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Title: In Situ Surface Temperature Measurement in a Conveyor Belt Furnace via Inline Infrared Thermography

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Author Questionnaire

1. Microscopy: Does your protocol involve video microscopy? **N**

2. Software: Does the part of your protocol being filmed demonstrate software usage? **Y**

3. Filming location: Will the filming need to take place in multiple locations? **N**

Introduction

1. Introductory Interview Statements

REQUIRED:

1.1. **Daniel Ourinson**: As it is crucial to measure the temperature of the objects processed in inline furnaces, here we present inline thermography as a promising alternative to classic temperature measurements by thermocouples **[1]**.

1.1.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera

REQUIRED:

1.2. **Gernot Emanuel**: Thermocouples damage the object, measure the temperature locally, and require a production interruption. Our inline thermography camera, however, measures the object temperature in a contactless, real-time, spatially resolved manner **[1]**.

1.2.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera

OPTIONAL:

1.3. **Florian Clement**: We use inline furnaces for contact firing of silicon solar cells. Therefore, we installed an inline thermography camera into our furnace to investigate these advantages **[1]**.

1.3.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera

Protocol

2. Infrared (IR) Camera Installation into an IR-Lamp-Based Conveyor Belt Furnace

2.1. Select a camera with a detection wavelength range **[1]** that matches the wavelength range of the highest emission of the object of interest in the temperature range of interest as much as possible **[2]**.

2.1.1. WIDE: Talent picking up/inspecting camera

2.1.2. LAB MEDIA: Screenshot_1 *Video Editor: please outline/emphasize vertical grey box*

2.2. To install the camera outside of the furnace chamber **[1]**, remove the furnace wall and isolation at the location where the optical path should be located **[2]**, avoiding disturbing objects, such as infrared lamps, in the optical path [3].

2.2.1. Shot of the furnace chamber from the lateral perspective without the window and camera.

2.2.2. Shot of a look into optical path from the hole.

2.2.3. Talent pointing at IR lamps while furnace chamber is shown in the lateral perspective.

2.3. Install a window that is as transparent as possible above the hole for the detection wavelength of the camera and that can isolate the furnace chamber thermally **[1]**.

2.3.1. Shot of window in furnace *Video Editor: please indicate window as necessary*

2.4. Then place the camera above the window so that the camera has a visual on the moving belt **[1]**.

2.2.2. Shot of camera above window

2.3. Avoid as much parasitic radiation detection by the camera as possible by avoiding objects that emit or reflect radiation within the field of view of the camera **[1-TXT]**.

2.3.1. LAB MEDIA: Screenshot_6 *Video Editor: please emphasize red data line* ***TEXT: e.g.*****, low portion IR lamp parasitic radiation**

2.4. Then examine the thermography **[added]** image via the infrared camera software to check the resulting field of view of the camera **[1]**.

Added shot: Talent working on the camera software

2.4.1. SCREEN: Screenshot_7: 00:06-00:14

3. Customer Factory-Calibrated IR Camera Temperature Correction for Silicon Solar Cells

3.1. For a customer temperature correction for silicon solar cells **[1]**, first check the solar cell for local optical artifacts **[2-TXT]**.

3.1.1. WIDE: Talent presenting both surfaces of silicon solar cell

3.1.2. SCREEN: Screenshot_8: 00:00-00:20 *Video Editor: At 00:20 please emphasize square and add "Optical artifact due to shading" text*

3.2. As the temperature correction is based on thermocouples, to check the thermocouple validity **[1]**, mount the thermocouple on the rear aluminum side of the wafer **[2]** and measure the time-temperature profile for a standard firing process **[3]**.

3.2.1. Shot of thermocouple

3.2.2. Talent placing thermocouple on wafer *Videographer: Important step*

3.2.3. Talent placing thermocouple system inside the furnace inlet

3.3. If the time-temperature profile shows a disruption in the form of a flatter curve at the aluminum-silicon eutectic temperature of 577 degrees Celsius, the thermocouple is most likely correctly calibrated **[1]**

3.3.1. LAB MEDIA: Screenshot_10 *Video Editor: please emphasize blue circle and/or disrupt* **TEXT: Check for characteristic temperature points; here Al-Si eutectic temperature shown**

3.4. Conduct thermocouple measurements with the validated thermocouple mounted on the rear side of the solar cell outside of the field of view of the camera **[1]** and record the wafer with the infrared camera **[2]**.

3.4.1. Talent putting thermocouple system with solar cell into the furnace inlet

3.4.2. SCREEN: Screenshot_27: 0:04-0:20 *Video Editor: please add "Thermocouple" near thermocouple encircled by cursor at 00:06-00:08*

3.5. Conduct multiple thermocouple measurements in the temperature range of interest at the same object spot **[1]** and at spatially various random object spots to obtain statistically significant time-temperature profiles **[2]**.

3.5.1. Talent preparing same spot

3.5.2. Talent preparing new spot

3.6. To determine the local uncorrected thermography solar cell temperature under the thermocouple, extract the local temperature at the position of the thermocouple [1-TXT].

3.6.1. SCREEN: Screenshot_28: 0:02-0:16 **TEXT: Extract temperature from same field of view spot for each measurement**

3.7. Plot the measured temperatures via thermocouples **[1]** against the determined temperatures via uncorrected infrared thermography **[2]** and obtain a curve fit as a general uniform global correction formula for the uncorrected thermography image **[3]**.

