Screen printing is the most cost effective method for producing c-Si (crystalline silicon) solar cells. Thick film and screen-printing technology are well established and require relatively low capital investment. Solar cells manufactured using this metallization technique are easy to mass produce and are highly reliable with low waste. In the effort to increase efficiencies and advance solar cell technology, novel metallization techniques are being explored. To maintain the advantages of screen printing, thick film materials that produce higher aspect ratios are required.

Solar cell manufacturers have been increasing sheet resistance to improve current and voltage by increasing blue response and decreasing recombination. Narrower finger lines that are spaced closer together are required for the front grid design to account for the higher sheet resistance and allow minimal shading of the light absorbing region. In addition, the cross sectional area of the conductive traces must transport current with low line resistance, so increased height is required. The relation of height versus width is defined as aspect ratio.

There are many other aspects of c-Si solar cells to realize the benefits of higher sheet resistance. But this paper will only be concerned with fine line screen printing and thick film paste.

Thick film and screen-printing technology are challenged with providing materials that achieve high aspect ratios. The solutions must provide viable options for high volume solar cell production, as this is where the advantage is gained over competing technologies.

**Thick Film Technology**

For solar cell metallization applications, thick film paste is a suspension of a functional (conductive) phase, binder, vehicle and additives. Silver is the most common conductive filler used for front contact paste. The binder is composed of a glass frit that is used to bind the functional phase to the silicon wafer. Specialized chemistry of the binder is also required to etch through anti-reflective and passivation layers and initiate effective ohmic contact between the silver and silicon. The
vehicle is an organic composition that provides printability of the pastes and is composed of resins, solvents, and modifiers. The resins support the solids of the other phases and keep them in homogeneous suspension. Solvents are used to dissolve the resins, and they must be stable in production conditions. These organic components of the paste must burn off cleanly in the fast-firing process so as not to contaminate the surface of the wafers or introduce sources of recombination near the p-n junction.

A pseudoplastic (shear thinning) paste rheology is best suited for high aspect ratio printing and is determined by the combination of all paste components. The paste viscosity will decrease as it passes through the screen. As the screen is peeled away from the substrate, the paste will flow together around the mesh while recovering to near resting viscosity. The paste should have minimal slumping for optimal fine line resolution, and it should retain its intended printed height and continuity. Drying of the solvents, burning out of the resins, and sintering of the conductive phase will reduce the wet thickness volume by approximately 50 percent.

Generally, the organic compositions that are best suited for high aspect ratio pastes do not lend themselves to a production environment. As an example, faster drying solvents could give improved slumping characteristics, but they would also lead to clogged screens. Additionally, they may not dissolve resins that burn out cleanly during firing. The organic composition also determines wetting and adhesion to the surface of the wafer and is of great importance. Critical choices in materials must be made to find the best balance of properties for screen printable pastes suitable for high aspect ratios.

The paste must transfer through the mesh material of the screen and the emulsion coating and adhere to the wafer. The surfaces of the wafers are textured to increase the probability of light absorption, and this provides additional difficulty for the screen printing process.

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**Screen Technology**

Screen technology plays an extremely important role in paste transfer. Most solar cell manufacturers use basic screen-printing techniques. A squeegee is used to move paste through a patterned screen to deposit onto the silicon wafer. The squeegee provides shear stress to the paste to reduce viscosity and allows it to flow through the screen. Fine mesh screens allow for the intricate patterns of solar cell grid designs. Stainless steel mesh is used by the majority of solar cell manufacturers for the front side metallization process. Because of its strength, small diameter stainless steel mesh can create larger open areas and higher screen tensions that are favorable over other materials for fine line applications. However, finer diameter wires also lead to lower theoretical line heights which are detrimental to high aspect ratio. For this case, emulsion is added over the mesh (EOM) of the screen to build additional theoretical thickness. The EOM provides a flexible gasket to the wafer, so the paste is deposited only in the area of the exposed pattern. The emulsion will wear during the use of the screen. The lifetime of the screen will be determined primarily by the screen printing parameters of off-contact distance, squeegee durometer, and pressure.

The emulsion is a UV imageable material that has been tailored for solvent resistance, durability, and exposure characteristics. A screen is exposed for a certain amount of time under a UV lamp during the patterning process. Imaging time increases

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<table>
<thead>
<tr>
<th>Mesh Count (wires/in)</th>
<th>Wire Diameter (μm)</th>
<th>Open Area (%)</th>
<th>EOM (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>280</td>
<td>25</td>
<td>52.5</td>
<td>8, 15, 24</td>
</tr>
<tr>
<td>290</td>
<td>20</td>
<td>59.5</td>
<td>9, 19, 24</td>
</tr>
<tr>
<td>360</td>
<td>16</td>
<td>59.8</td>
<td>10, 19, 27</td>
</tr>
<tr>
<td>500</td>
<td>18</td>
<td>41.7</td>
<td>8, 18, 23</td>
</tr>
</tbody>
</table>

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In 2010, SGIA’s Academy of Screen Printing Technology recognized Art Dobie and Dean Buzby with the David Swormstedt Sr. Memorial Award, which selects the best article or technical paper promoting advancements in the screen-printing industry. The article “Fine Line Screen Printing of Thick Film Pastes on Silicon Solar Cells,” first appeared in the Proceedings of the 41st International Symposium on Microelectronics, IMAPS 2008, November 2–6, 2008.
with the mesh count (number of wires per inch or cm) and emulsion thickness. A photopositive is placed in front of the emulsion to block the light from hardening that area. After exposure, the emulsion of the un-reacted area is washed out. This process would be simple if the emulsion were to wash out perfectly in the area blocked by the photopositive. The thicker the emulsion, the more difficult it becomes to accurately and repeatably register the exact finger line width that is desired. Additionally, increased mesh counts and finer wires must be used to be able to hold the intricate patterns.

