

ADVANTAGES OF HIGH ASPECT RATIO SCREEN-PRINTED SILVER LINES PRODUCED WITH HOT MELT TECHNOLOGY

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ABSTRACT: The use of Hot Melt technology in solar cell manufacturing achieves high aspect ratio silver lines that increase solar cell efficiencies due to reduced series resistance. This paper examines the relationship between aspect ratio and screen line width of fine Hot Melt lines after firing. The results demonstrate excellent print behavior for screen line widths down to 60 μm where aspect ratios over 0.20 with maximum values approaching 0.26 were observed in this study. The performance of solar cells using conventional ink and Hot Melt technology with 80 μm screen line widths are compared. Hot Melt technology enabled a relative improvement of 3.7% for the fill factor and 1.8% for the overall efficiency compared to reference cells utilizing standard screen printing.

Keywords: Screen printing, Contact, Characterization

1 INTRODUCTION

The use of Hot Melt technology for electrode printing in wafer-based solar cells is a promising approach to increase conversion efficiency and reduce both capital and manufacturing costs. This paper investigates the properties of high aspect ratio Hot Melt silver (Ag) lines as a function of screen line width. Various features of the Hot Melt process have been reported [1,2,3]. These publications have illustrated the importance of printing process variables such as the temperature settings of the heated screen, print stage and squeegee. When these variables are controlled aspect ratio value gains can be realized. It has been shown that an aspect ratio of 0.3 can be achieved after firing [3].

This paper will examine the relationship between screen line width and aspect ratio. The focus is on the capability of Hot Melt technology to be used in applications below the industry standard screen line width of 100 μm . The shape of Hot Melt lines after firing is analyzed as a function of screen opening. The use of both surface scanning and cross-sectional microscopy techniques yields understanding of the line properties and processes that occur during firing. The paper concludes with a comparison of solar cells containing a front Ag grid with 80 μm wide Hot Melt fingers against reference cells with a standard grid.

2 EXPERIMENTAL METHODS

2.1 Printing process

The use of a solvent with a melting point above ambient temperature allows Hot Melt pastes to be printed without intermediate drying steps. Typically the melting point for the front contact and back busbar Hot Melt pastes are 70°C and 55°C, respectively. This avoids remelting of the front contact printed in the first step when printing the back busbars in the second step. Ferro currently offers silver (Ag) Hot Melt pastes and can supply aluminum (Al) Hot Melt pastes. In conventional practices the Al backside coating is printed in the last print stage so that the layer can be dried in the first zones of the co-firing furnace. Ag Hot Melt pastes facilitate the elimination of all drying stations in a print line and, hence, may lead to a considerable reduction in capital

and processing costs while increasing utilization and yield attributed to fewer process steps and less wafer handling. Temperature settings for the screen, table and squeegee are critical to achieve optimal print quality. Both experimental tests and production operations confirm that the paste temperature, which is determined by the temperature of the screen and the squeegee, yields the best printing behavior a few degrees above the pastes' melting point. The temperature of the table has the largest influence on the aspect ratio of the printed lines.

Once optimal settings were found different FERRO sites were able to obtain reproducible print results using a variety of equipment suppliers which has since been confirmed in production environments. The uniformity of the screen temperature was found to be an important parameter to control. In order to enable fast and uniform temperature control a 12x12 inch screen requires 40 A and 12 V.

In this work we have focused on the standard front Ag Hot Melt paste NS33-552. Table I provides the temperature settings that have yielded optimal print results for this paste in various experiments.

Table I: Temperatures for Front Ag Hot Melt printing

Printer	Actual temperature (°C)
Screen	75 \pm 5
Paste	75 \pm 2
Table	70 \pm 5
Squeegee	60 \pm 5

We note that table temperatures below 65 °C can be used as well. This might lead to large line heights as a result of instantaneous solidification of the Hot Melt paste on the relatively cold wafer surface. However, this rapid solidification process that is on the order of less than one second may not enable stable process control and therefore our guidelines include the use of table temperatures greater than 65 °C to avoid issues with uniformity and reproducibility. Use of high table temperatures greater than 75 °C may lead to loss of aspect ratio due to enhanced line spreading. When printing the front Ag Hot Melt grid it is recommended to use a screen with a wire diameter of 25 μm or smaller in order to enable optimal paste transfer. Our guideline is to

use either 280 mesh combined with 25 μm wire diameter or 300 mesh combined with 20 μm wire diameter.