3.7.1. SCREEN: Screenshot_14 *Video Editor: please emphasize y-axis*

3.7.2. SCREEN: Screenshot_14 *Video Editor: please emphasize x-axis*

3.7.3. SCREEN: Screenshot_14 *Video Editor: please emphasize red data line and arrow and text*

3.8. Then use this curve fit data to correct the uncorrected thermography image globally **[1-TXT]**.

3.8.1. SCREEN: Screenshot_29 0:02-0:19 **TEXT: Correction applies to wafer only, not surrounding**

4. 2D Peak Temperature Distribution Map Creation and Spatial Surface Temperature Distribution Evaluation

4.1. To create a two-dimensional peak temperature distribution map, write a script in an appropriate programing language **[1-TXT]** to track the surface temperature for each object surface spot along the entire camera field of view to act as a “virtual thermocouple“ placed at all of the wafer spots simultaneously **[2]**.

4.1.1. WIDE: Talent at computer, writing script **TEXT: *e.g.*, MATLAB**

4.1.2. SCREEN: Screenshot_30: 0:10-0:43 *Video Editor: please speed up*

4.2. Then extract the peak temperature value for each spot **[1]** and plot these temperatures in a corresponding 2D distribution map **[2]**.

4.2.1. SCREEN: Screenshot_30: 0:42-0:52

4.2.2. SCREEN: Screenshot_30: 0:52-1:02

4.3. To perform an average temperature distribution in the throughput direction, average the 2D temperature distribution in the dimension perpendicular to the throughput direction **[1]**.

4.3.1. SCREEN: Screenshot_30: 1:00-1:11 Video of 2D temperature distribution in throughput direction being averaged

4.4. To perform an average temperature distribution perpendicular to the throughput direction, average the 2D temperature distribution in the dimension in the throughput direction **[1]**.

4.4.1. SCREEN: Screenshot_30: 1:10-1:21 Video of 2D temperature distribution in throughput direction being averaged

Protocol Script Questions

A. Which steps from the protocol are the most important for viewers to see?
3.5.1., 3.9.2.

B. What is the single most difficult aspect of this procedure and what do you do to ensure success?
n/a

Results

5. Results: Representative Temperature-Corrected Thermography and Distribution for Passivated Emitter and Rear Solar Cells (PERC)

5.1. As demonstrated in this figure, the corrected temperature of this silicon solar cell can be clearly detected by the infrared camera in different configurations **[1]** - monofacially metallized **[2]**, bifacially metallized **[3]**, and nonmetallized PERC (perk) samples **[4]**.

5.1.1. LAB MEDIA: Figures 3B-3D
5.1.2. LAB MEDIA: Figures 3B-3D *Video Editor: please emphasize Figure 3B*
5.1.3. LAB MEDIA: Figures 3B-3D *Video Editor: please emphasize Figure 3C*
5.1.4. LAB MEDIA: Figures 3B-3D *Video Editor: please emphasize Figure 3D*

5.2. In these analyses, the temperature range of interest resembled the typical peak temperature range of the firing process **[1]**.

5.2.1. LAB MEDIA: Figures 3B-3D *Video Editor: please add temperature range from Figure 3B*

5.3. As observed in this image **[1]**, the contacting thermocouple on the opposite side of the optical path caused a temperature drop around itself **[2]**, most likely due to heat dissipation and shading **[3]**.

5.3.1. LAB MEDIA: Screenshot_28 0:07
5.3.2. LAB MEDIA: Figure 3A *Video Editor: please add double arrow and formula as in original Figure 3A*
5.3.3. LAB MEDIA: Figure 3A

5.4. The latter drop is important for estimating the cell temperature during firing without thermocouples **[1]**, compared to the temperature measured by the thermocouple **[2]**, as for this cell positioned onto a frame when contacted by a thermocouple **[3]**.

5.4.1. LAB MEDIA: Screenshot_22 *Video Editor: please add TAV formula*
5.4.2. LAB MEDIA: Screenshot_25
5.4.3. LAB MEDIA: Screenshot_26

5.5. If placed directly on the belt, the infrared camera allows observation of the local heat dissipation of the cells by the conveyor belt **[1]**.

5.5.1. LAB MEDIA: Screenshot_23

5.6. Since silicon solar cells are typically around 160 micrometers thick and processed in the furnace for 30 seconds **[1]**, it is likely that the temperature distribution along the cell depth will be homogenous **[2]**.

5.6.1. LAB MEDIA: Figure 4 *Video Editor: please emphasize solar cell image*

5.6.2. LAB MEDIA: Figure 4 *Video Editor: please emphasize In Transport Direction data line*

Conclusion

6. Conclusion Interview Statements

6.1. **Gernot Emanuel**: As we use inline furnaces for the contact firing of silicon solar cells, we installed an infrared camera into our furnace to create an innovative thermography application **[1]**.

6.1.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera

6.2. **Daniel Ourinson**: Obtaining spatially resolved peak temperature distributions during the firing process allows the investigation of temperature distribution correlations to the spatially resolved solar cell parameters that are significantly affected by the firing **[1]**.

6.2.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera