In Situ Solar Wafer Temperature Measurement during Firing Process via Inline IR Thermography

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Herein, an inline IR thermography system as an innovative application for real-time contactless temperature measurement of wafers—both metallized and nonmetallized—during the firing process is successfully realized in an industrial firing furnace as proof of concept and example for a thermography system in a conveyor furnace. As observed by the new system, thermocouples (TCs) seem to measure lower temperature on wafers—especially in combination with TC frames—than wafers exhibit at standard firing conditions (here up to $\Delta T \approx 40$ K). Furthermore, highly resolved spatial temperature distribution can be successfully measured on the wafer.

IR thermography is an efficient measurement method, as it measures the temperature and its spatial distribution of object surface contactless in situ and real-time for a broad temperature range. Accordingly, thermography is used for many applications, such as heat-related building diagnostics, surveillance, or hot-spot detection of photovoltaic modules. Materials which are processed in conveyor furnaces must meet a certain temporally and spatially resolved temperature profile to achieve ideal process results. However, thermography is currently not commonly used for temperature measurement of these materials in inline production systems. This might be due to often unknown optical parameters for hot objects (especially for nonmetals), a hot environment in furnaces, and IR radiators—the standard heat (radiation) source in conveyor furnaces—which cause parasitic environmental radiation, as well as a challenging realization of an optical path through inline equipment. Accordingly, the temperature of objects in firing furnaces is commonly measured by thermocouples (TCs). However, the latter has a lot of disadvantages compared with thermography. TCs must contact the measured object; thus, they might damage the latter. As the setup has to be readjusted for each measurement, such measurements are time-intensive compared with thermography and can only cover a fraction of samples belonging to a batch. On the contrary, it is possible to measure each sample in situ thermography following an initial setup. Furthermore, a spatial temperature measurement cannot be realized as highly resolved as with thermography.

Motivated by the many advantages of thermography, this work presents the installation of an inline thermography system as a novel application into an industrial IR firing furnace, used for the contact firing process of industrial solar cells, serving as an example for successful thermography temperature measurement in a conveyor furnace. The contact firing process plays a crucial role taking place nearly at the end of the industrial crystalline silicon solar cell production process. During this step, contact formation, activation of the surface passivation, and influence on material defects take place. Controlling the temperature of wafers during the firing process is thus crucial for the performance of the final solar cell. Thermography is especially promising for the firing process because the application of TCs on wafers makes the latter useless for further cell production, which means, in turn, that the temperature of only few wafers of a batch can be measured (assuming the measured temperature for the rest of the wafers), implying measurement uncertainties. Furthermore, cell production gets interrupted by TC measurements. In contrast, thermography allows for a real-time, in situ measurement of every wafer with high spatial resolution.

As a proof of concept, in this work, a thermography system was installed in the peak zone of the furnace to capture the real temperature of wafers during the temperature peak of the process. The latter is the most important part of the firing profile because it crucially determines the contact formation. Furthermore, the aim was to evaluate the spatial temperature distribution as temperature homogeneity is desired to avoid wafer areas with less efficient performance.

It was possible to realize the thermography system in the peak zone of the firing profile, measuring successfully the peak...
temperature of monofacial, bifacial, and nonmetallized passivated emitter and rear cells (PERC) (see Figure 1). The camera field of view captures an entire wafer in the direction perpendicular to the wafer transport direction—further called “x-direction” (from left to right)—and ≈35% of the wafer in the direction parallel to the transport direction—further called “y-direction” (opposite to transport direction). Wafers and their geometry can be clearly seen. Figure 1b indicates that the camera field of view captures the temperature peak of the process, as it was aimed for. The position of the camera field of view was estimated by a parallel ongoing simulation of the firing process (details cannot be shown at this stage). The camera is positioned with an angle of about 13° in the y-direction. The images have not been corrected for the camera tilt, as the results are not expected to be affected for such small angles (all the distances, however, have been corrected for the camera tilt). All images were taken during the same firing process. All wafers were fired with the front side showing up. These settings are true for the following figures as well.

