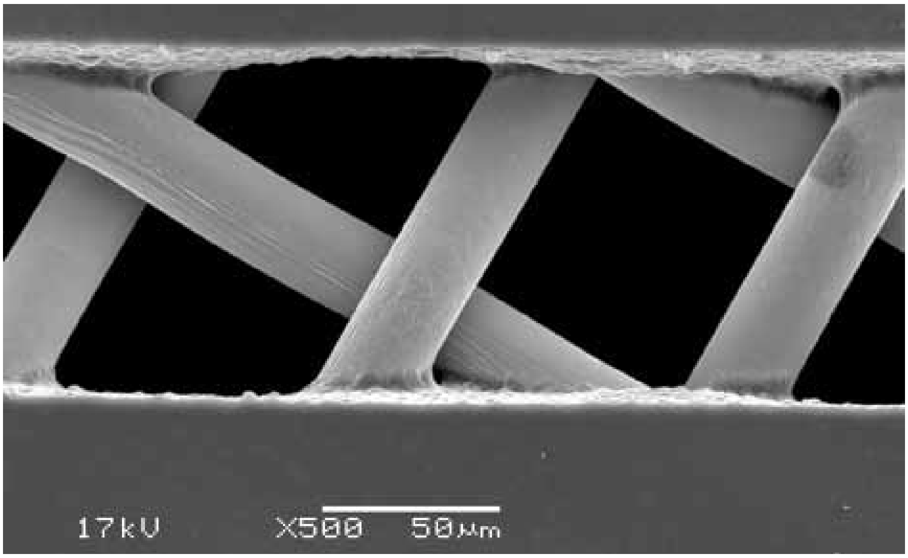
Fine Line Screen Printing of Thick Film Pastes on Silicon Solar Cells



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.

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 paste must maintain good printability throughout the time on the screen, and the screen parameters must allow for high throughput and repeatability of results. Time required for slow printing speeds, changing clogged or broken screens, replacing worn squeegees, or removing damaged wafers are costly procedures for solar cell manufacturers.

The subject of this study is to discuss the interactions of thick film paste and screen-printing technology in the effort to achieve high aspect ratio, fine line patterns.

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

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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.

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.

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

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.

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.

Frame Size	12"x12"
Off-Contact	1.2 mm
Pressure	96 N
Print Speed	200 mm/sec
Squeegee Durometer	80A

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 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

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: Height (μm) / Width (μm)
- **Line Width:** Line width was measured in microns using a calibrated

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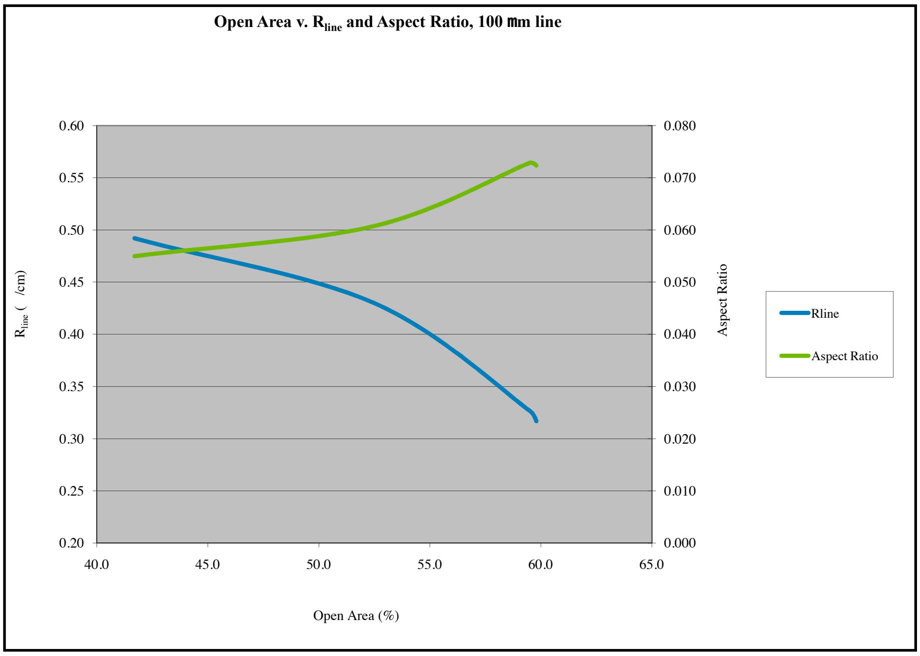

Figure 1: Open Area percent v. Rline and Aspect Ratio. Averaged data from the 100μm finger line openings.

finer wires must be used to be able to hold the intricate patterns.

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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 10μm 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.

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 7cm 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

Time required for slow printing speeds, changing clogged or broken screens, replacing worn squeegees, or removing damaged wafers are costly procedures for solar cell manufacturers.

100µm Finger line	280, 24µm EOM	360, 27µm EOM
Width	104.9	107.6
Height	6.5	7.8
Aspect Ratio	0.062	0.073
Rline	0.43	0.34

Table 3: Comparison of data for 280 mesh and 360 mesh for the highest emulsion thickness.

