Optimal screen mesh, emulsion chemistry and emulsion thickness for fine-line front-contact metallization pastes on crystalline silicon solar cells

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ABSTRACT

A common goal for screen-printable front-contact metallization pastes is to achieve thin and tall gridlines with high aspect ratios, which provide a decrease in grid resistance as well as an increase in short-circuit current via minimizing cell shading. There are, however, several limiting factors that exist in obtaining a high aspect ratio, a key one being screen design. The purpose of this paper is to examine commercially available screen designs (i.e. different mesh, emulsion over mesh (EOM) thickness and emulsion composition) in order to determine the optimal screen design for processing SOL9411, a commercially available Heraeus high aspect ratio front-contact metallization. For this, emulsion has been determined to be a critical component in maintaining a desirable aspect ratio. By optimizing EOM thickness and emulsion chemistry, one can limit the disadvantages of a relatively large open area mesh (line spreading or slumping) without compromising the advantage of such an open area at narrow finger apertures.

Introduction

With silver prices increasing to almost record highs, a heavy emphasis has been placed on decreasing silver usage. One approach to reducing silver consumption is to formulate new front-contact metallization pastes. Perhaps most commonly, materials containing a lower percentage of silver are being developed, but another possibility is to formulate metallization pastes with metals other than silver. However, other costs are incurred when using different metals: for example, Cu materials must be fired in an inert atmosphere using N_2 gas, which becomes costly when running a production facility.

Another approach is to use alternative technologies such as plating or double printing, which require the acquisition of new equipment and materials. Possibly the most cost-effective approach is to optimize processing conditions in order to use less metallization paste while improving cell performance/efficiency with currently available materials such as SOL9411.

This paper outlines process changes used to achieve an increase of approximately 0.3 to 0.6% in absolute cell efficiency while decreasing the Ag paste consumption by ~40%. The process changes include the following:

- Grid design changes
  - 80 → 60μm gridline apertures
  - optimization of gridline count
- Firing optimization using 6300mm/min belt speed
- Screen mesh optimization

Mesh (wires/in)	Wire diameter (μm)	Mesh opening (μm)	Open area (%)	Weave thickness (μm)
280	25	66	53	46–56
325	23	56	50.1	48–56
290	20	69	60	41–48
360	15	56	60	30–41

Table 1. Details of the considered screen meshes.

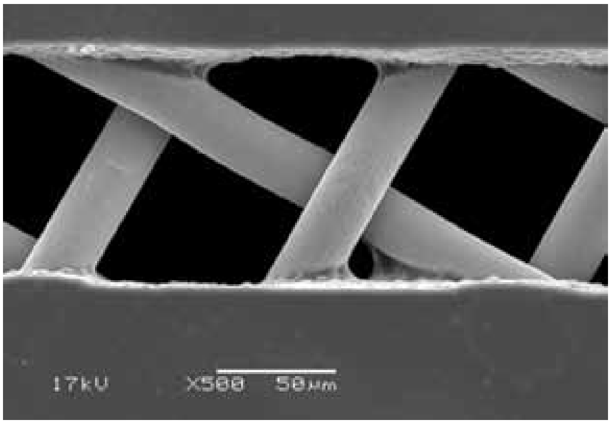


Figure 1. SEM image of 280 mesh: 53% open area.

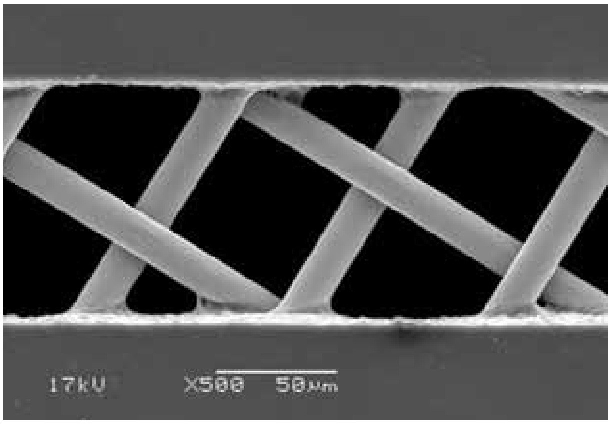


Figure 2. SEM image of 290 mesh: 60% open area.

- Screen emulsion over mesh (EOM) thickness optimization
- Screen emulsion chemistry optimization

Experimental

The wafers used were 156mm^2 commercially available multicrystalline wafers of 70Ω/sq, with a SiN_x anti-reflection coating (ARC). Sample sizes of 12 cells per condition were used throughout the trials. The optimal grid design for these studies was experimentally determined to be 72 gridlines at 60μm each line, with three busbars, as shown in Fig. 3. Gridline counts between 72 and 80 gridlines were considered for the optimization.

