HIGH EFFICIENCIES ON LARGE AREA SCREEN PRINTED SILICON SOLAR CELLS AND CONTACTING HIGH SHEET RESISTANCE EMITTERS USING HOTMELT INK

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ABSTRACT: This paper presents an update on current investigations of the hotmelt technology at Fraunhofer ISE. Efficiencies up to 18% with fill factors of 79.5% on large area industrially pre-processed monocrystalline wafers were achieved. In order to further increase the efficiency, V_{oc} and j_{sc} need to be improved, by e.g. reducing the doping level of the emitter. Solar cells with an average emitter sheet resistance up to 75 Ω/sq could be successfully contacted with hotmelt ink achieving fill factors up to 78%. These cells clearly showed an improvement in the short circuit current density compared to solar cells with a higher doped emitter. In a further investigation the ability of fine line printing has been analyzed.

Keywords: metallization, hotmelt, screen print

1 INTRODUCTION

In industrial production the most applied technique for the front side metallization of silicon solar cells is still screen printing, a reliable and well-known process with high throughput rates. Admittedly, the conventional screen print is limited, e.g. in attaining a high aspect (height to width) ratio of the final contact.

When using hotmelt ink for the front side metallization of silicon solar cells, higher aspect ratios can be achieved, reducing the line resistivity and hence the series resistance significantly. Thus fill factors over 80% for large area silicon solar cells with efficiencies up to 18% were achieved [1].

To further increase the efficiency of screen printed silicon solar cells, the open circuit voltage V_{oc} and the short circuit current density j_{sc} need to be improved. Focussing on the front side, this can be achieved by using lower doped emitters. However, due to less doping the series resistance of the solar cell rises, causing the fill factor to decline. One effect is that the contribution of the emitter sheet resistance to the total series resistance increases: This could be compensated by reducing the finger separation distance. But at the same time the line width needs to be reduced in order not to increase the shading loss.

The more significant effect is the difficulty to form a good electrical contact to the emitter. The contact resistance between finger and emitter rises and is at some doping level the limiting factor [2]. To utilize the advantages of lowly doped emitters, the formation of selective emitters could be an alternative to avoid contact resistance problems [3]. Nevertheless, this leads to additional process steps.

Another approach is to optimize the overall metallization process to form a contact of good quality to lowly doped emitters. This is currently under extensive investigation. Within the last years the standard sheet resistance emitter in industry increased from about 40 Ω/sq to currently 55 Ω/sq, which is mainly due to an improvement in the front side metallization paste.

This paper presents an update about current investigations in the field of hotmelt technology at Fraunhofer ISE. This includes cell results on large area silicon solar cells, current work about contacting high sheet resistance emitters and fine line printing using the hotmelt technology.

2 HOTMELT TECHNOLOGY

The hotmelt ink is solid at room temperature and can be processed as conventional ink when melted on a resistively heated Hotscreen [1,4,5]. Due to different paste properties compared to conventional ink, and the different printing processes applied, high aspect ratios can be achieved. Figure 1 shows a cross section of a printed and fired contact finger attained, using the hotmelt and the conventional technology. Whereas the finger width of 120 µm is the same, the height of 30 µm for the hotmelt printed contact is far higher than for the conventional printed with a maximum height of 13 µm. Electrical analysis shows, that the line resistance of 14 Ω/m is less than 50% of the 34 Ω/m of the conventional printed finger, mainly due to the larger cross section area.

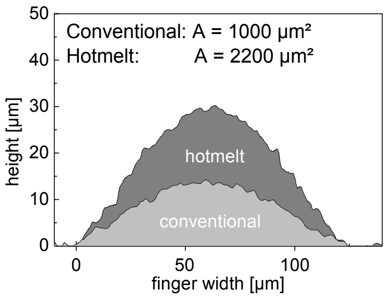

Figure 1: Cross sections of contact fingers formed by the hotmelt and the conventional technology.

Optical analysis have shown that the finger height of the hotmelt finger before the firing process is about twice as high as for conventional printed fingers; the main reason for the higher aspect ratio of the final contact finger.

Another reason for the higher aspect ratio is the higher silver content of the hotmelt ink. Figure 2 shows a thermo gravimetric analysis of a hotmelt and a conventional screen printing ink. At a temperature above 390°C for the conventional and above 510°C for the hotmelt ink, all solvents and organic compounds in the ink are evaporated. The non-volatile components of 89 m% (mass percent) for the hotmelt ink are 5 m% higher than for the conventional. Assuming that mainly silver is the remaining part and the finger height was the same before the temperature process, the final contact would have about 33% more volume.