In Figure 1, the temperature between different wafer types was compared. Comparing temperatures of single wafer spots would be unreliable, which is why a more reliable temperature comparison was needed. Therefore, in a first step, the images of a passing wafer were accumulated and averaged per pixel (for example, see Figure 1d). In a second step, the temperature of the accumulated picture was averaged in the x- and y-directions to one single value. Strictly speaking, the lower half of the shown accumulated wafer image in the y-direction as well as the edges in the x-direction were left out (indicated by the red rectangle in Figure 1d). The former exhibits an optical artifact in the form of parasitic shading. The latter experiences an optical artifact in the form of a steep temperature drop toward the wafer edge due to adjacent signal mixing (see Figure 2). If present, busbars were excluded as well. The resulting temperature does not necessarily represent the average temperature of the wafer, however, yielding a reliable temperature for comparing the temperature between different wafers, which has been done for the cases shown in Figure 1. Figure 1 indicates that the used monofacial wafers show no temperature difference with and without the front side grid for the same firing process. The latter shows ΔT ≈ 10 K lower temperature than the used bifacial front and rear metallized (FRM) wafers, which are, in turn, ΔT ≈ 10 K lower than the bifacial (solely) rear metallized (RM) wafers and nonmetallized wafers. These temperature differences are in accordance with conducted TC measurements and stem most likely largely from the mass differences of the contact layers: one standard grid seems to be rather negligible; however, two grids or a full area layer appears to be rather substantial regarding the temperature difference.

Thermography measurements enabled to observe that TCs create a local temperature drop around their vicinity on the wafer (see Figure 3). As TCs cover the measured wafer area when mounted on the front side, the used TCs were mounted on the rear side, as visualized in Figure 3c,e, to see the aforementioned heat drop clearly. One can see a temperature drop for areas contacted and not contacted by the TCs and the TC fork (needed to stabilize the wire TC). In the noncontacted case, the drop is assumed to stem from shading of background radiation by the TC and thus diminishing local heat absorption. In the contacted case, additional heat dissipation is assumed, as the temperature drop seems to be higher at the contacted spots. In this work, a local temperature drop of ΔT ≈ 10 K by both utilized TC types relative to its surrounding has been measured. This temperature drop has been considered for the wafer-specified thermography calibration. For TCs mounted on the front side, a steeper observed temperature drop can be expected due to reflection contribution of ambient radiation in the temperature (artifact); however, similar gradients have been measured

Figure 1. a) Representative thermography image captured by the installed thermography camera, featuring wafer including busbars (1), IR lamp (2), belt and furnace wall (3), and optical path walls (4). b) Standard firing temperature profile scheme as a function of the distance d, which is the distance of the furnace position to the furnace inlet (see Figure 4a) with the green bar representing the camera field of view. c) Representative images of a monofacial (moF) FRM PERC wafer, consisting of three time-shifted images (t1–t3) to visualize the entire wafer. d) Accumulated average image of a passing wafer in the y-direction showing the average temperature within the red rectangle (excluding busbars). e–h) Representative images of the last part (compared with t3 in (c)) of (solely) RM monofacial, FRM bifacial (bifI), (solely) RM bifacial, and nonmetallized wafers.
for both front and rear mounted TCs in this work. On the other hand, temperature differences of wafers fired under standard conditions compared with wafers embedded in a TC-frame system were clearly observed and are discussed in the following as a representative example of differences between TC-measured temperatures and those under standard firing conditions. Unlike the temperature calculation in the previous section (see Figure 1), it is not possible to accumulate the images in this section, as TCs would cause significant errors. Therefore, the average temperature of one line, as visualized in the pictures of Figure 3, was chosen for comparing the temperatures between the different cases, instead. Being positioned on the quartz frame (strictly speaking quartz pins, as can be seen in the top right image), the wafer temperature is $\Delta T = 5 - 10 \text{ K}$ lower compared with no frame, i.e. standard firing conditions (see top left image). This temperature decrease is probably caused by heat dissipation of the quartz pins (indicated by local temperature drop at the pins). When additionally contacted by one sheath TC, no change in temperature can be observed (see center left image), but being contacted by three sheath TC simultaneously shows further decrease by $\Delta T = 10 \text{ K}$. The latter might stem from bowing the wafer by the spring force of multiple TCs contacting and initiating a contact between wafer and belt, which would lead to additional heat dissipation by the belt. The clearly visible local temperature drop in the form of the belt geometry indicates the latter. When the wafer is positioned on the metal wires of the carbon fiber reinforced carbon (CFC) frame, the wafer shows further $\Delta T = 5 - 10 \text{ K}$ decrease (see bottom right), most likely

Figure 2. a) Temperature distribution on a (solely) RM monofacial wafer in the x-direction, represented by selected lines of an accumulated average image (see Figure 1d), as depicted in the bottom inset picture. b) Temperature distribution of the passing wafer in the y-direction at fixed furnace positions. These positions are visualized in the bottom inset picture, which is a snapshot of the passing wafer. It has to be noted that the only goal of both inset images here is the visualization of the measured spots across the wafer. These images do not represent the resulting 2D spatial temperature distribution.