Firing conditions were optimized according to the furnace profile in Fig. 4 for both 60 and 80μm grid designs. Each screen

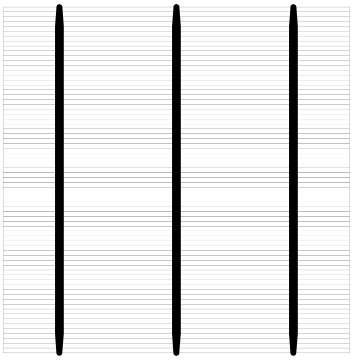


Figure 3. Grid design: 72 lines at 60mm each line with 1.5mm-wide busbars.

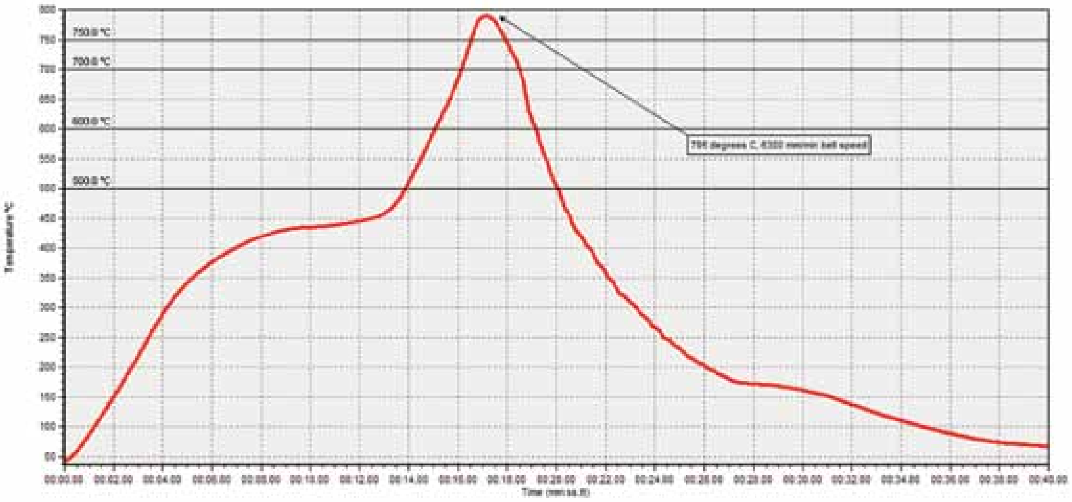


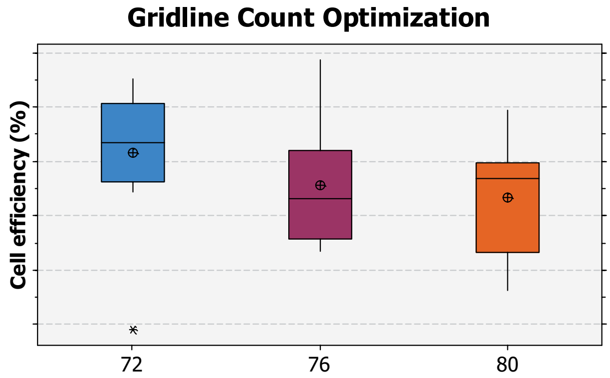
Figure 4. Firing: ~795°C peak, 6300mm/min belt speed.

mesh was tested with 15, 18 and 25µm of E-11 EOM. The four best screens (360 and 290 mesh with 15 and 18µm EOM) were then retested in order to reconfirm the trends from prior testing. After confirming the repeatability of previous trials, the best two screen conditions (360 and 290 mesh with 18µm EOM) were used to compare the effects of varying emulsion chemistry from E-11 to E-80, which are both relatively common photopolymers with slight chemical modifications. Additionally, an 80µm control was tested against a 60µm test screen in order to observe the baseline improvement when only the line width was decreased by 20µm.

Results and discussion

Gridline count optimization

The data in Fig. 5 indicate that 72 gridlines is the optimal gridline count for 60µm lines with SOL9411 and the emitter structure of the specific cells used for these experiments. This ~0.07% increase in absolute cell efficiency when going from 80 to 72 gridlines is mostly driven by a 0.07A increase in short-circuit current (I_{sc}). Paste deposit was also slightly less (~3mg) with 72 gridlines as compared to 80 lines.



