High aspect ratio triangular front contacts for solar cells fabricated by string-printing

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Abstract
We are presenting a novel method to fabricate high aspect ratio, triangular cross-section solar cell front contacts, henceforth referred to as string-printing. We optimized string-printing to yield contacts with an aspect ratio larger than 1 and a light redirection efficiency or effective transparency of 67%, thereby mitigating most of the optical losses inherent to flat metallic front grids. In string-printing, a string coated with silver paste approaches a substrate until contact is made. Withdrawing the string then leaves behind silver paste on the substrate. Here, we describe the fabrication method and show initial results including current density-voltage curves of string-printed silicon heterojunction solar cells, as well as the effective transparencies of the contacts. String-printing is a scalable, low-temperature process with high potential to boost commercial solar cell efficiency and lower the module price per Watt.

KEYWORDS
fabrication, metal printing, silicon heterojunction, silicon solar cells, solar cell front contacts, transparent contacts

1 | INTRODUCTION

Front contacts play a crucial role in the photovoltaic industry as their ability to conduct the generated charge carriers while simultaneously allowing the incoming photons to pass has a major influence on the performance of solar cells. Furthermore, metallization is a significant consumer of raw material (i.e., silver). Currently, the most prevalent front contact fabrication technique is screen-printing,\(^1,2\) which enables high throughput manufacturing, but only allows low aspect ratio (A/R, i.e., height to width ratio) contacts, resulting in decreased cell performance due to optical shading. As the terawatt-scale renewable energy future presents itself, new or optimized front contact manufacturing methods that improve performance, throughput, and materials consumption become more crucial.

In the past years, efforts in the screen-printing field have been made to reduce finger widths and silver consumption, as well as to increase the A/R. Optimized fine-line screen printing meshes were developed for this purpose and produced finger widths down to 15 \(\mu\)m\(^3\) and A/Rs up to 0.9.\(^4\) Other already industrialized methods for fabricating thin and light-redirecting contacts with reduced silver consumption include the parallel dispensing technique\(^5\) commercialized by HighLine® and the Smart Wire Connection Technology (SWCT)\(^6\) solution proposed by Meyer Burger® where the circular shape of the SWCT wires introduces a light-trapping effect, which reduces the shading of the wires by 25%.

In academic research, a plethora of ideas have been presented to mitigate front contact shading losses. Kik et al.\(^7\) showed that shaped catoptric electrodes significantly increase transmission of incident light with large metal coverages up to 50\% of the wafer area. Sachs et al.\(^8\) also proposed patterned interconnection ribbons allowing for light trapping with total internal reflection (TIR). Tabernig et al.\(^8\) and Jahelka et al.\(^10\) designed a patterned polymer coating that refracts normally incident light away from the metal grid.
In recent works by Saive et al.,\textsuperscript{11–13} triangular cross-section, high A/R effectively transparent contacts (ETCs) were presented which virtually mitigated all shading losses through efficient light redirection. These contacts were fabricated by a capillary action enabled 3-D micro imprinting technique,\textsuperscript{11} which yields excellent shape conformity and performance but is more involved than traditional screen-printing. Here, we propose a fabrication process, referred to as string-printing, which enables high A/R, triangular cross-section metal front contacts tackling performance, throughput and materials consumption simultaneously. We believe this method to be able to compete with the throughput of screen-printing, while also providing performances similar to ETCs. In this report, we present the first experimental demonstration to fabricate high A/R triangular contacts on Si substrates and silicon heterojunction (SHJ) solar cells with string-printing. We show contacts with A/R higher than 1 and demonstrate how the printing procedure impacts the shape of the prints. Furthermore, we were able to show that effective transparency of string-printed ETCs on SHJ cells reached 67% under AM1.5G conditions.

2 | METHODS

2.1 | String-printing

The string-printing method is explained in Figure 1. The cross-sections of the substrate and string are shown in step 1 and in step 2, and silver paste is applied to the string to cover it as homogeneously as possible. The coated string is then approached towards the substrate of interest until contact is made (steps 3 and 4). The paste wets the substrate, and in the next step, the string is withdrawn, stretching the adhered paste into an hourglass shape/meniscus. At a certain point, snap-off will occur, leaving behind the printed contact on the substrate.

