Illuminated lock-in thermography at different wavelengths for distinguishing shunts in top and bottom layers of tandem solar cells

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We investigate shunting in a micromorph silicon tandem solar module using dark and illuminated lock-in thermography (DLIT and ILIT). Shunts are identified and quantified using DLIT. We then show how to isolate the layer causing the individual shunts by using white, blue, and infrared excitation spectra for the pulsed illumination in ILIT.

1 Introduction
Lock-in thermography is an established laboratory tool to characterize lateral location and strength of shunts and other loss mechanisms in solar cells for a variety of conditions [1]. In multi-junction and tandem solar cells, however, the layer which is affected by the shunt cannot be derived from standard ILIT/DLIT.

For loss mechanism characterization, DLIT is usually the preferred method for two reasons. Firstly, the images can be more easily evaluated as the only relevant contribution in most cases is dissipative (I·V) everywhere in the sample. In contrast, Peltier contributions are always visible in ILIT images and need to be taken into account if quantitative information is desired [2, 3]. Secondly, the overall contrast is better in DLIT as no homogenous contributions from thermalization and optical losses needs to be considered; both of which can be difficult to control experimentally [2, 4].

Although ILIT is thus not well suited for quantitative evaluation, it has an additional free parameter that can be used to gather supplementary information about the loss mechanism: the spectrum of the excitation. The differential absorption in the layers makes it possible to identify the layers affected by the shunts.

In our contribution, we test the approach of characterizing the shunt using DLIT and then identifying the affected layer by spectrally selective ILIT. The test sample is an experimental micromorph silicon tandem module made at the FZ Jülich [5].

2 Theory
A single micromorph silicon tandem cell consists of an amorphous layer on top of a microcrystalline bottom layer. Both cells are series connected through a tunnel contact of low lateral conductivity. An electrical schematic and the cell design used [5] is shown in Fig. 1.

Figure 1 (a) Electrical schematic of a tandem cell in a micromorph module. The top and bottom layer cells are shown in the one-diode model with a diode and a current source in parallel. Ohmic resistance in the top and bottom contact is omitted for clarity in the electrical schematic. (b) Layer stack.

In DLIT, a periodic bias is applied to the terminals in the dark (inactive current sources in the Fig. 1a). If a shunt is visible in DLIT at a certain point in the module, there is...
no way of telling which layer is affected. For broadband ILIT with open terminals ($V_{oc}$-ILIT) this is also not possible. If, however, blue or infrared irradiation is used, only the amorphous or the microcrystalline layer, respectively, will be excited. For blue light, the amorphous layer has an absorption close to one while near infrared light passes unabsorbed as its photon energy is smaller than the a-Si:H bandgap. Therefore, under open circuit conditions, blue light will show only shunts that affect the amorphous layer, while infrared light will show shunts that affect the microcrystalline layer.

A straightforward shunt classification based on this effect is given in Fig. 2. From this classification and the above considerations, a visibility table of shunts in ILIT can be derived, Table 1.

![Shunt classification. Type (a) and (b) affect only one layer. Type (c) and (d) affect both layers at the same location, in contact with (c) or isolated (d) from the interface.](image)

Table 1 Visibility table for shunts in $V_{oc}$-ILIT using white, infrared and blue excitation.

<table>
<thead>
<tr>
<th>Type</th>
<th>White</th>
<th>Infrared</th>
<th>Blue</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>visible</td>
<td>visible</td>
<td>not visible</td>
</tr>
<tr>
<td>(b)</td>
<td>visible</td>
<td>not visible</td>
<td>visible</td>
</tr>
<tr>
<td>(c)</td>
<td>visible</td>
<td>visible</td>
<td>visible</td>
</tr>
<tr>
<td>(d)</td>
<td>visible</td>
<td>not visible</td>
<td>not visible</td>
</tr>
</tbody>
</table>

In a module, interaction between the individual cells might disturb this table. For that to be the case, neighbouring cells have to build up a voltage over a shunt in a layer that is not excited by the current illumination. Then this shunt would be visible, in contradiction to Table 1.

However, this can only happen under open circuit conditions if noticeable, cm-scale potential gradients on the contacts develop. These gradients can be reliably prevented by using low intensity illumination (< 0.1 sun).

3 Experimental

3.1 Light sources The three light sources used are: a tungsten light bulb, a blue and an infrared diode array. The light bulb (75 W) and the small array of blue diodes (1.6 W) both have a E27 standard socket and were widened in the lamp shade of a desk lamp and diffused using white PE foil or frosted glass. The resulting light is sufficiently homogenous for the classification according to Table 1.