2.2 Effect of screen line width

The viscosity of Hot Melt pastes can be controlled by the screen temperature (see Figure 1). Processing conditions can be adjusted to yield enhanced paste transfer at small line openings in the screen and accommodate a range of squeegee speeds and pressures.

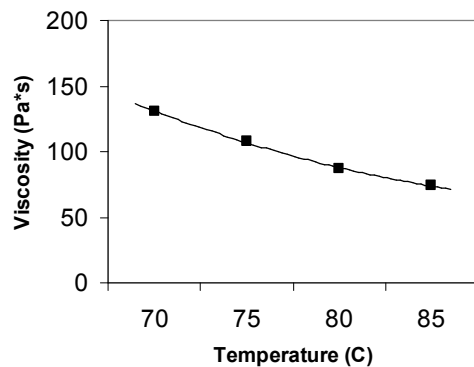


Figure 1: Typical viscosity behavior of front Ag Hot Melt paste as function of temperature.

In order to investigate the effect of paste transfer as a function of line opening a print experiment was conducted with variable screen line widths between 65 μm and 105 μm . As a substrate 156 mm^2 acid-textured multi-crystalline silicon wafers were used. After printing at pre-optimized settings the wafers were fired in a three-zone infrared heated firing furnace. The samples were fired with the Hot Melt grid face-down since this is known to yield a slightly higher aspect ratio compared to face-up due to minimal line spreading in the temperature ramp-up phase [3]. Apart from performing 2-D and 3-D surface scans a number of samples were selected for cross-sectional analysis in order to get a clear view of the shape of the finger lines.

2.3 Solar cell run

A set of solar cells with Hot Melt front side Ag were prepared using 156 mm^2 acid-textured multi-crystalline wafers with an emitter sheet resistivity of 65 Ω/\square . The front grid was prepared with the optimized settings found in the previous section. The screen line width of the grid lines was 80 μm . The performance of the Hot Melt cells was compared to standard cells with 80 μm wide front Ag grid lines with a standard ink version of NS 33-552.

3 RESULTS & DISCUSSION

3.1 Effect of screen line width

In order to obtain a complete picture of the line morphology we obtained plan and three-dimensional views before and after firing. Figures 2 and 3 show typical examples for a Hot Melt line printed with 85 μm screen line width.

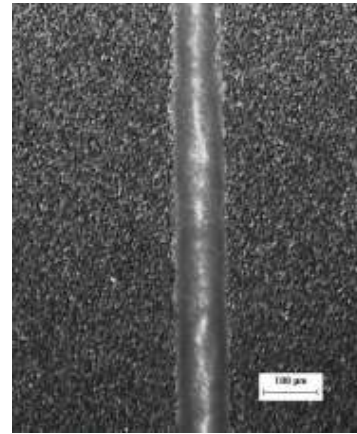


Figure 2: Plan view of Hot Melt finger printed with 85 μm screen line width before firing.

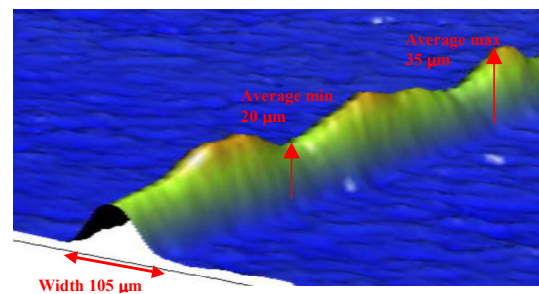


Figure 3: 3-D micrograph of Hot Melt finger printed with 85 μm screen line width after firing.

Aspect ratio analysis of fired cells can be subjective, which is illustrated by Figure 4. Line width measurements of fired finger lines should include the areas along the edges of the line referred to as 'bleeding'. If these areas are not taken into account the reported aspect ratio could be up to 20% larger than its actual value. The aspect ratio values reported in this paper are based upon maximum line width values, including 'bleeding' areas when applicable, at all times.

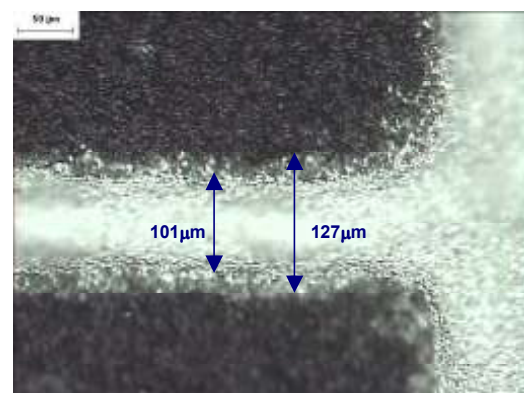


Figure 4: 'Bleeding' effects that may occur at the edges of fired lines. The recorded line width should be 127 μm .