2.1.1 | String-printing device

To enable reliable and controllable prints, we developed a prototype string-printing device (see Figure 2) allowing for multiple degrees of freedom in varying parameters such as withdrawal speed, substrate temperature, and printing location. The tool is composed of three major components: the support stage, the linear actuator, and the string holder. The linear actuator is used to approach and withdraw the string to and from the support where the Si substrate or solar cell is placed and is automated using an Arduino program.

The string-printing prototype shown in Figure 2 was used for printing the contacts shown in Sections 3.1–3.3. However, this prototype lacks the ability to control the amount of paste applied on the string. To tackle this issue, an upgraded version of the prototype was built where the printing mechanism remained unchanged, but the amount of paste applied on the string was controlled by the use of dies such that a fixed maximum paste volume could be applied on the string. The prints that resulted from the upgraded prototype are shown in Section 3.4.
2.1.2 | Printing process

A sample, such as a piece of a silicon wafer or a solar cell, is placed on the sample holder and fixated by double-sided tape on the support to ensure stability during printing. The string is fixed to the shaft of a stepper motor, which is used to apply tension. In this work, the impact of the nature of the strings used was not investigated. Further research is encouraged to determine the influence of the string composition on the string-printing process. Once the string is tense, ethanol is then used to wipe the string clean of any contamination. A thick layer of paste, which is resting on the tip of a syringe needle, is brought into contact with the string. The needle is moved along the string such that some of the ink is transferred from the syringe needle to the string, on the desired printing length. The interfacial energy allows for the paste to wet the string ideally homogeneously. Once the paste is applied, the string is lowered onto the substrate until contact is made. The string must be tense and parallel to the substrate to make good contact. There is a short delay time that precedes the withdrawal step. The withdrawal speed and procedure are modulated through the Arduino code. The process can be performed while heating the substrate at temperatures in the range of 30 to 150°C.

To obtain triangular shapes, printing parameters such as the withdrawal procedure need to be optimized. Withdrawing too fast will lead to snap-off before the structure has sufficiently hardened, causing it to slump down, whereas withdrawing too slowly will lead to the structure hardening too much, bonding the string to the substrate. We will differentiate between two procedures: The first is referred to as the non-optimal withdrawal method, where once contact is made (see Figure 1 step 4), the string is withdrawn at a constant speed until snap-off occurs. The second procedure will be referred to as the optimal withdrawal method, where interruptions are introduced to the withdrawal, to let the paste set for a bit longer. This second procedure is optimal for generating triangular-shaped structures as it allows more time for the paste to be pulled upwards, while solvent evaporation takes place at the base due to the heating of the substrate. As the string is pulled upwards, the “bridging” paste connecting the string to the substrate will get smaller in width, leaving behind a triangular shape after snap-off.

Furthermore, aspect ratios are limited by both the finger widths of the prints and the amount of paste transferred on the substrate. Higher A/R can be achieved by decreasing the finger width or by printing multiple times on the same area. The same principle has already been applied to screen-printing and as expected, resulted in higher A/R contacts.

2.1.3 | Substrates

In this study, three types of substrates have been investigated: polished silicon wafers, textured silicon substrates with a SiN$_x$ anti-reflective coating (ARC), and textured SHJ cells with indium tin oxide (ITO) as the top layer. Some experiments were also performed on silanized substrates to tune the paste-substrate wetting angles. The silanization was performed by reacting O$_2$-plasma-treated substrates with a droplet of silanizing agent overnight in a desiccator placed under primary vacuum. The two agents used were 1H,1H,2H,2H-perfluorooctyltrimethoxysilane (which contains fluorine atoms) and octadecyltrimethoxysilane (non-fluorinated). When using the fluorinated agent for silanizing the SHJ cells, visible degradation of the ITO layer was observed. This can be explained by the presence of the highly electronegative fluorine atom that can bring about the reduction of In$_2$O$_3$ in ITO to the zero-valent In state. For this reason, the non-fluorinated silanizing agent was used to treat the SHJ cells.