Figure 3. Comparison of a wafer fired under industrial conditions (a), on a quartz frame (d), in a sheath TC/quartz frame system with one (b) and three (e) TC contacts, on a CFC frame with metal wires (f) and a wire TC/CFC frame system with one TC contact (c) for the same firing process. Numbers denote a shading artifact for the lower wafer half of the image (1), sheath (2,3), and wire (4,5) TCs including TC fork (6) from front (2,4) and back (3,5), quartz (7) and CFC (8) frame, and heat dissipation by quartz pin (9) and metal wire (10). The red circles indicate the contacting area of the TCs. Green frames indicate added images.
coming from heat dissipation of the wires (indicated by local temperature drop at the wires). Steel—the material of the metal wires—dissipates heat faster than quartz because the thermal conductivity of steel is significantly higher than that of quartz,[1] which could explain the larger temperature decrease by the CFC frame (strictly speaking metal wires) than by the quartz frame. Being additionally contacted by a wire TC, the temperature decreases by further $\Delta T \approx 5$ K, which probably stems from heat dissipation of the TC and shading by the TC fork. Considering the measured $\Delta T \approx 10$ K local temperature drop by the TCs, the resulting temperature decrease by the sheath TC/quartz frame system yields $\Delta T \approx 15–20$ K and the wire TC/CFC frame system $\Delta T \approx 40$ K for one TC contact compared with standard firing conditions.

As previously mentioned, thermography allows for more detailed evaluation of (2D) spatial wafer temperature distribution than TCs. To estimate the temperature distribution in a simple way, we investigated the average distribution in the x- (see Figure 2a) and y-directions (see Figure 2b).

To estimate the distribution in the x-direction, the sequence images of the wafer were accumulated similar to Figure 1d as a first step. This way, averaging in the y-direction was conducted. This accumulated image is shown as an inset in Figure 2a. Following this, line scans in the x-direction at different levels of the y-direction have been done, as indicated in the inset image of Figure 2a. No line scans have been conducted in the lower half of this image due to previously mentioned optical artifacts around that area (see Figure 1). The temperature distribution of these lines (thin black curves in Figure 2a) has been averaged (thick green curve in Figure 2a) to estimate the mean temperature distribution in the x-direction. Ignoring the wafer edge area (up to about 2 cm for each edge, see explanation further down), a small gradient of $dT/ds \approx 1$ K cm$^{-1}$ can be observed. However, it is not clear at this point whether this gradient originates from the wafer temperature itself or is a reflection artifact or a mixture of both because both highly emissive and highly reflective objects including varying thermal diffusivities show all the same trend. It should be noted here that the influence of primary radiation of the furnace radiators on the wafer distribution is unknown because there is a high amount of secondary radiation coming from the highly reflective furnace walls. Thus, one cannot deduce the power distribution of lamps based on the temperature distribution in the x-direction.

To estimate the distribution in the y-direction, fixed positions of the camera field of view have been defined as a first step. The inset picture of Figure 2b shows these fixed positions in a snapshot of the passing wafer. The temporal change in temperature has been recorded for these fixed positions from the point of the wafer passing with its trailing edge to the point of the wafer passing with its leading edge. On account of constant belt velocity, the recorded temporal distributions were linearly converted to spatially resolved distributions and visualized as thin black curves in Figure 2b. These curves were averaged to estimate the mean temperature distribution in the y-direction (see thick green curve in Figure 2b). Ignoring the wafer edges again, the wafer experiences a significantly lower temperature for the first incoming wafer quarter ($\approx$4 cm). The average temperature gradient from 2 to 4 cm is $dT/ds \approx 7$ K cm$^{-1}$ compared with the following wafer rest with a much lower average gradient of $dT/ds \approx 0.5$ K cm$^{-1}$. As the wafer gets heated up in the peak zone, the incoming front parts of the wafer probably heat up faster, inducing a lateral heat flow from the front to the back parts of the wafer. This heat flow might additionally heat up the back parts of the wafer while there is no heat flow to the front parts during their passing of the peak zone.

For approximately the last 5 mm of the wafer edge, a very steep temperature decrease can be seen in Figure 2 for all the four wafer edges. Temperature decrease at wafer edges has been previously observed but not with such high decreasing gradients. It is rather likely that this steep decline stems from mixing thermography-measured temperature with the colder outside boundary (furnace wall, belt). For the leading edge (see Figure 2b), a slight temperature decrease with a gradient of $dT/ds \approx -1$ K cm$^{-1}$ for the last 2 cm of the wafer can be observed. Also, for the right and left edges, temperature drops for the last 2 cm can be seen. However, the gradient is way steeper than for the leading edge and might be misleading due to a superposition of possible afore-mentioned reflection artifacts in the x-direction. As the trailing edge is difficult to evaluate due to the steep temperature increase for the first wafer quarter, the trailing edge seems to be the most reliable regarding temperature drop evaluation at the wafer edge and suggests a rather small drop at the edge.

