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From short-term hotspot measurements to long-term module reliability

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Abstract

In order to reach high module reliability, all solar cells with a potentially critical hotspot have to be neglected during cell sorting. This is essential to avoid delamination in case of partial shading of the module. Due to throughput considerations, the finished solar cell has to be classified within some milliseconds. In consequence the short-term hotspot heating measurement has to be correlated to absolute hotspot temperatures for various module conditions in the field. Previously it has already been shown that a definite mapping of these quantities is not possible, requiring further investigations in order to quantify the risk for possible module damage.

In this contribution, the probability distribution for absolute hotspot temperatures in the module will be calculated from short-term hotspot measurement data, considering temperature-dependent reverse biases. Together with experimental data for module delamination temperatures, the probability of module failure can be calculated in a direct way.

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1. Introduction

Local hotspots of solar cells can cause local heating and subsequently delamination of the module in case the concerned solar cell is shadowed (see for example [1]). In order to avoid such local heating, critical hotspots have to

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be detected during classification of solar cells. Therefore a fast measurement of hotspots is needed. Common systems evaluate the local solar cell heating during the acquisition of the dark reverse IV curve using an infrared sensitive thermography camera. This measurement is typically performed within some milliseconds. For module reliability, it is the long-term steady-state temperature of hotspots that matters, hence necessitating a correlation between the short-term hotspot heating and the long-term absolute hotspot temperature. In [2] it was shown that a simple approach of a linear correlation is not constructive, hence further investigations are required.

2. Correlation between short-term and long-term hotspot measurements

Long-term thermograms were acquired using a calibrated infrared camera (InfraTec ImageIR 8300). The measurement time was at least 60 seconds and additionally checked for stable cell temperature, while the cell was reverse biased at – 12 V. The actual voltage for hotspot measurements was determined by the maximum voltage the remaining cells of a cell string within a module can build up. Commonly, for cells with an open-circuit voltage of 630 mV and 20 cells in one cell string, this leads to 19 x 0.63 V ≃ 12.0 V.

For our evaluation, 150 monocrystalline Al-BSF solar cells with a short-term heating of 10 K to 15 K, but electrically ok, were chosen. Short-term thermograms were acquired during the dark reverse curve after 60 ms using a FLIR A325 infrared camera. In Fig. 1 the correlation between short- and long-term infrared hotspot detection for these cells is depicted. Although there is an overall linear correlation, it can be seen that a definite mapping is not possible. This makes it impossible to determine a short-term heating threshold.

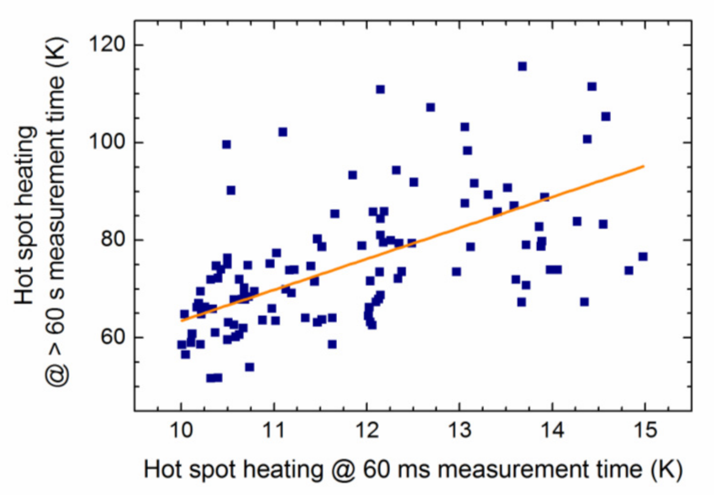

Fig. 1. Correlation between short- and long-term infrared hotspot detection for 150 monocrystalline Al-BSF solar cells.

One way to deal with this uncertainness would be to increase the acquisition time of the hotspot measurement. However, preliminary data indicate that the acquisition time should be in the range of seconds, which would limit the throughput of cell sorters drastically. In the following sections, another way is presented to deal with these short-term hotspot measurement limitations.

3. Correlation between hotspot heating and hotspot temperature

During cell classification, but also during steady-state hotspot measurements in the laboratory, only the relative heating of the hotspot is measured. For module reliability, it is the absolute long-term steady-state temperature of hotspots that matters and a correlation between the measured hotspot heating and the absolute hotspot temperature in the module is necessary.