2.1.4 | Silver pastes

First, two commercially available low viscosity silver inks (Metalon JS-B40G, 40 wt.%, 10 cP at 1000 s$^{-1}$ and PFI-RSA6004, 60 wt.%, 100 cP at 1000 s$^{-1}$) from Novacentrix have been tested with the previously explained procedure. However, these pastes showed poor wetting on the used strings and resulted in discontinuous contacts. The corresponding results are not shown here for brevity. We have then opted for thicker pastes (DM-SIP-3102S, 65 wt.%, 15,000 cP at 50 s$^{-1}$ and DM-SIP-3109S, 85 wt.%, 10,000–15,000 cP at 50 s$^{-1}$) from Dycotec Materials, which showed improved wetting behaviors. Henceforth, the DM-SIP-3102S and 3109S pastes will be referred to as the low silver content paste and the high silver content paste, respectively. The volume resistivity of the DM-SIP-3102S paste is reported at 25 μΩ.cm at 140°C curing temperature. More information on paste properties can be found on the Dycotec Materials website.
2.2 Solar cell prints and solar simulations

After optimizing the printing process on flat and textured silicon substrates with different surface properties, we applied string printing to SHJ solar cells which were from the same fabrication batch as the cells described in Saive et al., using the fabrication method reported in Herasimenka et al. The print design used in this report can be seen in Figure 3A. The locations of the contacts were chosen such that the distance between contacts was equal to twice the spacing between a contact and the edge of the active area. The busbars were also printed using the string-printing method, by applying a larger amount of paste to the string and then approached on top of and perpendicular to the already printed ETCs. Two other print designs were also used and are shown in the Supporting Information.

The current density-voltage (j-V) curves of the solar cells were obtained by using a Wavelabs LED solar simulator SINUS-70 under AM1.5G. The AM1.5G conditions were calibrated using a reference n-type passivated emitter and rear contacted (PERC) cell with class AAA requirements (IEC 60904-9, JIS C8912, ASTM E 927-05 criteria for spectral match, non-uniformity, and temporal stability).

Three types of measurements were performed as shown in Figure 3B–D. In the first measurement, an aperture made of black photo paper was used, which only exposed the active area of the SHJ solar cell excluding the busbars. This mask prevents stray light and photocarrier generation outside of the active area falsifying the j-V curves; second, it allows for a constant active area when comparing the j-V curves of different measurements. Note that on each mask, a small cut-out is made so that contact can be made between a probe and the busbar. Measurements 2 and 3 were performed with the same aperture (i.e., identical mask) which is smaller than in measurement 1. In measurement 2, an area with only ITO remains uncovered, while in measurement 3, the uncovered area contains one ETC. Note that we were unable to measure the j-V curve of an uncontacted cell due to high series resistance. Comparing the j-V characteristics of measurements 2 and 3 allows us to calculate the effective transparency of the uncovered contact. The calculation is performed as follows:

\[ j_{SC2} = \frac{j_{SC2}}{A} \]

where \( j_{SC2} \) represents the short-circuit current density obtained in measurement 2, which is equal to the ratio of the short-circuit current \( j_{SC2} \) and the area of the aperture A. In the same way, \( j_{SC3} \) can be

FIGURE 3 (A) Print design of the SHJ cell measured in Section 3.3 (i.e., SHJ1). (B–D) Schematics of three types of j-V measurements for accurate determination of contact effective transparency. [Colour figure can be viewed at wileyonlinelibrary.com]
calculated from $I_{SC}^3$ obtained in measurement 3 with the same aperture of area A. We can then define a quantity $Q$ as the ratio between the $I_{SC}$ obtained in measurements 3 and 2, respectively:

$$Q = \frac{I_{SC}^3}{I_{SC}^2}$$  \hspace{1cm} (2)

