole T, Gethin D. Deposition of high conductivity low silver content materials by screen printing. Coatings. 2015;5(2):172-185. https://doi.org/10.3390/coatings5020172

18. Ju M, Lee Y-J, Lee J, et al. Double screen printed metallization of crystalline silicon solar cells as low as 30μm metal line width for mass production. Sol Energy Mater Sol Cells. 2012;100:204-208. https://doi.org/10.1016/j.solmat.2012.01.018

19. Tepner S, Ney L, Linse M, Lorenz A, Pospischil M, Clement F. Studying knotless screen patterns for fine line screen printing of Si-solar cells. IEEE J Photovolt. 2020;10(2):319-325. https://doi.org/10.1109/JPHOTOV.2019.2959939

20. Yang H, Davis CS. Silver pastes capable of narrow line, high aspect ratio and high pastes transferability for knotless high mesh screen printing. In: 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC): (a joint conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC) 10–15 June 2018. Piscataway, NJ: IEEE; 2018:1079-1080.

21. Zhang Y. Knotless screen printing for crystalline silicon solar cells. Konstanz; October 23rd, 2017.

22. Ney L, Tepner S, Linse M, et al. Optimization of fine line screen printing using in-depth screen mesh analysis. AIP Conf Proc. 2019; 020006-1–020006-8. https://doi.org/10.1063/1.5125871

23. Strauch T, Demant M, Lorenz A, Haenschel J, Rein S. Two image processing tools to analyse alkaline texture and contact finger geometry in microscope images. 29th European Photovoltaic Solar Energy Conference and Exhibition 2014.

24. Clement F, Linse M, Tepner S, Wengenmeyr N, Krieg K, Lorenz A, Pospischil M, Bechmann S, Oehrle K, Steckemetz S, Preu R. “Project FINALE”—screen and screen printing process development for ultra-fine-line contacts below 20μm finger width. 36th EU PVSEC Conference Proceedings 2019: 259–62. DOI: https://doi.org/10.4229/EUPVSEC20192019-2DO.5.1

25. Fraunhofer ISE. Press release: innovative fine-line screen printing metallization reduces silver consumption for solar cell contacts. Available at: https://www.ise.fraunhofer.de/en/press-media/press-releases/2019/innovative-fine-line-screen-printing-metallization-reduces-silver-consumption-for-solar-cell-contacts.html; 2019.

How to cite this article: Tepner S, Ney L, Linse M, et al. Screen pattern simulation for an improved front-side Ag-electrode metallization of Si-solar cells. Prog Photovolt Res Appl. 2020;28:1054–1062. https://doi.org/10.1002/pip.3313