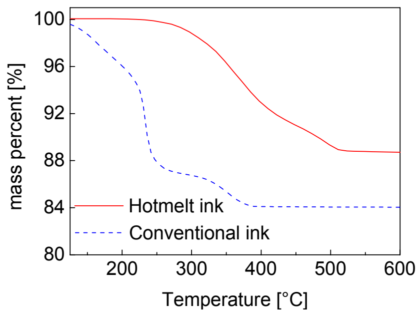

Figure 2: Thermo gravimetric analysis of hotmelt and conventional ink.

3 LARGE AREA SILICON SOLAR CELLS

3.1 Monocrystalline Silicon Solar Cells

125 x 125 mm² textured monocrystalline silicon solar cells with a sheet resistivity of 40 Ω/sq and 55 Ω/sq were processed as shown in the process flow diagram of Figure 3. The solar cells were pre-processed in an industrial line including the antireflection coating. After conventional screen printing and drying of the backside, the front grid was printed with hotmelt ink. Finally the wafers were co-fired in an inline fast firing furnace and edge isolated by laser scribing and breaking.

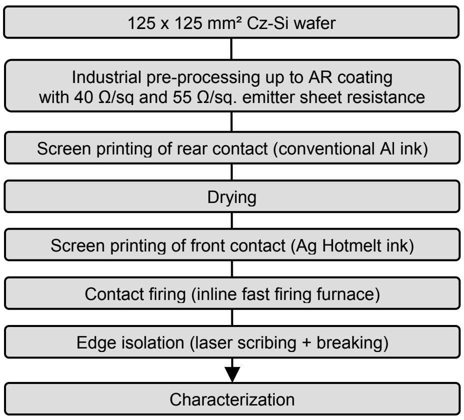

Figure 3: Flow diagram of the processed Cz-Si solar cells with hotmelt screen printed front contacts.

The results are summarized in Table 1. High efficiencies up to 18.0% for solar cells with a 55 Ω/sq emitter sheet resistivity and up to 17.8% for the 40 Ω/sq were achieved (see Table 1). The average efficiency of 17.9% for 12 solar cells processed under the same conditions clearly states the reproducibility of the process on a high level.

Comparing the IV-parameters of the solar cells with the 55 Ω/sq emitter with the 40 Ω/sq emitter, the open circuit voltage nearly remains the same, whereas the remarkable high fill factor of 79.4% drops by about 0.6% relative to 78.9%. This is due to the increased contact and emitter sheet resistance, which also increases the series resistance of the solar cell. However, the short circuit current increases by 1.7% relative due to the improved internal quantum efficiency in the short wavelength region (compare Figure 5). This significant increase in j_{sc} surpasses the loss in fill factor and results in an efficiency increase of 1.1% relative.

Table 1: IV parameters of 125 x 125 mm² Cz-Si solar cells with front contacts printed with hotmelt ink featuring an emitter sheet resistivity of 40 Ω/sq and 55 Ω/sq.

Cz-Si material	V_{oc} [mV]	j_{sc} [mA/cm^2]	FF [%]	η [%]
40 Ω/sq emitter sheet resistance				
Best cell	621.0	35.7	80.4	17.8
Average of 12	619±1	35.9±0.1	79.4±0.4	17.7±0.1
55 Ω/sq emitter sheet resistance				
Best cell	621.0	36.5	79.5	18.0
Average of 12	620±1	36.5±0.2	78.9±0.3	17.9±0.1

3.2 Multicrystalline Silicon Solar Cells

At Fraunhofer ISE 125 x 125 mm² multicrystalline silicon solar cells were processed similar to the flow diagram shown in Figure 3. Contrary to the monocrystalline silicon solar cells, the wafers were non textured, had a sheet resistivity of about 40 Ω/sq and were fired in a rapid thermal single wafer reactor. In the latter, extensive process variations have been performed, amongst others the gas flow ratio nitrogen to oxygen.

The IV-parameters of solar cells fired under different gas atmosphere ratios are presented in Table 2. Fill factors up to 80.4% were measured when firing under oxygen rich atmosphere, resulting in efficiencies up to 15.8%. However, the fill factor drops significantly, if the contact formation atmosphere has a nitrogen to oxygen ratio similar to ambient air [6]. For the best process found, fill factors just over 77% were obtained. This is due to high contact resistivities in the range of 6 to 14 mΩ cm², as measured by the transfer length method [7].

For the type of hotmelt ink used, the contact formation process seems to be different for textured mono- and non textured multicrystalline silicon solar cells. The formation process depends mainly on the emitter doping, surface texture, the SiN deposition technology and also on the ink's etching behavior on different crystal orientations.

Further solar cell processing will focus on contacting iso-textured multicrystalline silicon wafers, as this is the trend in industry.

Table 2: IV-parameters of 125 x 125 mm² non textured mc-Si solar cells fired under different gas atmospheres.

