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NEW APPROACH FOR FIRING OPTIMISATION IN CRYSTALLINE SILICON CELL TECHNOLOGY

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ABSTRACT: A new approach for firing optimization is introduced and demonstrated on 10 different pastes. The approach uses fewer settings and is faster than the methods traditionally used. Therefore the approach will make evaluation of new pastes and processes easier. The method uses a cross belt temperature profile to subject a cell with screen-printed paste to different temperatures while firing in the infrared furnace. J-V data, spatially resolved wafer peak temperatures and spatially resolved contact resistances using the Corescan, are used to determine settings for final optimization. Optimal settings for the ten evaluated pastes were obtained in only two steps and using few cells. With only three cells, a scan over a temperature range of about 180°C could be performed. In this way also the firing window could be assessed. The method is applicable both in industry and R&D.
Keywords: metallization, IR-firing, Corescan

1 INTRODUCTION

Firing of front and rear contacts in the IR firing furnace dominates the quality of the electrical contact. This is especially important in evaluating new front side metallisation schemes, such as new pastes, AR coatings, or emitters. To find optimum furnace settings is an elaborate effort, since many settings of temperature and belt speed may have to be explored. With new or alternative front side pastes it is even more difficult or tedious to find an optimum, since no data is available in the furnace temperature and belt speed domain. Another draw-back is that firing furnaces of most PV manufacturers are constantly in use for cell production; there is little time for testing, let alone that all kind of firing furnace settings can be explored to determine if a paste "works". This means that in practice, there is only very limited time available for evaluating or testing new pastes. In order to shorten the effort and to use fewer settings to determine if a paste works well and to find near optimum settings, a new approach is invented at ECN, and presented in this paper. In the next section the approach is explained in more detail, and also the method to demonstrate the approach is given.

2 EXPERIMENTAL METHOD

The approach is based on relating local contact resistance to local cell temperature. Spatially resolved wafer temperatures are measured as a function of relevant furnace settings using a Datapaq temperature profiler. The Corescan instrument is applied to map the contact resistance distribution of the front contact. To reduce the number of trials effectively the approach uses the cross belt temperature gradient to fire a cell. This means that in one run, various locations on the cell are exposed to different temperatures. By relating the local contact resistance to the local wafer temperature, the temperature setting for optimal firing can easily be established.

In order to limit the number of Corescan analyses, standard J-V and Suns-Voc measurements are performed first to check if an electrical front contact has been established. On cells with relevant fill factor, the Corescan instrument is used.

The approach assumes that the front contact is the limiting factor in achieving optimal cell results. Further the method applies furnace settings in an established temperature and belt speed domain; i.e. rear side contacts and BSF are formed. The approach is elucidated in the next paragraph.

2.1 Details of new approach for firing optimization

2.1.1 Datapaq measurements

The cross belt temperature profile, as measured on a wafer with fine wire thermocouples attached, is measured using a Datapaq temperature profiler [1] as depicted in figure 1. The application and procedure are reported in [2].

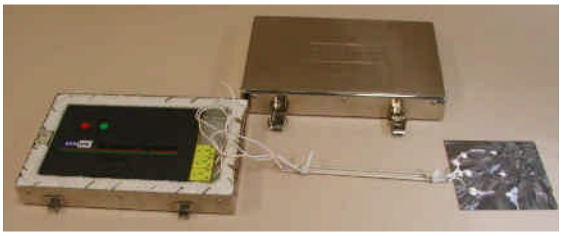


Figure 1: Data logger placed in opened thermal barrier with TCs attached to a wafer as used in [2].

The data logger is the Datapaq 9000 type DP9064, equipped for 6 K-type thermocouples. The thermal barrier used in this study is model TB2015. The TCs are 0.5 mm in diameter, and the high temperature junction is attached onto the silicon wafer surface using ceramic cement. As demonstrated in [2] the use of fine wire thermocouples enables approximation of real wafer temperatures.

2.1.2 Furnace settings

The cross belt temperature distribution in our furnace is influenced by side heating and by the presence of wear strips. Our IR firing furnace (Radiant Technologies Co.) uses wear strips of fused quartz to support the belt. There are 3 wear strips of about 20 mm in diameter, parallel to the belt direction and located at the edges of the belt and in the center. In our furnaces the center wear strip in the high temperature section was removed by RTC to realize a flat cross belt temperature distribution at the center [2]. The furnace is perfectly capable of processing the 16.5% multi-crystalline cells as being presented at this conference [3]. Now the presence of the side wear strip is deliberately used to achieve a large temperature difference over the cell, when placed at the edge of the belt. In addition the side heater, normally used to flatten the cross belt profile, was turned off.

2.1.3 Characterization

The contact resistance (R_c) of the front side metallization is mapped using the Corescan instrument, which has been developed by ECN [4]. Reports on the background of the instrument and its applications are available at [5]. Application of the Corescan to study the contact formation on lowly doped emitters is presented at this conference [6].

From earlier work it is known that the contact resistance is strongly related to the firing temperature and is often very non-uniform [5,7]. Also it was found that there is an excellent correlation between the variation of the measured temperatures over a wafer and the contact resistances found with the Corescan [2].

Suns-Voc setup [8] gives the series resistance less fill factor. The method is to expose the cell to a light flash and analyze the response of the Voc. The value of the series resistance less fill factor indicates whether the cell has been over-fired. At the same time the difference between the Suns-Voc FF and the FF from the J-V analysis is a good measure of the cells series resistance. For near optimal screen printed cells a difference of about 2.5 - 3.5% in FF value is realistic. Larger values are mostly attributed to higher contact resistance. See also [6].

2.2 Summary procedure

The procedure is summarized here below.

1. Realize non-flat cross-belt settings: Use Datapaq profiler to evaluate wafer temperatures and establish cross belt profiles.
2. Cell firing and characterization: Fire on edge of belt. Characterization using solar simulator, Suns-Voc, and Corescan. Relate R_c to wafer temperature to determine best settings.
3. Final optimization: Fire with flat profiles at settings around optimum found in 2.

2.3 Experimental set-up

For a series of furnace settings, based on setting for our standard firing, cross belt temperature profiles were made using the Datapaq system. The side heater was switched off in order to realize a maximum temperature difference near the edge of the belt. Various settings of the high temperature zone were explored to cover a wide range of temperature profiles. Five TCs were attached to a 156 cm² SiN coated and texturized mono crystalline wafer. The TCs are mounted as depicted in figure 2.

Figure 2: Wafer with 5 K-type thermocouples.

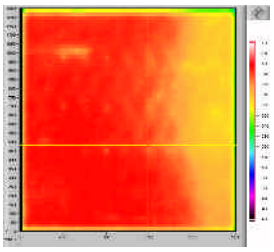


Figure 3: Voc map at setting CBM (full scale 450 - 620mV)

The wafer with thermocouples perpendicular to the belt direction was first placed on one edge of the belt, and in different runs moved towards the center of the belt. In this way a detailed cross belt distribution was achieved.

To demonstrate the new method, cells are made of 156 cm² square texturized mono crystalline silicon (CZ) with a 40 - 45 Ohm/square emitter and SiN anti reflection coating. Two cells were processed for each firing furnace setting.

The approach is demonstrated in this work by optimizing 10 different pastes. Some of the pastes are commercially available; the others are research pastes. The metal contacts are screen printed on the cells and co-fired in the IR firing furnace using fixed settings for the belt speed. Also on several cells only the rear side contact was printed and fired. These cells were used for Voc mapping with the Corescan instrument.

To show how successful the new approach is, additional firing steps were done using standard, i.e. a flat cross belt temperature distributions with different belt speeds.

3 RESULTS AND DISCUSSION

3.1 Voc mapping

To ensure functional rear side contacts and BSF for the settings used in this work Voc scans were performed using the Corescan instrument on cells with only rear side metallization. In figure 3 a Voc mapping is presented of a cell fired by using the non-flat Cross Belt profile and at Medium peak temperature (CBM). The figure shows a variation of Voc of about 25 mV, with for the right part of the cell a lower value. This is due to the lower local temperature as caused by the wear strip. For all conditions used a proper BSF was realized.

3.2 Wafer temperature measurements

Three cross belt profiles with settings CBH, CBM, and CBL are measured on a SiN coated wafer without contacts (figure 4).

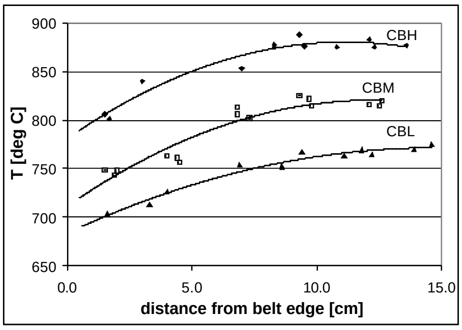


Figure 4: Cross belt temperature distribution at one belt speed for three peak zone temperatures.

The TC data used are the peak temperatures as obtained from the longitudinal temperature profile measured during travel of TCs on wafer on the belt through the furnace. The temperature profiles show a temperature difference over the cell width of about 60°C. For the three settings in total about 180°C is covered this way.

3.2 Cross belt firing

Cells were made using the three set temperatures of the peak temperature zone at a fixed belt speed (v+15 cm/min). In table 1 the averaged J-V fill factor results are presented.

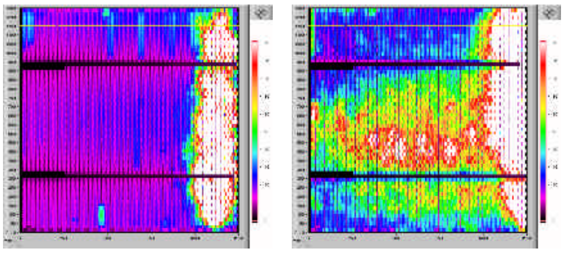
Tset	**CBH**	**CBM**	**CBL**
Paste	FF [%]	FF [%]	FF [%]

1	69.1	47.8	32.9
2	63.0	46.3	28.0
3	63.1	39.9	32.0
4	27.5	27.2	27.2
5	28.2	27.8	27.1
6	32.4	28.9	27.4
7	35.0	29.3	29.0
8	46.0	33.3	29.2
9	31.2	26.8	24.6
10	65.2	50.7	28.6

Table 1: J-V fill factor results

From the results, it can be seen that pastes 1, 2, 3 and 10 give already reasonable cells. For all pastes the FF increases at higher temperature in this range. From the other pastes only paste 8 shows some ability to make a cell, although it seems that an optimum furnace setting is not reached. None of the pastes seems to be (too) aggressive; no firing through the emitter has been observed, as is indicated by fill factors from Suns-Voc analysis that are all in the range of 80 to 82%.

Examples of the contact resistance distribution for pastes 1 and 2 are given in figure 5.



875°C 790°C
Paste 1; FF = 70.3%
Scale 0 - 50mV

875°C 790°C
Paste 2; FF = 63.4%
Scale 0 - 50mV

Figure 5: Corescan examples for the cells fired with the cross belt temperature profile CBH.

In the Corescan figures the dark color corresponds to "good" contact resistance, while the light color corresponds to "bad" contact resistance. The range of the color scale settings is 50mV. A value of about 5 - 10mV represents a good contact resistance (<10 m• cm^2).
The area on the left side of the graph is exposed to a high temperature of about 875°C. On the right side the temperature drops to about 790°C due to shadowing by the wear strip. Paste 1 shows a large area of good contact resistance; only the area at the wear strip has too high contact resistance. This paste seems already to be fired at a near optimum setting. By comparing paste 1 and 2 in this temperature range paste 1 shows a wider operating window than paste 2.

Figure 6 shows a compilation of Corescan mappings for pastes 8 and 10 as a function of the wafer temperature. The Corescan pictures for the settings CBH, CBM, and CBL have been used. For maximum visibility of scan values, the range of the color scale is increased to 150mV. For both pastes, the contact resistance decreases with increasing temperature.

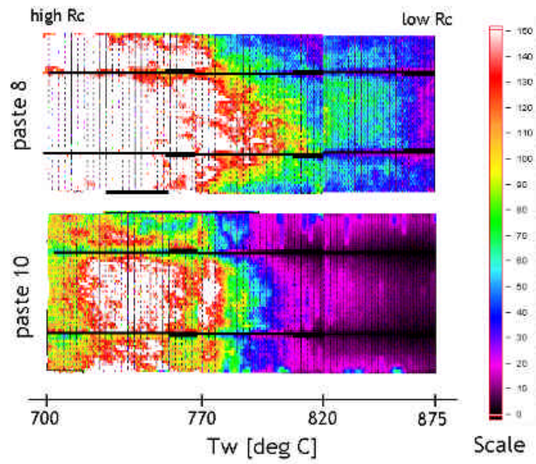


Figure 6: Contact resistance mappings as function of wafer temperature for pastes 8 and 10. Temperature scale is not linear.

The local contact resistance data obtained with the Corescan are related to the local wafer temperatures obtained with the TCs for pastes 1, 2, 3, 8, 9, and 10 (figure 7). Some of the pastes reach a minimum R_c. Pastes 8 and 9 still need a higher temperature to reach a minimum, as could also be observed for paste 8 in the Corescan mapping in figure 6.

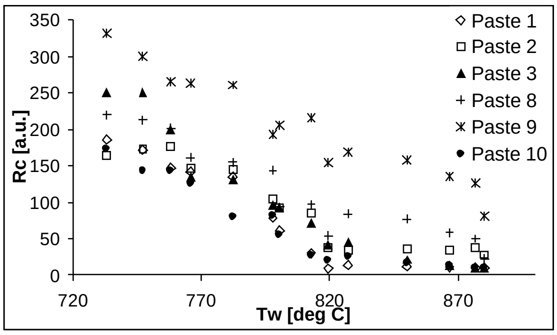


Figure 7: Local contact resistance as function of measured wafer temperature for pastes 1, 2, 3, 8, 9, and 10.

Based on these results a final firing step is performed with a flat profile to assess optimal furnace settings. In this case it was decided only to vary the belt speed, in effect increasing the cell temperature.

3.2 Results after final firing

For the 10 pastes again two cells were fired at the three settings as concluded above: same set temperature, three different belt speeds, but now with the side heaters on and the cells positioned at the center of the belt. So subjected to a flat cross belt temperature profile. In table 2 the best fill factors from the J-V analyses are given per paste and setting.

Pastes 1, 2, 3, 8, and 10 improved with the used settings in their contacting behavior, leading to better FFs. Pastes 1, 2, 3, and 10 perform well for the three belt speed settings. The FF values of these pastes change less than 2%, showing that these pastes are not very sensitive to temperature profile changes. On the other hand it seems that paste 8 has not reached its maximum yet. The FF for paste 8 differs from 63 - 47% for different belt speeds.

Belt speed Paste	V-15 [cm/min] FF [%]	V [cm/min] FF [%]	V+15 [cm/min] FF [%]
1	76.4	76.3	76.3
2	67.5	66.9	68.2
3	75.8	75.9	76.1
4	28.1	28.3	27.3
5	28.7	28.1	27.2
6	36.4	33.6	34.5
7	34.4	31.0	31.5
8	63.1	52.0	46.7
9	36.5	38.4	36.7
10	71.7	71.7	70.8

Table 2: Fill factors from J-V results.

Pastes 4, 5, 6, 7, and 9 do not lead to FF results >60%. Different firing settings outside the scope of this work might be successful.

To summarize, the best results from the J-V analyses are given in table 3 together with the line resistance R_L. J-V data are measured with two Kelvin probes per busbar and not corrected for mismatch.

Since the paste rheology is different per paste, and only one screen printer setting has been used, the print definition of the front side pattern might not be the same for the pastes. This is reflected in the line resistance. The line resistance also might show that there is some difference per paste in the silver conduction of the fingers. Calculations [9] show that for paste 10, about 2.4% relative is added to a fill factor loss by the high line resistance value as compared to using the value of paste 1.

Paste	J-V FF [%]	Suns-Voc FF [%]	eta [%]	Jsc [mA/cm2]	Voc [mV]	R_L [Ω/cm]
1	76.4	81.6	16.7	35.61	613	0.443
2	68.2	81.9	14.8	35.41	611	0.549
3	76.1	81.4	16.5	35.43	614	0.402
4	28.3	82.0	5.1	29.35	618	0.648
5	28.7	81.9	5.2	29.48	616	0.697
6	36.4	82.6	7.8	35.01	612	0.639
7	36.9	82.1	7.9	35.12	613	0.631
8	63.1	82.0	14.0	36.30	613	0.746
9	38.4	81.9	8.4	35.67	615	0.631
10	71.7	81.4	16.1	36.80	612	1.033

Table 3: Best cell results.

With the new approach it was found that cell results for paste 1 and 3 are near optimal. Pastes 2, 8, and 10 prove to be viable pastes but would need further statistical optimization on larger number of cells in case of industrial application.

4 CONCLUSIONS

A new method for firing optimization, using a cross belt temperature distribution over the cell, has been successfully used to assess the capabilities of pastes to make cells with good electrical contacts. With only three cells, a scan over a temperature range of about 180°C has been performed. Also in this way the firing window could be assessed.

The new approach, and inherent use of the Datapaq and the Corescan, is applicable in furnaces for production or R&D and can be used as a time saving alternative for existing procedures for firing optimization.

5 REFERENCES

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6 ACKNOWLEDGEMENTS

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Note: The paper with figures in full colors is available from www.ecn.nl/solar and www.sunlab.nl