Our infrared light source is an array of 850 nm diodes, $16 \times 16$ cm$^2$ that cause a short circuit current in silicon solar cells corresponding to (up to) 2.5 sun. This high wavelength is advantageous for ILIT as (homogenous) thermalization losses are minimized and thus a better signal contrast is achieved.

The spectra of the three light sources were measured using a lab-built spectrometer setup, with a monochromator of type HB550i by Jobin-Yvon. They are shown in Fig. 3.

![Spectra of the light sources used for selective excitation of the µc-Si:H and a-Si:H layers of the micromorph tandem module. Amorphous silicon is clearly insensitive to the light from IR array and the light from the blue array passes the µc-Si:H undisturbed. For comparison, the quantum efficiencies of the top and bottom cells are also shown (dotted lines).](image)

Figure 3 Spectra of the light sources used for selective excitation of the µc-Si:H and a-Si:H layers of the micromorph tandem module. Amorphous silicon is clearly insensitive to the light from IR array and the light from the blue array passes the µc-Si:H undisturbed. For comparison, the quantum efficiencies of the top and bottom cells are also shown (dotted lines).

Comparison of the illumination spectra and the quantum efficiencies (measured on the same sample) shows that the condition of selective layer excitation is well satisfied.

3.2 LIT setup Our LIT setup is a Thermosensorik TDL 640-XL based on a 640 × 480 pixel InSb infrared detector array. The thermal signal caused by pulsed excitation (module voltage for DLIT, illumination for ILIT) is recorded for every pixel. Due to the lock-in correlation, environment radiation is removed and good signal to noise ratios can be achieved, such that temperature modulations smaller than 1 mK can be measured reliably [1].

Shunts are most clearly visible when series resistance effects and recombination currents are low. This is the case for a bias well below maximum power point voltage in DLIT and illuminations below 0.1 sun in ILIT. A low illumination in ILIT has the additional benefit that interaction between the cells in the module is minimized (see Sec. 2).

The LIT measurements shown here were taken at a lock-in frequency of 0.5 Hz (except 1 Hz for ILIT with blue light) and using integration times of 5 min per picture.
(except 1 h for ILIT with blue light due to the low intensity of this array).

DLIT voltage was 5 V (8 cells in the module), illumination intensity was measured using a calibrated high efficiency silicon solar cell as a fraction of its 1 sun output current of 40.2 mA. This value was 0.04 sun for both the light bulb and the red diode array and 0.01 sun for illumination using the small blue diode array.

4 Results Figure 4 shows amplitude images for DLIT and ILIT taken under the conditions described above. In the DLIT image, the shunts are labelled with capital letters A–H.

The resulting shunt type classification is shown in Table 2 below. Additionally, the cell voltage for a module bias of 5 V was measured (assuming homogenous potentials at the contacts, which is well satisfied for such a low module bias). With this additional information, the power signal derived from the DLIT images could be translated in current per shunt (also shown in Table 2).

Table 2 Shunt type classification, shunt voltage and current at 5 V module bias (derived from DLIT and direct cell voltage measurement).

<table>
<thead>
<tr>
<th>shunt label</th>
<th>infrared</th>
<th>blue</th>
<th>probable shunt type</th>
<th>shunt voltage/current at 5 V module bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>not visible</td>
<td>visible</td>
<td>(b)</td>
<td>940 mV/486 µA</td>
</tr>
<tr>
<td>B</td>
<td>not visible</td>
<td>not visible</td>
<td>(d)</td>
<td>223 mV/536 µA</td>
</tr>
<tr>
<td>C</td>
<td>visible</td>
<td>not visible</td>
<td>(a)</td>
<td>373 mV/752 µA</td>
</tr>
<tr>
<td>D</td>
<td>visible</td>
<td>not visible</td>
<td>(a)</td>
<td>438 mV/410 µA</td>
</tr>
<tr>
<td>E</td>
<td>visible</td>
<td>visible</td>
<td>(c)</td>
<td>844 mV/333 µA</td>
</tr>
<tr>
<td>F</td>
<td>not visible</td>
<td>not visible</td>
<td>(d)</td>
<td>926 mV/28 µA</td>
</tr>
<tr>
<td>G</td>
<td>visible</td>
<td>visible</td>
<td>(c)</td>
<td>926 mV/561 µA</td>
</tr>
<tr>
<td>H</td>
<td>not visible</td>
<td>not visible</td>
<td>(d)</td>
<td>158 mV/66 µA</td>
</tr>
</tbody>
</table>

5 Conclusions We have shown how to complement the quantitative information about shunt impact derived from DLIT images with the qualitative information which layer in a micromorph tandem cell is causing the shunt. Following the design of the infrared light source, better homogeneity can in principle be achieved for the white and blue light sources as well.

This method can be applied to other tandem cell concepts in a straightforward manner or even to triple junction cells if a more selective illumination is provided.

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