Screen technology has kept pace with fine line printing to offer a range of products suitable for solar cell applications.

**Experimental Method**

For this study, Sefar Printing Solutions provided a variety of stainless steel meshes and emulsion thicknesses that were used to examine the impact on fine line resolution and aspect ratio. An industry standard paste, Heraeus SOL950, was used for initial testing.

A range of finger line widths from 60–100 µm in increments of 10 µm were designed in a pattern that was printed on one c-Si wafer. Finger lines of the same width were grouped together. The widths were varied at random across the pattern, and two sets of seven-centimeter lines were used to eliminate possible effects from printer setup. Two groups of similar line widths were printed on each wafer resulting in 10 groups of finger lines. Squeegee travel was perpendicular to the finger lines. Multi-crystalline, 156 square millimeters, 200 µm thick wafers were used for this testing. They were surface textured using acidic etching chemistry. The metrics used for comparison were wet paste weight, line width, line height, aspect ratio, and line resistance.

- **Aspect Ratio**: Aspect Ratio was calculated by the following formula: 
  \[ \text{Height (µm)} / \text{Width (µm)} \]
- **Line Width**: Line width was measured in microns using a calibrated PaxCam3 digital camera system with PaxIt software.
- **Line Height**: Line height was measured in microns using a Cyber Vantage Laser Profilometer 3-D measurement system. A 1 cm area on one line from each group of widths was scanned. The average line height was recorded.
- **Line resistance**: Line resistance was measured using a 4-point probe system from GP Solar. The wafers were cut with a dicing saw into 7 cm widths, and each line resistance was measured. Units for line resistance are Ω/cm.

**Results and Discussion**

Percent open area of the particular screen meshes had the largest influence on aspect ratio and line resistance. Line resistance decreased with increasing open area, and the aspect ratio increased. Little variation was seen for aspect ratio and line resistance within the emulsion thicknesses from the

![Open Area v. Rline and Aspect Ratio, 100 µm line](image-url)
same screen mesh. Therefore, the average was taken across all of the emulsion thicknesses.

The open area is the space that the paste would actually pass through. More space will allow more paste to transfer through the screen and adhere to the wafer. A visual comparison of open area can be seen in Figures 2 and 3 for the 280 mesh and 360 mesh respectively. The obstruction by the larger wire diameter is easy to see. Additionally, the area that the larger wire of the 280 mesh occupies near the edges of the finger line makes paste transfer challenging. Both of these screen meshes are used in solar cell manufacturing, but there are cost differences between them. Generally, thinner wire and increased mesh count increase price.

Table 3 provides interesting data to support the influence of open area. Though the theoretical print thickness for the 280 mesh, 24µm EOM is approximately 10 percent higher than the 360 mesh, 27µm EOM, the actual fired film thickness is 17 percent lower.

Theoretical thickness is calculated by: \[
\text{[(2 x wire diameter) x open area %] + EOM}
\]

Despite the thicker EOM, the larger open area of the 360 mesh was more influential on paste transfer.

Figure 4 illustrates the influence of emulsion thickness on line height and aspect ratio. The data did not show a dramatic increase in line height or improvement in aspect ratio by increasing the EOM thickness.

Looking deeper into paste transfer, there are competing forces from the wire mesh, the emulsion sidewalls, and the surface of the wafer for the adhesion of the paste. Figures 5 and 6 provide a good view of the emulsion sidewalls. As evident, the walls are not perfectly smooth, and the paste will adhere to that surface when it passes through the screen. As the emulsion thickness increases, the paste is required to transfer through more of that surface area. Therefore, screens with higher emulsions may not be the best option. A paste chemistry and rheology must be carefully developed to take into account these processing conditions.

Line width data was also examined in this study, but there was no significant difference across either the screen meshes or emulsion thicknesses.

**Conclusion**

Crystalline silicon solar cell manufacturing is moving toward higher sheet resistance emitters to improve conversion efficiencies. The front grid design must be modified to have narrower lines with finer pitch to account for the increased resistance and minimize shading of the cell. Thick film paste formulations and screen technology are challenged with providing these materials with fine line printing capabilities while providing sufficient current transport. Additional line height is required to accomplish this low line resistance, so the aspect ratio of the paste formulation is critical.

The data demonstrated that proper paste transfer is essential to the front grid design for aspect ratio and line resistance. Using
four different mesh count screens, the parameter of percent open area provided the most influence on paste transfer. The testing was performed with one paste of a certain rheology profile, so further investigation with varying pseudoplastic rheology pastes must be explored to further support this evidence.

Acknowledgements
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