N_2:O_2 ratio	V_{oc} [mV]	j_{sc} [mA/cm^2]	FF [%]	η [%]
3:1	616.9	31.7	77.3	15.2
1:1	616.8	31.8	79.7	15.6
1:3	615.9	31.9	80.2	15.8

4 HIGH SHEET RESISTANCE EMITTERS AND FINE LINE PRINTING

4.1 Solar Cell Processing

At Fraunhofer ISE 270 µm thin solar cells on 125 x 125 mm², 0.5-2 Ω cm, p-doped, Cz silicon wafers were processed similar to the process flow shown in Figure 3. The solar cells were wet chemically textured, diffused in a $POCl_3$ diffusion furnace and the front surface covered by a sputtered SiNx:H antireflection coating. After the backside had been conventionally Al screen printed and dried, the front side was printed with hotmelt ink. Finally the wafers were co-fired in an inline fast firing furnace and edge isolated.

For high sheet resistance investigations an emitter variation of 40 Ω/sq, 55 Ω/sq and 75 Ω/sq was performed. The front side metallization pattern consists of three 50 x 50 mm² grids with a finger width of 70 µm, 80 µm and 100 µm as well as test structures for optical and electrical investigations. This included structures for "fine line printability" and contact and line resistance measurements. For each finger width an optimum cell design was calculated, expecting a fairly good contact resistance and line conductivity. For screen-printing a Hotscreen with a 350 mesh was used. Due to processing problems the final wafer thickness of the solar cells with a sheet resistivity of 40 Ω/sq and 55 Ω/sq was 200 µm, compared to 250 µm for the 75 Ω/sq emitter.

4.2 High sheet resistance emitter

Representative IV-parameters for each type of emitter doping level are shown in Table 3. The fill factor declines from a value of about 80% for cells with a 40 Ω/sq emitter sheet resistance to about 78% for the 75 Ω/sq. Corescan [8] and transfer length method (TLM) [7] measurements were performed to compare the voltage drop due to the emitter sheet resistance as well as the contact resistance between the finger and the emitter.

The TLM measurements showed that for both, the cells with 40 Ω/sq and 55 Ω/sq emitter sheet resistance, the contact resistivity between emitter and finger is sufficiently low not to influence the series resistance significantly. Values in the range of 2 to 6 mΩ cm² were measured. The contact resistivity for the 75 Ω/sq emitter is in the range of 9 to 15 mΩ cm². This relatively high value has certainly a significant effect on the series resistance of the solar cell. The low voltage also indicates a J_{02} problem. Nevertheless, fill factors up to 78% could be achieved.

The Corescan measurements showed that for all cells the contact and sheet resistance was homogeny over the cell surface. As illustrated in Figure 4, the voltage potential between the fingers increases with increasing emitter sheet resistance. This is on the one hand due to the increased voltage parabola caused by the emitter sheet resistance, on the other hand due to the increased voltage jump at the finger edge caused by the contact resistivity.

Table 3: IV-parameters of processed 50 x 50 mm² monocrystalline silicon solar cells printed with hotmelt ink and different sheet resistance emitters with a finger width of about 100 µm.

R_{sh} [Ω/sq]	thickness [µm]	V_{oc} [mV]	j_{sc} [mA/cm^2]	FF [%]	η [%]	R_S [Ωcm²]
40	200	620.6	34.7	79.9	17.2	0.46
55	200	621.7	35.0	79.6	17.3	0.53
75	250	620.3	36.3	78.0	17.6	0.70

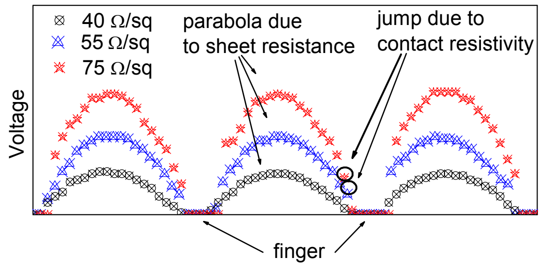

Figure 4: Voltage potential over the length of four fingers, measured by Corescan.

The higher current for the 55 Ω/sq emitter compared to the 40 Ω/sq emitter can be explained by the improved internal quantum efficiency in the short wavelength region as illustrated in Figure 5. The same is valid for the 75 Ω/sq emitter. The higher IQE in the long wavelength region of the cell with the 75 Ω/sq emitter sheet resistance is due to the thickness of the solar cell.

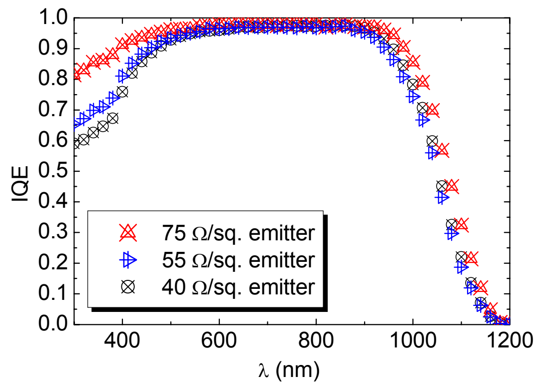

Figure 5: IQE data of the solar cells with 40 Ω/sq, 55 Ω/sq and 75 Ω/sq emitter sheet resistance.