3.1. Relative hotspot heating

For measuring the heating of a hotspot after applying a reverse voltage, the temperature of the solar cell without applying any voltage is subtracted from the measured hotspot temperature with applied reverse voltage. Due to the fact that the determination of hotspot heating is only carried out at one fixed reverse voltage (here – 12 V), the relative hotspot heating for varying reverse voltages is of interest. For this, the hotspot heating of six solar cells with a hotspot heating of 63.0 K to 113.3 K (at – 12 V) were measured for varying reverse voltages. It was found that the relative hotspot heating is nearly the same for all solar cells, independent from the hotspot temperature at – 12 V (see Fig. 2), which allows the correlation of acquired hotspot heatings to different reverse voltages.

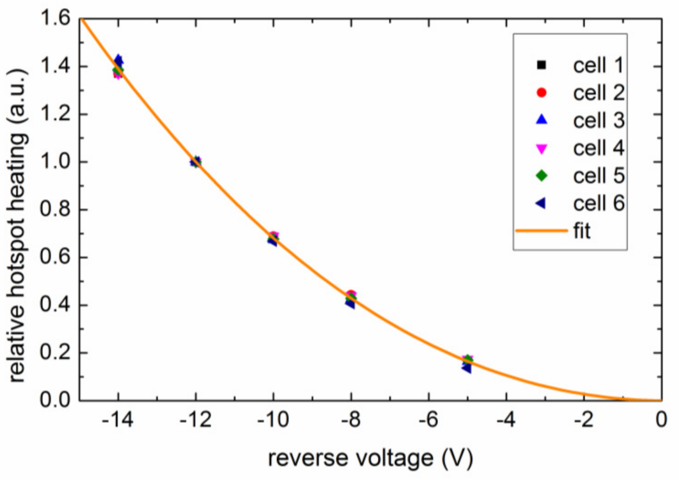

Fig. 2. Relative hotspot heating for varying reverse voltages. Cells with different long-term hotspot heatings from 63 K to 113 K were chosen, showing the same relative behavior.

3.2. Absolute hotspot temperatures

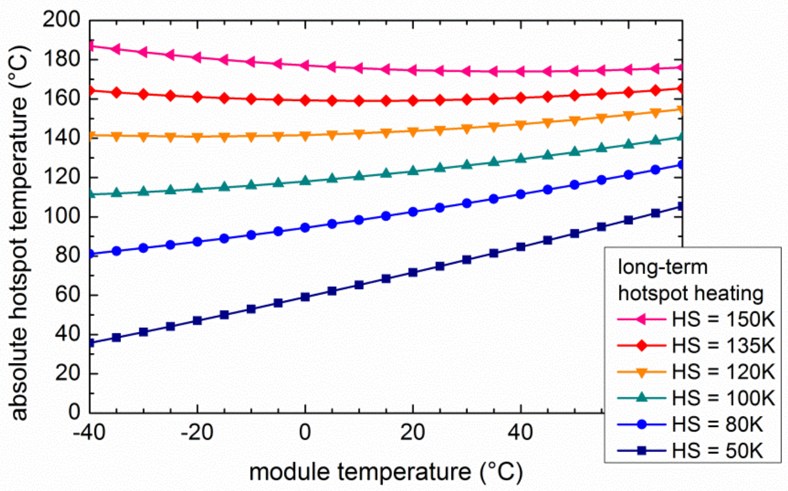

Fig. 3. Calculated absolute hotspot temperatures for varying module temperature and different hotspot heatings. Temperature-dependent reverse voltages were accounted by appropriate temperature coefficients.

For varying module temperatures and different hotspot heatings, the resulting absolute hotspot temperature can be calculated. Since the open-circuit voltage of a solar cell is temperature dependent, the change in maximum possible reverse voltage at the hotspot cell has to be accounted for. Therefore it is assumed an open-circuit voltage of 630 mV (at 25 °C) and a temperature coefficient for the open-circuit voltage of – 2.1 mV/K for the investigated solar cells.

As can be seen in Fig. 3, high module temperatures lead to the highest hotspot temperatures, except for hotspots with a heating above 135 K, which lead also under low temperatures to high hotspot temperatures. This trend gets worse for modules with more cells in series, what is not depicted here.