The quantity $Q$ already gives the first indication of how transparent the contacts are. If the contacts are fully transparent, then $Q$ takes the value of unity. On the other hand, if the contacts are fully reflective, $Q$ will be equal to $(1 - C)$, where $C$ is the coverage of silver paste on the active area inside the aperture. Then, we can introduce a final parameter $R$, which gives the redirection efficiency, or in other words the effective transparency of the ETC:

$$R = \frac{Q}{(1 - C)}$$  \hspace{1cm} (3)

This factor shows how much of the light incident on the contact will be redirected towards the solar cell. A value equal to 1 corresponds to a perfectly redirecting contact for which no light is lost, a value of 0 corresponds to the worst contact possible in which all light incident on the contacts is lost.

3 | RESULTS

In this section, we will discuss some of the most important findings, such as the shape dependence on the withdrawal procedure, the aspect ratio, reproducibility, solar cell characteristics, and effective transparency of the string-printed contacts.

3.1 | Withdrawal procedure

Figure 4 shows scanning electron microscope (SEM) images of contacts that were printed with a polypropylene string with a diameter of around 50 $\mu$m, with the low silver content paste, on a silanized, polished silicon wafer. Here, the substrates were silanized to decrease the substrate-paste affinity (i.e., increase the surface energy) in order to increase the impact of the withdrawal procedure on the contact geometry. The contact in Figure 4B was printed with the optimal withdrawal method, and the contact in Figure 4D was printed with the non-optimal method. The optimally printed contact displays a triangular geometry with high A/R for the reasons explained in Section 2.1. The non-optimally printed contact reached the snap-off step too soon, which led to a flat shape. The impact of the contact shape on effective transparencies can qualitatively be observed in FIGURE 4. Optimized (A, B) versus non-optimized withdrawal method (C, D). (A) and (C) show A/R of (B) and (D), respectively. (E) and (F) show reflection microscopy images of (B) and (D), respectively. [Colour figure can be viewed at wileyonlinelibrary.com]
Figure 4E,F, where reflection microscopy images of the two contacts are shown. The bright areas in these two images represent areas of the contact where light is reflected at angles close to normal incidence. As expected, the contact printed with the optimized withdrawal method reflects almost no light back to the source, whereas the non-optimally printed contact reflects more light over a larger area.

3.2 High A/R versus reproducibility

Aspect ratios up to 3.16 were achieved by printing sequentially on the same location (see Figure 5). Here, the contact lines were printed with the high silver content paste, on a textured silicon wafer with a silanized SiNₓ ARC on top, using a 50 µm diameter platinum string. This sequential printing method produced homogeneous prints as can be seen by the different contacts in Figure 5B–D. This method allows for higher A/R prints without being limited by the amount of paste applied to the string. However, increasing the number of sequential prints leads to the loss of the triangular shape and low reproducibility. For the demonstration on SHJ solar cells, we opted for sequentially printing twice, and have achieved high A/R, triangular-shaped contacts. As can be seen in the SEM image in Figure 6, many similar lines

![FIGURE 5](image_url) Different high A/R contacts fabricated by multi-step printing. (A) shows the aspect ratio of (B), obtained by sequentially printing seven times. (C) and (D) were obtained by sequentially printing five times.

![FIGURE 6](image_url) Triangular contacts obtained by sequentially printing twice.
were printed showing robustness and reproducibility of the method. Two busbars were printed on the edge of the wafer perpendicular to the contacts using string-printing (see SEM image in Figure 7).

### 3.3 j-V characteristics and effective contact transparencies

Overall, five SHJ cells were printed and characterized in this study (referred to as SHJ1–5). SHJ1 was printed following the design shown in Figure 3A with 2 ETC contact fingers. The results of SHJ2–5 are shown in the Supporting Information, as no accurate description on the error on these measurements could be provided, unlike with SHJ1. Table 1 summarizes the printing parameters of SHJ1, which was printed the same way as the contacts printed in Figure 6, with the exception that the surface of the solar cell was not silanized.

