A SCREEN PRINTABLE FRONT SIDE SILVER CONDUCTOR PASTE ACHIEVING HIGH ASPECT RATIO FINGER LINES FOR SOLAR CELL APPLICATIONS

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ABSTRACT: Screen printing is still the most cost effective and dominant technology used in the solar cell industry for front side metallization. In this paper, we discuss our approach of developing a silver paste which is capable of achieving high aspect ratio finger lines using a standard industrial screen printer. Many factors affecting the aspect ratio were studied: screen parameters (emulsion thickness, wire diameter, mesh count, and weave), printing parameters (pressure, downstop, speed, snap off, squeegee hardness), and paste formulation. The paste formulation played a critical role in building extremely thick prints and fine line resolution. Our paste formulation coupled with the optimization of these factors produced a dried finger line thickness of 42 ± 5 µm, a dried line width of 108 ± 6 µm, and a fired thickness of 31 ± 4 µm, while a reference paste gave a dried thickness of 25 ± 4 µm, a dried line width of 116 ± 6 µm, and a fired thickness of 17 ± 3 µm. The electrical performance of the cells that were screen-printed with this high aspect ratio paste was better than that of the reference paste; the high aspect ratio paste showed a fill factor and efficiency of 0.5-2% and 0.2-0.6% greater than the reference paste, respectively, mainly due to lower cell series resistance of high aspect ratio finger lines.

Key words: front side Ag paste, high aspect ratio, efficiencies, screen printing, photovoltaic

1 INTRODUCTION

Increasing solar cell efficiency is at the forefront of photovoltaic research. Narrowing front side Ag finger width for reducing shading loss is one of the key approaches to boost output current density, and thus, efficiency. Unfortunately, due to the limitations of current commercial paste performance and screen printing technology, narrow finger width is usually achieved at the expense of finger thickness. This reduction in finger thickness could significantly increase cell series resistance, thus decrease fill factor and, ultimately, efficiency. Alternatives to screen printing techniques such as ink jet printing and plating were introduced into the solar cell industry in attempts to address this issue, but long term reliability and the scale-up capability of these techniques remain questionable.

In this paper, a new screen-printable paste is introduced that exhibits an extremely high aspect ratio lines, and thus, a high fill factor and high efficiency.

2 EXPERIMENTAL PROCEDURE

2.1 Process and Equipment

Typical non-textured multi-crystalline wafers were used in the study. The lifetimes of all wafers were determined with the WCT-120 Silicon Wafer Lifetime Tester from Sinton Consulting; only wafers with similar lifetimes were chosen for this study. Two solar cell pastes were compared. The first paste was one of our own commercial products used as the "reference" paste. The second was a newly developed paste called CL80-9154. The pastes were printed on the wafers using the X1-SL screen printer from EKRA. Printed wafers were dried in an oven at 150 ^oC for 10 minutes, and then fired in an IR Furnace from BTU with different temperature profiles. Finger line thicknesses and widths were measured using the Cyberscan Vantage 50 from Cyber Technologies and PAXcam, respectively. Cell efficiency and fill factor were measured with Solar Cell & Module Test Equipment from PV Measurements. For adhesion testing, tinned copper wire was hand-soldered to the silver on the finished wafers. The soldering iron was operated at about 400^oC using the solder Sn62/Pb36/Ag2. The solder was about 15-20 mm thick. In order to prevent fracturing of the silicon wafer during adhesion testing, the wafers were glued to alumina substrates and heat treated at 125 ^oC for >30 minutes. After cooling, the wafers were tested for silver adhesion with the Carrier Tape Peel Force Tester PFT-500. SEM photos were taken with the JSM-6060 from JEOL.

2.2 Formulations

The reference paste formulation was modified significantly in order to obtain the formulation for CL80-9154. For instance, as seen in Table 1, the reference paste contains ingredient C while CL80-9154 contains ingredients A and B instead.

Table 1. Paste Formulations.

Ingredients	Reference	CL80-9154
Ag	Yes	Yes
Glass	Yes	Yes
Ingredient A	No	Yes
Ingredient B	No	Yes
Ingredient C	Yes	No
Other Ingredients	Yes	Yes

2.3 Screen and Printing Parameters

Different screen and printing parameters were studied in order to print lines with high aspect ratios and low standard deviations. The aspect ratio is defined as the finger height divided by the finger width. The parameters were optimized for each paste as seen in Table 2 and Table 3. The parameters vary between each paste. For instance, we have found that a screen with a thicker emulsion helps to increase wet film thickness for CL80-9154. However, for the reference paste, a thicker emulsion hinders the transfer of the reference paste, resulting in a poor aspect ratio lines and even worse electric performance.