Directly after printing aspect ratio values up to 0.5 are observed for Hot Melt lines caused by the

instantaneous solidification of the ink on the wafer. Table II shows the average values for line width and line height obtained for Hot Melt lines after firing. The sintering of Ag particles inside the paste leads to post-firing values over 0.20 for all screen line widths provided in Table II. No appreciable gains in aspect ratio were realized with screen line widths under 75 μm in our study, yet difficulties with printing at these narrow screen line widths were not encountered.

Table II: Line width and line height after firing (μm)

Screen width	Fired width	Fired height	Aspect ratio
65	100 ± 6	23 ± 5	0.23
75	99 ± 7	24 ± 5	0.24
80	109 ± 10	28 ± 6	0.26
85	107 ± 10	26 ± 6	0.24
105	131 ± 10	27 ± 6	0.21

Figure 5 shows typical cross sectional micrographs of Hot Melt front Ag lines for different line widths. The pictures demonstrate that the overall shape of the fired lines do not depend on the screen line width for values down to 65 μm .

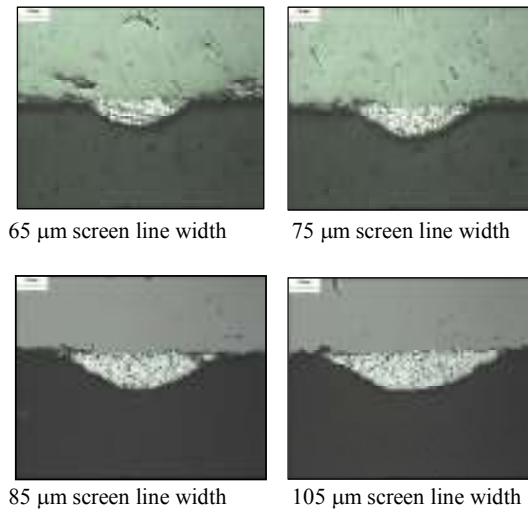


Figure 5: Cross sections of fired Hot Melt front Ag lines

The results demonstrate that Hot Melt technology is capable of producing finger lines with high aspect ratio of over 0.20 for all screen line widths. The use of narrow screen line widths in the range of 65 – 75 μm yielded fired line widths of approximately 20 μm narrower than the industrial standard while maintaining excellent line height. On the cell level this has the potential to reduce shadow losses resulting in enhanced short circuit current without compromising series resistance. The aspect ratio values of Hot Melt lines after firing are up to 50% higher than those reported with standard screen printing.

3.2 Solar cell results

As described in section 2.3 a series of solar cells with 80 μm finger width were produced. One group was made using a conventional Ferro front Ag paste, NS 33-502, that provides excellent contact with emitters under 70 Ω/\square , and the second group with the Hot Melt version of

NS 33-502, the NS 33-552. The group size was 45 cells each. After firing at pre-optimized settings the IV performance of each group were measured that is compared in Table III. The following trends were noted:

- The Hot Melt cells yield nearly 20% lower series resistance than the reference cells which results in a 3.7% higher fill factor FF. This is the direct result of enhanced fine line printability and high aspect ratio which was also confirmed by approximately 40% higher line resistance for the reference cells compared to the Hot Melt cells.
- The deposition of standard paste through 80 μm screen opening was more challenging and resulted in poor paste transfer compared to the Hot Melt paste. This yielded a smaller line width for the reference paste after sintering resulting in slightly higher V_{oc} and I_{sc} values in this particular experiment.
- The overall efficiency gain is 1.8% relative for the Hot Melt cells, showing that the improved FF is the overall dominating factor.

Table III: Relative IV output of cells with Hot Melt front Ag compared to reference cells with 80 μm screen line width (45 cells each)

V_{oc}	I_{sc}	FF	R_s	Eff.
-0.4%	-1.5%	+3.7%	-19.2%	+1.8%

Given the promising results described in this paper we plan to continue our investigation to achieve fine Ag lines without loss of aspect ratio to further characterize the benefits of Hot Melt technology for high efficiency cell concepts. Emphasis will be placed on maintaining narrow Ag lines during firing, thereby targeting on both a higher fill factor and short circuit current, as the Hot Melt pastes did not present printing challenges at narrow screen line widths.

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4 REFERENCES

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