4.3 Fine line printing

An advantage of printing thinner lines is that the power losses caused by the emitter sheet resistance can be decreased by increasing the amount of printed fingers, but without increasing the shaded area. The main challenge is on the one hand to print continuous lines with a high aspect ratio, on the other hand to achieve a low contact resistance to the silicon surface, as the total contact area is typically reduced.

Printed lines with a width between 50 µm and 120 µm were optically and electrically investigated. With decreasing width, also the height of the finger declines as illustrated by the cross sections in Figure 6.

As also illustrated in Figure 6, the finger resistance increases slowly up to a printed width of about 80 µm. Below this value the risk of line interruptions increases significantly, causing the line resistance for those fingers to rise strongly. However, at a width of 70 µm or below the line resistance is higher than for a typically conventional printed finger with a width of 120 µm.

As mentioned above 50 x 50 mm² silicon solar cells were processed with different finger widths and emitter

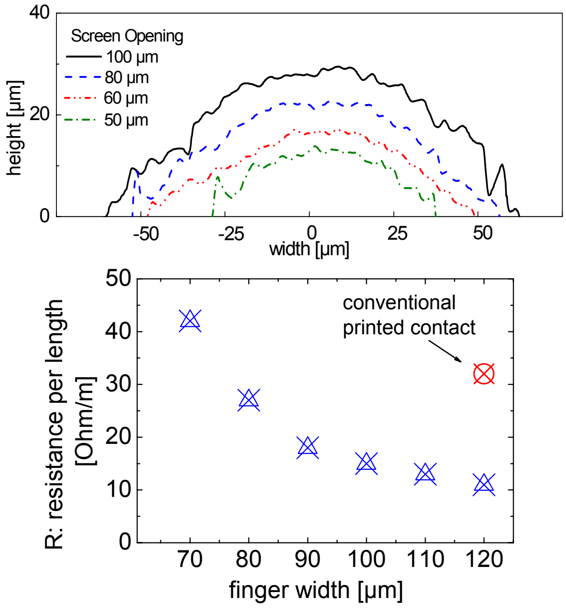

Figure 6: Top: Cross section of contacts with different finger width. Bottom: Finger resistance against the finger width.

sheet resistance. From the IV-parameter in Table 4 it can be concluded, that with decreasing finger width, the fill factor declines. Comparing the fill factor for each type of emitter, for the 40 Ω/sq and 55 Ω/sq emitter the difference between the 100 µm and 110 µm finger width is negligible, whereas the difference to the 80 µm is about 0.5% to 0.6% relative. Even larger are the differences comparing the line width for the 75 Ω/sq emitter: 0.4% relative to the 110 µm wide finger and even 2.6% relative to the 80 µm wide fingers. Because the relative difference increases with increasing sheet resistance emitter, the limiting factor seems to be the contact resistivity. This also could be confirmed by contact resistivity measurements.

To fully exhibit the advantage of fine line printing on high sheet resistance emitters, the hotmelt ink needs to be further improved with respect to the contact resistance.

Table 4: IV-parameters of processed 50 x 50 mm² solar cells with different finger widths and emitter sheet resistances.

R_{SH} [Ω/sq]	width [µm]	V_{oc} [mV]	j_{sc} [mA/cm^2]	FF [%]	η [%]
40	80	619	34.6	79.3	17.0
	100	620	34.4	79.6	17.0
	110	620	34.2	79.8	16.9
55	80	620	34.7	79.1	17.0
	100	622	35.1	79.4	17.3
	110	619	34.5	79.5	17.0
75	80	619	36.3	76.3	17.2
	100	620	36.3	78.0	17.6
	110	620	36.1	78.3	17.5

5 CONCLUSION

Efficiencies up to 18.0% on 125 x 125 mm² industrial pre-processed monocrystalline silicon solar cells with an emitter sheet resistance of about 55 Ω/sq have been achieved.

Sheet resistance emitters of 75 Ω/sq could be successfully contacted with the hotmelt technology. These cells showed a significant increase in the short circuit current density in comparison to higher doped emitters. The transfer to large area silicon solar cells is the next step under investigation.

Fine line printing in combination with hotmelt technology has been investigated. Printing continuous lines with a width of 70 µm and a height of 20 µm has been demonstrated. Further ink optimization need to be performed to achieve lower contact resistance between the finger and the emitter, especially as the doping level of the emitter is reduced.

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