Note: Each efficiency tick mark represents 0.1 delta

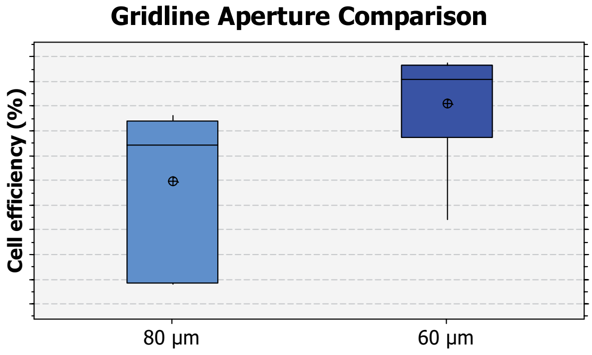
Figure 5. Boxplot of various gridline count results – 72 lines used for remainder of trials.

Gridline aperture comparison

Fig. 6 demonstrates that an increase in absolute cell efficiency of approximately 0.3% can be achieved by decreasing gridline apertures by 20µm, from 80 to 60µm. After decreasing gridline apertures by this amount, a reduction in paste deposit of ~70mg (from 220mg to 150mg) was subsequently observed. These improvements in performance are mainly caused by an increase in I_{sc} and FF.

Screen mesh and EOM thickness optimization

Overall results indicate that cell efficiency does not increase proportionally with aspect ratio ($AR = gridline \times height/width$) in all cases. Rather, cell efficiency was more closely dependent on the percentage of open area of the screen mesh (see Table 1). Table 2, which is arranged by decreasing aspect ratio from top to bottom, confirms that trends in aspect ratio do not necessarily correlate with the observed trends in cell performance as shown in Figs. 6 and 8. For instance, Fig. 8 indicates that 360 mesh/18µm E-80 EOM performs better, achieving an absolute cell efficiency of ~0.05% more than for 290 mesh/18µm E-80 EOM, which correlates with the aspect ratio data in Table 2. However, Table 2 illustrates that 325 mesh/15µm E-11 EOM performs better than 290 mesh/18µm E-11 and E-80 EOM, whereas cell efficiency results in Fig. 6 demonstrate that the opposite trend is observed when considering actual cell performance. Table 2 proves that the standard deviation of line height and width is a better indication of print quality than aspect ratio. For example, the screens with a standard deviation of less than 7.8µm for both width and height of the gridline correlate more closely with screens that produced cells of higher efficiency.



Note: Each efficiency tick mark represents 0.05 delta
Screen used for comparison: 290 mesh, 18 µm EOM

Figure 6. Boxplot of gridline aperture comparison results: ~0.3% increase in absolute cell efficiency.

Further improvement in cell efficiency for each of the considered screen meshes was achieved by varying EOM thickness. Fig. 7 indicates that screen meshes with less than 55% open area performed better with a lower EOM thickness; specifically, 15µm EOM performed better than 18 and 25µm EOM. Additionally, meshes with greater than 55% open area performed the best with 18µm EOM and performed the worst with 25µm EOM.

Emulsion chemistry optimization

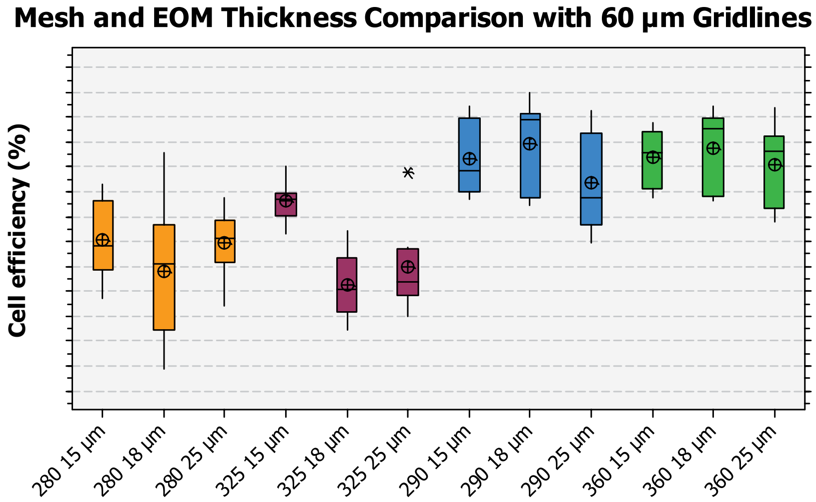
Additional cell efficiency gains were observed when considering different emulsion chemistries. Fig. 8 shows a 0.05–0.28% absolute efficiency increase solely by changing emulsion type. As shown by the results in Fig. 8 and Table 2, slight variations in emulsion composition have been proved to yield improvements in the transfer of Ag metallization at narrow gridline apertures. These improvements are expected to be caused by a decrease