Table 2. Screen Parameters.

	Reference	CL80-9154
Emulsion Thickness	0.7 mil	1.3 mil
Wire Diameter	1.3 mil	0.9 mil
Mesh (wires/inch)	280	325
Weave	30 °	22.5 °
Line Opening	100 µm	100 µm

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Table 3. Printing Parameters.

	Reference	CL80-9154
Pressure	1.2 bar	1.2 bar
Downstop	33 µm	23 µm
Speed	200 mm/s	200 mm/s
Snapoff	1.3 mm	1.3 mm
Squeegee Hardness	70A	80A
Squeegee Angle	50 °	45 °

2.4 Firing Profiles

Different firing profiles were used for each paste. Set points of a typical firing profile are shown in Table 4, while the corresponding profile is shown in Figure 1.

Table 4. Set points of a typical firing profile.

Zone	Set point	Gain	Integral	Derivative
1	520 °C	10	30	0
2	590 °C	10	40	0
3	600 °C	15	30	0
4	660 °C	10	30	0
5	830 °C	10	30	0
6	860 °C	10	30	0

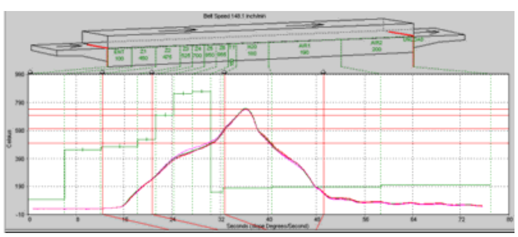

Figure 1. A typical firing profile.

3 RESULTS

3.1 SEM Cross Sections of Printed Finger Lines

SEM cross sections of the printed finger lines of CL80-9154 and the reference paste can be seen in Figures 2 and 3, respectively. It can be seen that CL80-9154 has a much higher thickness and narrower line width, or a much greater aspect ratio than the reference paste. Also, its cross sectional profile looks very different than the reference paste.

3.2 Profiles of Printed Finger Lines

An SEM top view of a printed finger line of CL80-9154 can be seen in Figure 4, with its Cyberscan profile shown in Figure 5. These figures further demonstrate the high aspect ratio achieved with CL80-9154.

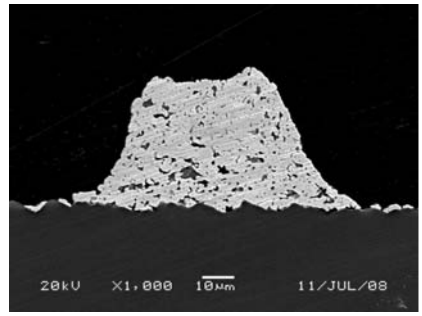

Figure 2. SEM cross section of CL80-9154 on a solar cell wafer.

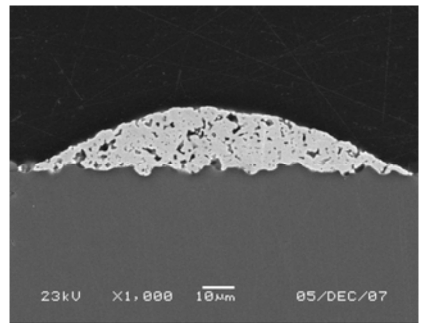

Figure 3. SEM cross section of the reference paste on a solar cell wafer.

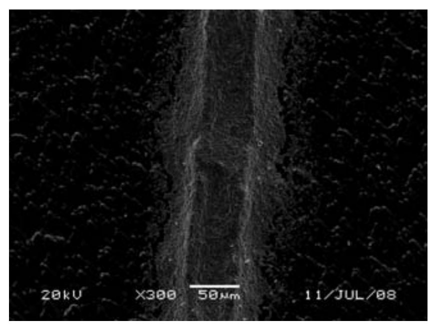

Figure 4. SEM top view of a printed line of CL80-9154 on a solar cell wafer.

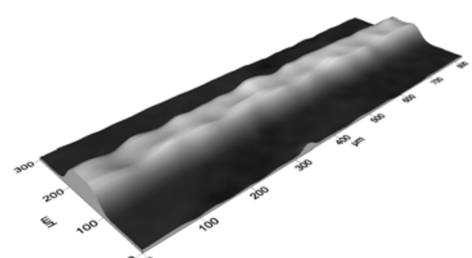

Figure 5. Cyberscan of a printed line of CL80-9154 on a solar cell wafer.

