SIMPLE, DETAILED & FAST FIRING FURNACE TEMPERATURE PROFILING FOR IMPROVED EFFICIENCY

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ABSTRACT: A new temperature profiling method in a firing furnace is demonstrated. A data logger in a thermal barrier is connected to a thermocouple traveling through the furnace. The use of smaller and multiple thermocouples attached to a wafer enable more accurate profiling than the commonly used method. Possibilities for improving the firing furnace could be determined using the data logger and contact resistance scans made with the Corescan.
Keywords: contact firing, temperature profiling, manufacturing and processing

1 INTRODUCTION

In solar cell production, improved cell performance and a narrow efficiency distribution are targeted. The fill factor is a limiting factor, largely due to the sensitivity of the contact firing process in the belt furnace [1]. Therefore, adequate control of the contact firing furnace is necessary and exact knowledge of the temperature distribution should be obtained.

Infrared belt furnaces are nowadays standard for firing the metal contacts on a solar cell. Typical specifications for contact firing furnaces are [2]:

- Operating temperature up to 1000 ºC.
- Belt width up to 600 mm.
- Belt speed up to 120 ipm.
- Up to 4 sections to control the required shape of the temperature profile.
- Product dwell time at a temperature above 80% of the maximum in the order of seconds.
- Up ramp of around 50 ºC/s.
- Down ramp of around 30 ºC/s.
- Maximum cross belt temperature variation in the order of several degrees.

To control the temperature in the furnace, thermocouples (TC's) are mounted in each heating zone of the furnace. These measurements are not sufficient to determine the actual wafer temperature as a function of time. This can be achieved by temperature profiling.

1.1 Standard way of product temperature profiling

The traditional way of profiling is to use a thermocouple, attach it to a wafer, and have it travel through the furnace, while recording the temperatures along the way. This approach is relatively straightforward and cheap; modern furnaces are equipped with TC data acquisition software for temperature profile investigation. There are however several drawbacks and limitations to this method. The thermocouple needs to be sturdy since it has to be pulled back when it reaches the end of the furnace, but a thick thermocouple has a large response time to temperature changes. Also the attachment of the thermocouple to the silicon substrate is ambiguous, and can lead to uncertainty in position and measured values. Using this approach, several measurements are necessary to get a full picture of the temperature distribution on a wafer or across the belt width.

1.2 Profiling with data logger

Currently, a new instrument is available that makes temperature profiling much easier. It is a data logger protected by a thermally isolated box (called thermal barrier) to which several thermocouples can be connected. The product with thermocouples attached to it is transported through the furnace with the logger following at a short distance. The data logged in the furnace can be read and evaluated afterwards with extensive data acquisition software that is supplied with the logger.
Figure 1 shows a picture of logger, thermal barrier and 3 thermocouples attached to a 10 x 10 cm² wafer.

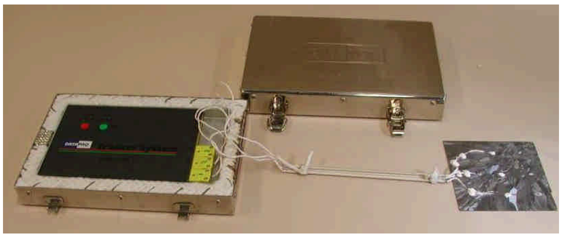


Figure 1: Data logger placed in opened thermal barrier with thermocouples attached to a wafer.

Although these systems have been available for some time and are extensively used in other manufacturing processes [3], they have not been used in the PV industry thus far. The main reason for this might be that the temperature limits for thermal barriers are lower than the temperatures reached in solar cell firing furnaces. However, it will be shown that the barriers can be used in solar cell firing furnaces, since the dwell time at high temperatures is sufficiently short.

1.3 This study

In this study, a data logger and a thermal barrier are applied to measure the temperature distribution along the furnace and across the belt width. The feasibility of this instrument is demonstrated and the improvement, compared to the traditional method of profiling, is shown.