With these findings, it is now possible to correlate the experimentally acquired short-term hotspot heatings from cell classification with absolute long-term hotspot temperatures in the module for arbitrary module temperatures in the following way:

- Measure short-term hotspot temperature increase $T_{st\text{-}increase}$
- Measure long-term steady-state hotspot temperature increase: $\mathrm{T}_{\mathrm{lt\text{-}increase}}$
- Calculate relative hotspot temperature increase $a_{rel\text{-}increase}$ for varying cell / module temperatures; input for the calculations: open circuit voltage at 25°C, temperature coefficient for open-circuit voltage, cells in series in one string, fit from Fig. 2
- Calculate the resulting absolute hotspot temperature for varying module temperatures: $\mathrm{T}_{\mathrm{absolute}} = \mathrm{T}_{\mathrm{module}} + a_{rel\text{-}increase} \times \mathrm{T}_{\mathrm{lt\text{-}increase}}$, correlate it to $\mathrm{T}_{\mathrm{st\text{-}increase}}$
- For different thresholds of $\mathrm{T}_{\mathrm{st\text{-}increase}}$ calculate the resulting $\mathrm{T}_{\mathrm{absolute}}$-distribution

4. Module limitations

In order to evaluate the consequences of the above findings for module reliability, the temperature, at which module delamination starts, has to be determined. For this, modules with one cell each were built using materials from standard module process. Using the same calibrated infrared camera setup from above, the temperature, where the module delamination process starts, was experimentally determined by increasing the reverse voltage. This was repeated for several modules. The resulting probability distribution is shown in Fig. 4 as a dashed line.

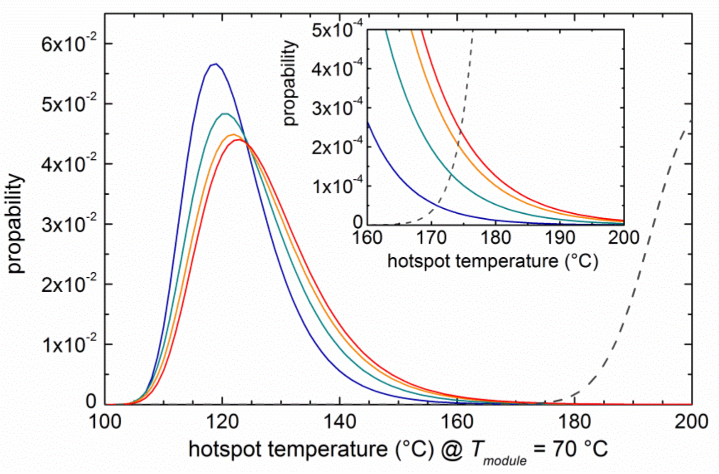

Fig. 4. Distribution of the hotspot temperature for different classification thresholds (blue = 12 K, green = 13 K, orange = 14 K, red = 15 K). The experimentally determined probability curve for module delamination due to hotspots is shown as a dashed line.

Dependent of the actual threshold for hotspot classification, different probability distributions for the resulting steady-state absolute hotspot temperature can be calculated. The calculated distributions for the extreme case of a module temperature of 70 °C and an incident light intensity (which influences the open-circuit voltage) of

1000 W/m^2 are depicted in Fig. 4. These calculations were performed for a threshold of 12 K (blue line), 13 K (green line), 14 K (orange line), and 15 K (red line), respectively.

From the overlap of the hotspot temperature probability distribution with the probability for module delamination, the actual percentage of cell failure can be calculated.

Knowing the number of investigated cells (here 150) and percentage of such cells from the total production output, the total risk for cell or module failure, respectively, can be calculated for the (very unlikely) assumption that the hotspot afflicted cell is being critically shaded while the module has a temperature of 70 °C and is illuminated with 1000 W/m^2.

Table 1. Risk of cell and module failure, respectively. The module consists of 60 cells, interconnected in 3 strings.

Risk of cell failure	Risk of module failure
0.027 ppm	1.6 ppm

5. Summary

In this contribution, it was shown that a direct correlation between measured short-term heating of a local hotspot and the long-term absolute temperature is not possible.

However, a method was proposed, to estimate the risk of module failure due to hotspots. Using this method, probability distributions can be calculated, based on experimentally accessible data for short-term and long-term heating. Taking temperature-related effects into account, the absolute hotspot temperature can be calculated subsequently. Together with experimental data concerning module delamination processes, the risk of module failure can be calculated in a direct way, allowing for optimizing the short-term hotspot heating threshold for yield and module reliability.

References

[1] F. Fertig, et al., “Impact of junction breakdown in multi-crystalline silicon solar cells on hotspot formation and module performance”, 26th EU-PVSEC, Hamburg, Germany, 2011

[2] T. Roth, et al., “Determining the temperature of bare solar cells and local hotspots during IV measurements”, 28th EU-PVSEC, Paris, France, 2013