The combination of the trends in the x- and y-directions as well as at the edges yields an estimation of the spatial 2D temperature distribution on the wafer surface. The temperature distribution appears slightly inhomogeneous across the wafer. The edge drop probably has a minor effect on the resulting cell performance; the observed inhomogeneities across the wafer, however, might have a detectable influence.

In summary, in this work, an inline IR thermography system as an innovative approach for real-time and contactless temperature measurement of wafers during the firing process has been successfully realized in the firing zone of an industrial IR firing furnace, measuring the wafer temperature during the temperature peak as proof of concept and example for a thermography system in a conveyor furnace. Temperature measurements of monofacial, bifacial, and nonmetallized PERC wafers have been presented. Using spatially resolved, in situ thermography, it could be observed that TCs seem to measure lower temperature on wafers—especially in combination with TC frames—than wafers actually yield for standard firing conditions (here up to $\Delta T \approx 40$ K), most likely due to heat dissipation and shading of radiation by TCs and frames. Furthermore, spatial measurements suggest a slightly inhomogeneous wafer temperature distribution for this investigation, representing a possible situation of wafer temperature distribution during the firing process in a firing furnace.

After the successful realization of the presented thermography system, the latter will help to improve measurement accuracy and statistics of the peak temperature during the firing process. The real-time feature allows for on-the-fly corrections of possible temperature fluctuations that can easily be spotted because of the thermography system. Such adaptations have the possibility to run automatized and wafer-specific by interfacing the firing device with the thermography system. Furthermore, this system allows for correlation between temperature, respectively, furnace settings, and current–voltage parameters for each measured cell. Thus, IR thermography has the potential of improved process control and quality assurance of the firing process.
Further investigations regarding spatial wafer temperature distribution and potential artifacts will be conducted. Temperature gradients in the x-direction could be mitigated by radiation intensities with opposed gradients, whereas gradients in the y-direction could be controlled by time-varying radiation intensities. Both methods are planned to be realized via corresponding radiators to achieve a homogeneous wafer temperature distribution.

**Experimental Section**

In this work, an IR thermography system with an "Image IR 8300" thermography camera by InfraTec® at its centerpiece has been installed into the last firing zone of an "RFS 250 Plus" IR conveyor belt furnace by Rehm Thermal Systems,® located at the Photovoltaic Technology Evaluation Center (PVTEC) at Fraunhofer Institute for Solar Energy Systems (ISE) (see Figure 4).

![Figure 4](image)

To create an optical path between camera and processed wafer, an opening through the furnace wall and isolation has been realized and thermally isolated by a highly transmissive material. The thermography image was displayed by the software IRBIS Professional by InfraTec. Furthermore, InfraTec provided the general calibration of the IR camera, i.e., calibrated for black bodies as well as a certain wavelength and temperature range. At Fraunhofer ISE, the subsequent wafer-specified calibration has been conducted with the help of TC-measured temperature. In this work, two TC types (systems) were used, namely, a wire TC that contacts the wafer with the help of a CFC frame and a sheath TC, which contacts the wafer with the help of a quartz frame (constructed by Heraeus Noblelight). First, the accuracy of the TC-measured temperature has been validated with the help of the eutectic temperature of Al–Si which can be clearly detected in the firing profile. If a TC is calibrated correctly, it shows a disruption in the form of a flatter curve around the eutectic temperature of Al–Si (about 577 °C) during the cooling phase of the firing profile when put on an Al layer. However, if a TC is calibrated incorrectly, it shows the latter disruption at temperatures deviating from that of the eutectic Al–Si temperature. Here, only those TCs have been used, which showed the aforementioned disruption around the eutectic Al–Si temperature, when mounted on the rear side full area Al layer of a wafer. Subsequently, multiple TC measurements including spatial spot variation on the wafer and wafer variation itself have been conducted. The noncalibrated temperature of the TC (TC') (°C) contacted spots has been adapted to the corresponding TC (TC) measured temperature via linear fit calibration, according to Equation (1), with a being the slope and b (°C) the y-intercept.

\[ T_{TC} = aT_{TC'} + b \]

In this work, the thermography measurements have been demonstrated on PERC wafers, which is the current industrial standard. Hereby, three PERC structures have been evaluated. First, wafers with a standard full area Al rear contact with and without a standard H-pattern Ag grid (called “grid”) front contact (“monofacial” configuration) were investigated, as this type represents the industrial standard type, making up the lion share of PERC production. Second, wafers with an Al grid rear contact with and without an Ag grid (“bifacial” configuration) were studied, as this type grows annually in market share within the PERC section. Finally, nonmetallized wafers were investigated as well, as this configuration serves as an important test structure for quality assurance of PERC precursors. For each configuration, separate thermography-measured temperature calibration has been conducted. Hereby, optical artifacts have been considered, as well.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Keywords**

contact firing, conveyor furnace, infrared thermography, quality assurance, temperature measurement

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