Also demonstrated is the relation between measured temperature profiles and the quality of the front side contact of the cell. Cells are produced at standard temperature settings, and at both lower and higher temperatures than standard. The cells are analyzed using J-V measurements, contact resistance scans and profiling of the BSF.

2 EXPERIMENTAL APPROACH

The work is divided in 1) testing the system in solar cell IR furnaces, and 2) performing experiments to identify its benefits.

2.1 Application of the data logger

The data logger is the Datapaq 9000 type DP9064, which has six connections for K type thermocouples. A sample rate of 10/s is selected to be fast enough to follow the profile in a firing furnace. Two Datapaq thermal barriers were tested in combination with the data logger. The thermal barrier dimensions are given in table I.

Table I: Dimensions of thermal barriers used.

	TB2015	TB4021B
LxWxH (mm)	210x160x40	210x130x25

The temperature that the datalogger itself reaches within the furnace can be easily checked since this value is also read into the PC after each measurement. It was found that furnace (peak) temperatures up to 970 ºC at belt speeds down to 30 ipm did not lead to overheating of the logger for both barriers. Apparently, the residence time of the thermal barriers in the high temperature zone is always sufficiently short for the fast firing process that is used for solar cell contact formation.

To obtain proper heat transfer between the TC and the wafer, the TC junctions (K type, dimension 0.5 mm) were attached to the wafer with ceramic cement. The cement must enable a firm attachment of the TC to the wafer and must be stable at high temperatures. Also it must be possible to use little cement, to obtain a small thermal mass at the TC tip. Several ceramic cements have been used; also cements were modified to improve their behavior. From the 18 cements tested, three performed well. The others were too brittle after being exposed to the high temperature. The best one was used further on.

To be sure that the presence of the thermal barrier does not influence the local temperature in the furnace and the temperature at the wafer, the distance between the barrier and the wafer was stepwise increased. If the distance is larger than the longest heating zone length, no influence was observed.

2.2 Experiments

Several experiments were conducted to compare the traditional profiling method with the data logger approach and to correlate results of contact resistance scanning with the cross belt temperature distribution.

- Firstly, the temperature profile was measured in a standard way by feeding long TC's of 1 and 2 mm thickness into the furnace, without any wafer. After that, the profile was measured with a 0.5 mm TC and the data logger.
- The experiment just mentioned was repeated, the only difference being the attachment of the TC to a wafer.
- The cross belt temperature distribution was measured using 3 TC's of 0.5 mm that were fixed to a 10 x 10 cm² silicon wafer. One TC was positioned in the center, the other two at 30 mm from the center. The wafer was placed at various positions across the belt width to obtain a complete picture. For several furnace settings, 10 x 10 cm² multi crystalline silicon cells were produced. The contact resistance of the front side metallization was mapped using the Corescan instrument, which is developed by ECN [4]. From earlier work it was known that the contact resistance is strongly related to the exact firing temperature and is often very non-uniform [4,5]. So far, the relation between contact resistance non-uniformities across a cell and the cross belt temperature variations was not investigated in detail.
- Since the back surface field (BSF) thickness is also temperature dependent, BSF profiles were made at the center and the edge for one of the cells. This was done by Electrochemical Capacitance Voltage (ECV) profiling.
- From the results of the experiments above it was concluded to modify our furnace to improve it. More temperature profiles were then made with the logger to check if the modification had lead to the expected effect.

3 RESULTS AND DISCUSSION

Thermocouples of three diameters have been used to measure the air temperature at the belt center for a temperature setting in the hottest zone of T_{max}. The differences between measured maximum temperature and the set temperature are shown in table II.

Table II: Deviations from T_{max} for varying TC thickness. No wafer is used.