Images observed through a stereoscope of the printed finger lines of the reference paste and CL80-9154 are displayed in Figure 6 and Figure 7, respectively. Both materials printed smooth lines while CL80-9154 had a profile like “The Great Wall”.

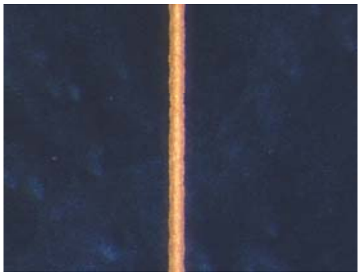

Figure 6. Printed line of the reference paste on a wafer.

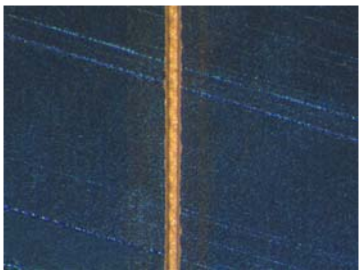

Figure 7. Printed line of CL80-9154 on a wafer.

3.3 Line Thicknesses, Widths, and Aspect Ratios

The printed line thicknesses and widths are listed in Tables 5 and 6, respectively. This gives an average aspect ratio of 0.147 for the reference paste and a value of 0.287 for CL80-9154.

Table 5. Line thicknesses.

	Reference Thickness (µm)		CL80-9154 Thickness (µm)	
	Dried	**Fired**	**Dried**	**Fired**
	23	16	37	33
	22	15	34	28
	26	14	40	36
	25	22	45	32
	23	14	44	29
	22	17	48	40
	30	19	44	25
	32	22	42	26
	23	17	46	33
	34	21	45	27
	21	17	39	26
	29	15	51	28
	21	16	34	30
	24	10	41	32
	22	22	47	38
	19	14	42	36
	25	12	46	26
	21	19	36	30
	23	18	35	36
	35	12	40	33
Average	**25**	**17**	**42**	**31**
STD	**4**	**3**	**5**	**4**

Table 6. Line widths.

	Reference		CL80-9154	
	Width (µm)	STD (µm)	Width (µm)	STD (µm)
	118	6	109	6
	114	5	107	6
	116	6	108	6
Average	**116**	**6**	**108**	**6**

3.4 Line Resistance and Contact Resistance

The finger line resistance and contact resistance were measured. The results are listed in Table 7. CL80-9154 had much lower line resistance and contact resistance than the reference.

Table 7. Line resistance and contact resistance.

	Reference	**CL80-9154**
Line R (Ω/cm)	0.27 ± 0.04	0.17 ± 0.01
Contact R (Ω)	1.07 ± 0.48	0.81 ± 0.24

3.5 Electrical Performance

Electrical performance was evaluated for CL80-9154 and the reference paste. CL80-9154 displays a fill factor and efficiency in the range of 0.5-2% and 0.2-0.6% greater than the reference paste, respectively. Typical electrical performance data on one of non-textured multi-crystalline wafers are listed in Table 8. The data show that the new paste, CL80-9154, has a higher fill factor and efficiency than the reference paste.

Table 8. Typical electrical performance on non-textured multi-crystalline wafers.

	Reference	**CL80-9154**
J_{sc} (mA/cm^2)	31.05	31.16
I_{sc} (A)	7.532	7.558
V_{oc} (V)	0.6056	0.6095
Fill Factor (%)	77.38	78.01
Efficiency (%)	14.55	14.81

3.6 Bus Bar Line Adhesion and Solderability

A comparison of the printed bus bar line adhesion of CL80-9154 and the reference paste is shown in Table 9. Solderability of CL80-9154 is shown in Figure 8. These figures show that CL80-9154 provided good adhesion and solderability as well.

Table 9. Comparison of bus bar line adhesion.

	Reference	**CL80-9154**
Adhesion (g)	513 ± 66	738 ± 50

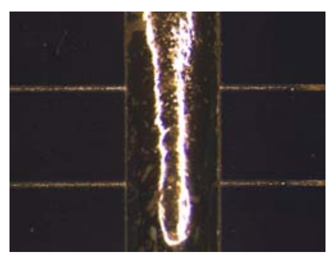

Figure 8. Bus bar solderability of CL80-9154.

4 SUMMARY

A new silver paste for solar cell front side metallization was developed and printed on solar cell wafers using a typical screen printer. The new paste printed lines with much higher aspect ratios such as “The Great Wall”, which provided lower series resistance, higher cell fill factor and higher efficiency than the reference paste. The printed bus bar also provided good solderability and adhesion.