Table 2 shows the measurement parameters, including the aperture area and the corresponding calculated coverage. Here, we use the effective aperture area, which was obtained by measuring the reference cell (with known $j_{SC}$) under AM1.5G, covered by the aperture used for measurements 2 and 3. The measured $I_{SC}$ then allows us to recalculate the effective aperture area. The coverage was determined using the Image-J software, comparing photographs taken of both measurement configurations 2 and 3, which are available in the Supporting Information. To ensure the validity of the measured $I_{SC}$, the cells were placed at the same height in the solar simulator as when calibrated with the reference cell, such that the number of incoming photons yielding AM1.5G conditions with the reference cell was equal to the amount of photons incident on our string-printed cells during the measurements.

The calculated effective transparency of the string-printed solar cell (SHJ1) is $67\% \pm [−13.6; 10.0]\%$. A large error bar accompanies this result and is caused by two main factors: the error of the measurement and the error on the coverage estimation. A standard deviation of 0.013 mA on the $I_{SC}$ measurement was calculated by performing 10 measurements on the reference solar cell covered by the aperture used for measurements 2 and 3 at AM1.5G. The error on the $I_{SC}$ measurement contributes $6.4\%$ to the total error on the effective transparency. The $I_{SC}$ standard deviation was then used to determine the error on the effective aperture area, which had been recalculated using the solar simulator. The error on the effective aperture area does not have a direct impact on the effective transparency measured, as the identical mask was used to compare measurements 2 and 3. A significant absolute error of $1.55\%$ on the coverage is caused by the large pixel size ($25 \times 25 \text{μm}^2$) of the images taken, which were used in the image-treatment software. This means that the finger width has a $±50\%$ error. The error on the coverage estimation contributes $±[−7.2; 3.6]\%$ to the total error on the effective transparency.

**TABLE 1** Printing parameters of the string-printed SHJ1 cell.

<table>
<thead>
<tr>
<th>Cell</th>
<th>Silanized</th>
<th>Printing temperature (°C)</th>
<th>Sequential printing steps</th>
<th>Post-print curing step</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHJ1</td>
<td>No</td>
<td>50 °C</td>
<td>Two optimized printing steps with high Ag content paste</td>
<td>None</td>
</tr>
</tbody>
</table>

**TABLE 2** j-V characteristics with the corresponding measurement parameters of the string-printed SHJ1 cell.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Effective aperture area (mm²)</th>
<th>Coverage (%)</th>
<th>$V_{OC}$ (mV)</th>
<th>$I_{SC}$ (mA)</th>
<th>FF (%)</th>
<th>Effective transparency (%)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHJ1, Bare ITO</td>
<td>10.52 ± 0.36</td>
<td>0</td>
<td>630.44 ± 0.36</td>
<td>3.793 ± 0.013</td>
<td>71.47 ± 0.05%</td>
<td>/</td>
<td>16.25 ± 0.48</td>
</tr>
<tr>
<td>SHJ1 (measurement 3)</td>
<td>10.52 ± 0.36</td>
<td>10.06 ± 1.55</td>
<td>630.46 ± 0.36</td>
<td>3.667 ± 0.013</td>
<td>70.96 ± 0.05%</td>
<td>67.0 ± [−13.6; 10.0]</td>
<td>15.59 ± 0.46</td>
</tr>
<tr>
<td>SHJ1 (measurement 1)</td>
<td>42.60 ± 0.36</td>
<td>/</td>
<td>690.60 ± 0.36</td>
<td>14.899 ± 0.013</td>
<td>70.72 ± 0.02%</td>
<td>/</td>
<td>17.08 ± 0.12</td>
</tr>
</tbody>
</table>

Note: The bare ITO (measurement 2) measurement was performed in-between two printed contacts of the cell, the SHJ1 (measurement 3) measurement was performed with one contact inside the mask area, and finally, the SHJ1 (measurement 1) measurement was performed with all the contacts inside the mask area. Effective transparency is calculated using the ratio between the $j_{SC}$ obtained from measurement 3 and the $j_{SC}$ obtained from measurement 2 of SHJ1. The overall error on the effective transparency is calculated using the absolute error on the coverage estimation and the absolute error on the measured $I_{SC}$. The standard deviation on the $V_{OC}$ was calculated with the same set of data that was used to calculate the standard deviation of $I_{SC}$.
transparency, when already taking into account the $I_{SC}$ error. Note that the error on the effective transparency does not scale linearly with coverage error and the $I_{SC}$ error (see Equation (3)). For this reason, the error in effective transparency is not symmetrical to 67%.