TC	0.5 mm	1 mm	2 mm
Deviation (°C)	-155	-305	-436

Further measurements were done using the 1 mm TC loosely in contact with the wafer and the 0.5 mm TC cemented on the wafer. Results are shown in table III.

Table III: Profiling comparison for different TC thickness, both were attached to a wafer.

	0.5 mm	1 mm
Deviation from T_{max} (°C)	-82	-135
Ramp up (ºC/s)	72	50
Ramp down (ºC/s)	40	24

The smaller temperature deviation and increased up- and down ramp for the 0.5 mm TC clearly show that it has indeed a much shorter response time. Note also that the temperature difference between the situation with and without wafer is very large; this means that a correct measurement cannot be made without a wafer.

With three TC's cemented on the wafer, several measurements were made across the belt, again using standard furnace settings. The data for the 3 TC's logged for the hottest part of the profile is displayed in Figure 2.

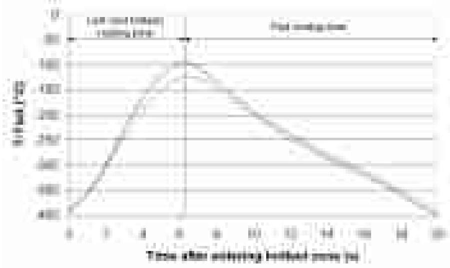


Figure 2: The peak for the center TC (lowest curve) is tens of degrees lower than the outer TC's.

By choosing different wafer positions across the belt, it was possible to measure across the belt (width = 24 cm). In this way, it was also possible to get an idea of the accuracy of the method by positioning different TC’s on the same location on the belt. The cross belt temperature that was found in this experiment is shown in Figure 3. A polynomial was fitted through the measurement points to guide the eye.

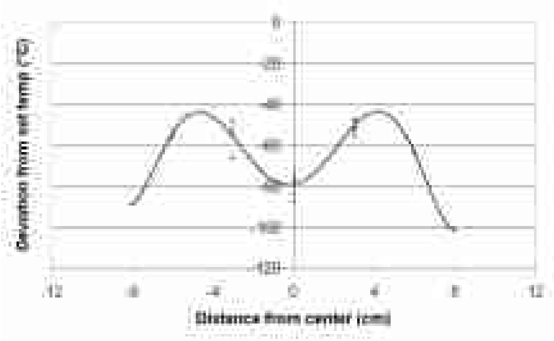
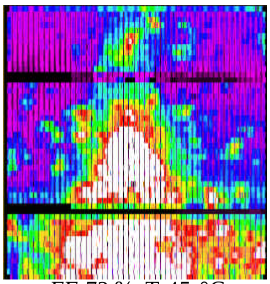


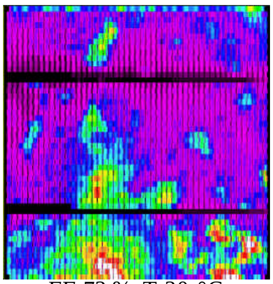
Figure 3: Cross belt temperature distribution. The different temperatures at a specific belt location are obtained from different TCs by shifting the wafer in TC spacing units (3 cm).

It is clear that the distribution is very non-uniform. At the center a dip is observed of about 35 °C, near the edges of the belt the temperature is lower by 45 °C.

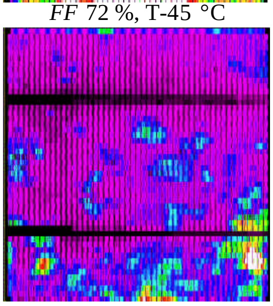
To check how the cross belt temperature does affect the firing of cells, scans of the front side contact resistance are made for cells fired at several conditions. In Figure 4, the Corescans of cells fired between T-45 °C and T+45 °C are shown (T is optimum setting); the belt direction is perpendicular to the busbars. These scans show that an area in the center has good contact resistance from T+0 °C up to T+45 °C, whereas at the edge of the cell a good contact resistance is found from T-45 °C to T+0 °C. This leads to the conclusion that the cell is coolest at the central region. From observations of the color differences across the rear side metallization at various temperature settings [5] the temperature difference was estimated to be 45±10 °C. This is in agreement with the data logger results.



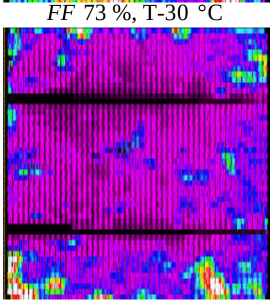
FF 72 %, T-45 °C



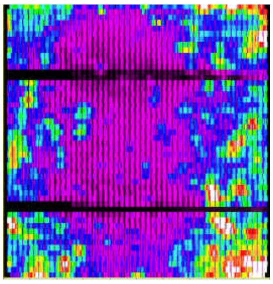
FF 73 %, T-30 °C



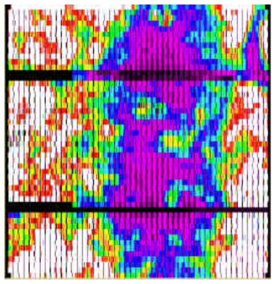
FF 74%, T-15 °C



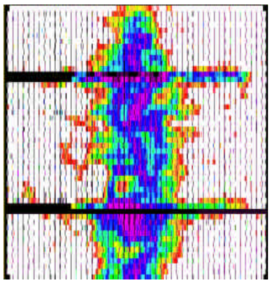
FF 75 %, T+0 °C



FF 74 %, T+15 °C



FF 69 %, T+30 °C



FF 62 %, T+45 °C

Figure 4: Corescans on cells fired at different set temperatures. Lighter areas have higher potential and thus higher contact resistance.

A non-uniform cell temperature also has an influence on the BSF formation. Therefore, ECV measurements of the BSF were performed at the cell center and at the edge (see Figure 5).

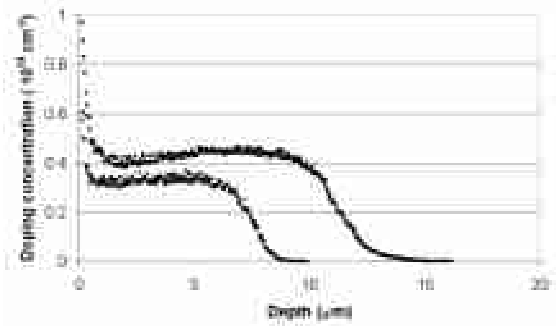


Figure 5: BSF at cell edge (upper curve) is about twice as deep as the BSF at the center of the cell.

The profile at the edge is about twice as deep as that at the center; this depth difference must have been caused by a temperature difference of at least 40 °C.

It will be clear that it is important to find out the reason for the observed temperature dip at the belt center. The source was thought to be one of the wear strips of fused quartz that are used to support the belt. In this furnace there are 3 of them, located at the edges and the center. They are parallel to the belt direction and about 20 mm in diameter. In our case cells are usually positioned at the belt center.

To check if the mechanism of heat temperature lowering was local IR radiation reduction, an experiment was done with only the top lamps on in the hottest zone (normally the lower lamps are also needed to reach the required temperature). The temperature dip at the belt center disappeared in this experiment, supporting the IR radiation reduction hypothesis.

It was concluded that the central wear strip had to be removed from the hottest zone. After that, the temperature profile was measured again; the result is shown in Figure 6.

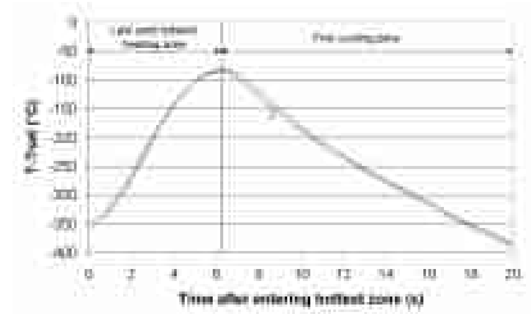


Figure 6: Profile around peak with wear strip removed from hottest zone.

The cross belt temperature temperature distribution was also determined again and is shown in Figure 7:

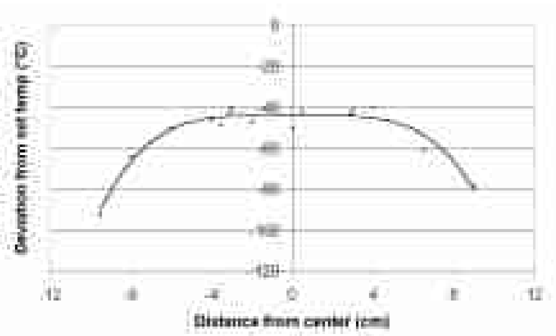


Figure 7: Cross belt temperature without wear strip.

It is clear that the wear strip removal has solved the problem of the temperature dip at the belt center. The constant temperature region near the center is ~12 cm wide, being sufficient for up to 12.5 cm cell size.

After this experiment, a series of (neighboring) cells of 12.5 x 12.5 cm² were fired at various set temperatures and the IV results were measured. Their fill factors and efficiencies are given in Figures 8 and 9.

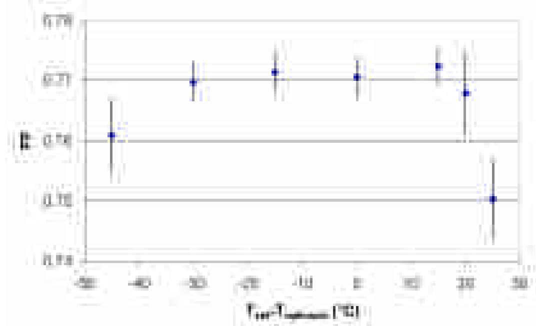


Figure 8: Fill factor as function of firing set temperature.

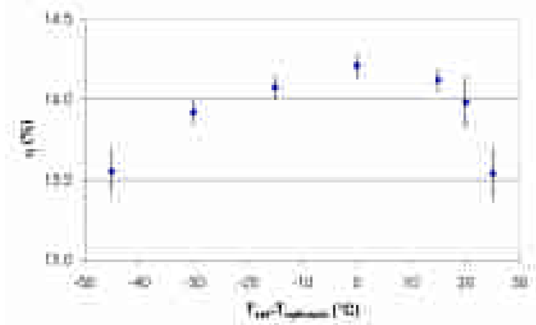


Figure 9: Efficiency as function of firing set temperature.

The fill factor is constant from T-35 °C to T+20 °C. In the same range, a small dependence on firing temperature is observed in the efficiency. This is attributed to improved short circuit currents possibly due to a higher diffusion length in the bulk of the material. Due to the improved temperature profile in the furnace, a higher efficiency is reached.

4 CONCLUSIONS

- The thermal barriers and data logger have successfully been tested in a solar cell firing furnace up to 970 °C set temperature at belt speeds ranging from 30 to 70 ipm. The thermal barriers are able to withstand the wide range of operating conditions for contact firing.
- Up to three thermocouples of 0.5 mm junction diameter have been used on one wafer, giving more accurate and detailed information on wafer temperature distribution, cross belt temperature, etc.
- There is an excellent correlation between the measured temperature variations over a wafer and the contact resistance variations found on solar cells with the Corescan.
- The measured temperature variations also correlate with BSF depth variations across a cell.
- The temperature dip at the belt center was caused by IR radiation reduction by the quartz wear strip. After removing the center wear strip from the hottest zone, the temperature dip disappeared.
- The data logger enables:
    - Improved process control from batch to batch by detailed monitoring, and
    - Optimization of the firing process by improving the temperature distribution across and along the furnace.

5 REFERENCES

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