Mesh	EOM thickness [µm]	EOM type	Average line height [µm]	Standard deviation height	Average line width [µm]	Standard deviation width	Aspect ratio
360	18	E80	18.5	7.78	55.5	2.12	0.333
325	15	E11	21	9.9	65.5	4.95	0.321
290	18	E80	22.7	6.08	75	5.66	0.303
360	25	E11	21.5	19.09	77	15.56	0.279
360	15	E11	19	4.24	70.5	4.95	0.27
290	25	E11	18.5	13.44	70	14.14	0.264
280	18	E11	18.5	7.78	70	14.14	0.264
290	18	E11	19.5	6.36	74.5	6.36	0.262
360	18	E11	15	2.83	63	5.66	0.238
280	15	E11	18.5	7.78	78.3	11.67	0.236
290*	15	E11	21.9	8.7	94.2	13.48	0.232
325	25	E11	13.1	7.14	64.6	3.51	0.202
280	25	E11	13.3	8.84	69.5	7.78	0.191
325	18	E11	12.7	7.5	68.5	6.36	0.185

Note: All results are based on a 60µm gridline aperture screen unless otherwise specified.
*80µm gridline aperture.

Table 2. Printability results for various screens, EOM thicknesses and emulsion types.

in standard deviation of gridline height and/or width as shown in Table 2. The root cause of the improvement in material transfer between various emulsions is hypothesized to be more closely related to solvent compatibility (between organics in the screen emulsion and organics in the Ag metallization) than to surface roughness or gridline resolution of the emulsion, as



Note: Each efficiency tick mark represents 0.05 delta

Figure 7. Boxplot of screen mesh and EOM thickness matrix results.

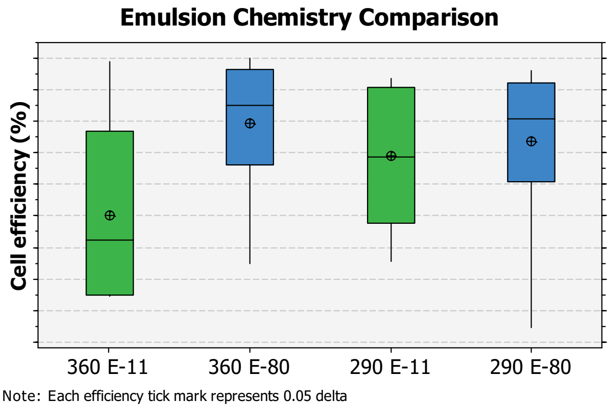


Figure 8. Boxplot of results from emulsion type comparison: E-11 vs. E-80.

different wetting characteristics were observed while screen printing the different emulsions.

Conclusions

Cell efficiency was observed to increase proportionally with the percentage of open area of mesh (as opposed to aspect ratio), and minimizing the standard deviation in gridline dimensions was determined to be critical to improving cell performance. Additionally, 18µm EOM was established to be the optimal emulsion thickness for printing 60µm gridlines with meshes having a greater than 55% open area (in this case 290 and 360 mesh); 25µm EOM was found to perform the worst. Further improvements were measured by optimizing emulsion chemistry. Aside from efficiency gains, 290 mesh screens have been successfully used in high-throughput cell production. When combined with a 60µm grid, the use of 290 mesh screens can significantly decrease paste consumption, which greatly improves the cost per watt ratio. This exemplifies two major, industry-wide goals of decreasing Ag consumption and improving cell efficiency in order to significantly improve the cost per watt ratio. Although performance gains were observed when varying emulsion chemistry, further work is needed in order to determine the root causes of these benefits. Reported gains were achieved with SOL9411, a Heraeus metallization that is widely used by cell manufacturers across the world.

The next steps are to repeat these experiments with mesh types commonly available in different regions of the world, as well as attempting to further decrease the consumption of Ag metallization via paste formulation and grid design. Additional analyses (such as contact resistance/resistivity, SEM cross-section and etch-back analysis) of current and future samples are also planned.

Acknowledgements

The entire Heraeus team are thanked for their expertise and support throughout the duration of these experiments and analyses. Thanks are also given to the members of the Sefar team involved in screen preparation, and for providing materials and information pertaining to these experiments.

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