Table 2 also shows the $j$-$V$ characteristics of the string-printed SHJ1 cell (both measurements 1 and 3) as well as the characteristics of the bare ITO measurement. The full $j$-$V$ curves are displayed in Figure 8. It is clear that the bare ITO has a higher $I_{SC}$ than the contacted cell, due to the absence of reflecting contact lines. The $j_{SC}$ values of the bare ITO are lower than state-of-the-art SHJ solar cells which we attribute to the error on the aperture area, as well as the bluntness of the texturing due to poor storage conditions, rendering the light trapping in the stack less efficient. The measured $V_{OC}$ of measurements 2 (bare ITO) and 3 (single contact line) are lower than of measurement 1 as a smaller area is exposed and therefore, the dark current is higher. The characteristics of the remaining cells (SHJ2–5), as well as their $j$-$V$ curves, are available in the Supporting Information.

3.4 | Miniaturizing the string-printing process

The dimensions of the contacts presented in the previous section were still larger than the dimensions of contacts obtained with state-of-the-art screen printing.\textsuperscript{3,4} Although much higher A/R were obtained with string-printing, the finger width remains too large compared to the screen-printed finger widths. The first step to miniaturization (i.e., reduction of finger width) of the string-printing process was achieved with the upgraded string-printing prototype. As can be seen on Figure 9, high A/R can also be achieved with finger widths comparable to the current state-of-the-art screen-printed contacts.\textsuperscript{3} More efforts will be made to achieve triangular shapes on this scale and on textured substrates.

**FIGURE 8** $j$-$V$ curves of bare ITO and SHJ1 (measurements 1 and 3). The SEM image displays the texture of SHJ1, which is showing some erosion likely due to storage degradation. [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 9** One-step, string-printed contacts on a flat, silanized silicon substrate with the upgraded prototype, using a 25 $\mu$m diameter tungsten string with the low Ag content paste. (A) SEM image of one individual line, printed with optimal withdrawal method. (B) SEM image of the cross-section of (C), showing one individual line, printed with non-optimal withdrawal method. (D) SEM image of several lines showing reproducibility between different prints.

4 | CONCLUSION

We have demonstrated fabrication of high A/R triangular silver front contacts using our novel string-printing method. Aspect ratios of up
to 1 were achieved with a single-step printing procedure and up to 3.16 with multiple prints. It was found that using higher viscosity silver pastes resulted in uninterrupted lines which is an important aspect for scaling up the technology. We investigated the performance of silicon heterojunction (SHJ) solar cells using string-printed contacts and demonstrated up to 67% effective transparency of the contacts. Experimental optimization of the procedure was limited by parameters that could not be controlled with the first prototype, such as the exact quantity of paste applied on the string, as well as its homogeneous spread across the string. We have then demonstrated that with an upgraded prototype, the string-printing process could generate contacts with finger widths comparable to state-of-the-art screen-printed contacts, but with much higher A/R. In our next steps, we will further develop the upgraded string-printing tool focusing on increased reproducibility, and scalability with a one-step printing process as well as improving the contact shape on a miniaturized scale.

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We acknowledge Aaron Chan from Dycotec Materials®, for advising as well as improving the contact shape on a miniaturized scale. Increased reproducibility, and scalability with a one-step printing process could generate contacts with finger widths comparable to state-of-the-art screen-printed contacts, but with much higher A/R. In our next steps, we will further develop the upgraded string-printing tool focusing on increased reproducibility, and scalability with a one-step printing process as well as improving the contact shape on a miniaturized scale.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

SUPPORTING INFORMATION
Additional supporting information can be found online in the Supporting Information section at the end of this article.

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