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.

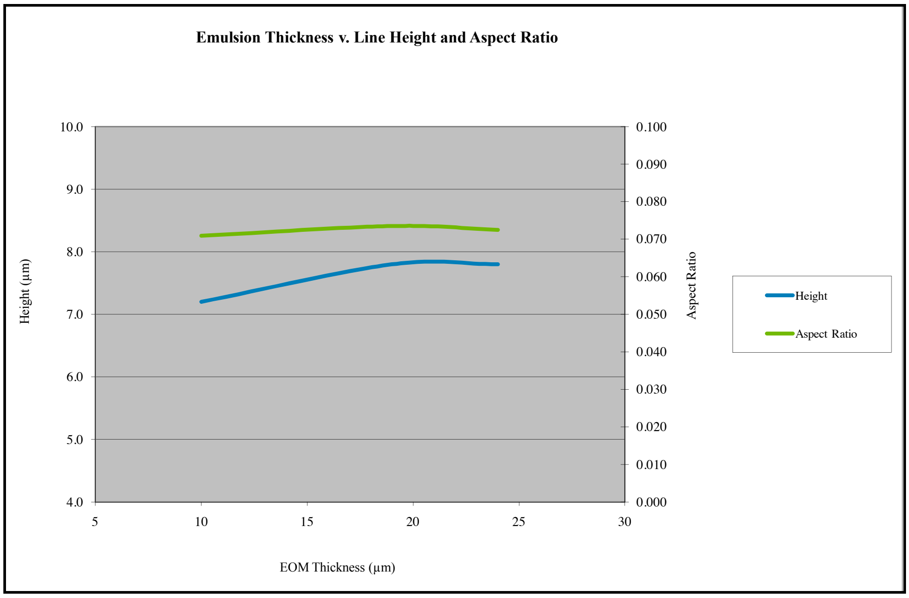

Figure 4: Emulsion Thickness v. Line Height and Aspect Ratio. 360 mesh screen, 15µm wire diameter.

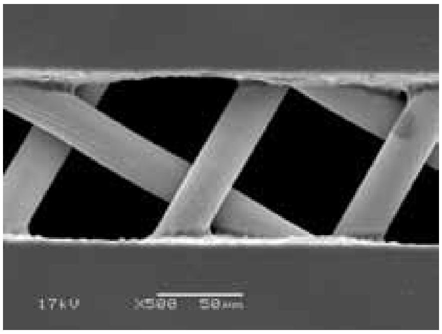

Figure 2: 280 mesh, 25µm wire diameter, 100µm finger line opening, 24µm EOM. Open area is 52.5 percent. SEM photo is directly over finger line opening, 500x.

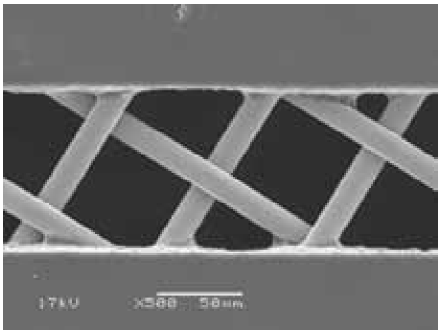

Figure 3: 360 mesh screen, 16µm wire diameter, 100µm finger line opening, 27µm EOM. Open area is 60 percent. SEM photo is directly over finger line opening, 500x.

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: [(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

Thank you to Sefar Inc. for dedicating resources and imparting knowledge for this project, and many thanks to the Heraeus TFD Technical Service Group and the Photovoltaic Group for technical discussions.

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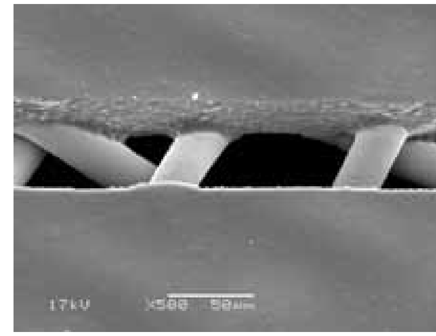

Figure 5: 280 mesh, 25µm wire diameter, 60µm finger line opening, 24µm EOM. SEM photo was taken at 30 degrees from the top view, 500x.

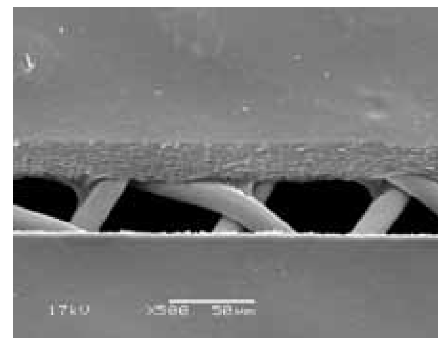

Figure 6: 360 mesh, 15µm wire diameter, 60µm finger line opening, 27µm EOM. SEM photo was taken at 30 percent from the top view, 500x.