LOCK-IN THERMOGRAPHY INVESTIGATION OF SOLAR MODULES

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ABSTRACT: Lock-in thermography (LIT) can be used both for single solar cells and for modules consisting of a series connection of single cells. Until now LIT has been used nearly exclusively for single cells and only rarely for modules, which have been investigated only by standard (steady-state) thermography. There are some differences between LIT applied to single solar cells and to modules. The purpose of this contribution is to point out these differences. One issue is the fact that, in a module, the cell biases are floating. Another issue is that, in readily processed modules, the cells are covered by glass, EVA, or some laminate. Even before lamination the active layer is often covered by some metal layer which shows a low infrared emissivity. It is shown that in this case a good emissivity may be obtained by sucking-on a thin black plastic foil. Glass-laminate modules may be imaged best "from behind" through the laminate layer. Even glass-glass modules may be imaged "through the glass" if the lock-in frequency exceeds 0.5 Hz. However, in this case the temperature drift during the measurement is especially disturbing and must be compensated properly. It is found that the advantages of LIT compared to steady-state thermography (improved sensitivity and spatial resolution) are valid also for investigating solar modules.
Keywords: Shunts, Module, Characterization, lock-in thermography, hot spots

[1] Now with Sovello AG, Thalheim

1 INTRODUCTION

By using infrared (IR) thermography methods, irregularities in solar modules like local shunts, hot spots, broken cells, or series resistance problems, may be imaged [1, 2]. If the illumination or an externally applied bias is time-modulated and the IR images are evaluated according to the lock-in principle, the method is called lock-in thermography (LIT, [3]). While in steady-state (d.c.) thermography the surface temperature distribution of a module is imaged after the steady-state has been reached or at least some 10 seconds after applying the bias (heating up the module takes some time), in LIT the illumination/electrical heating is pulsed typically between 1 and 10 Hz. Thus, the LIT signal represents the amount of the local temperature modulation amplitude, which is a measure of the locally dissipated power density. The main advantages of lock-in thermography as compared to d.c. thermography are a better signal-to-noise ratio and an increase in spatial resolution. The latter is due to the fact that, due to the dynamic nature of this measurement procedure, the lateral heat diffusion (thermal blurring) is considerably suppressed. Moreover, LIT results may be easily interpreted quantitatively in terms of measured current densities [3, 4].

Until now LIT has been applied mostly to the investigation of solar cells and only rarely to the investigation of solar modules. One reason is that, since solar modules are much larger than single cells, thermal blurring is indeed less disturbing for modules than for cells. Moreover, glass is nominally opaque for thermal radiation. The IR radiation was expected to originate generally from the glass surface, hence the spatial resolution was expected to be limited by the glass thickness. It will be shown below that this holds only for steady-state thermography but not for LIT. Finally, since in a solar module all cells in a string are series-connected, their individual biases are floating, which indeed disturbs the quantitative interpretation of the results. Nevertheless, it will be shown below that the application of LIT may provide clear advantages compared to conventional (d.c.) thermography. In the following, first the consequences of the 'floating bias' problem are discussed. Then various imaging conditions for solar modules are compared with respect to their sensitivity and spatial resolution.

2 THE 'FLOATING BIAS' PROBLEM

One decisive difference between LIT performed on solar cells and on modules is the following: If a single cell is investigated, the biasing occurs in constant voltage mode. Hence, if the series resistance of the interconnection is negligible, a well-defined voltage is applied to the cell and, within the resolution limit of about one thermal diffusion length (a few mm in Si), the LIT signal is proportional to the locally flowing current density. In a solar module, on the other hand, all cells are series-connected; hence, they all carry the same current. Then the individual cell biases are floating according to the individual cell characteristics. Only the sum of all biases is the bias applied to the module.

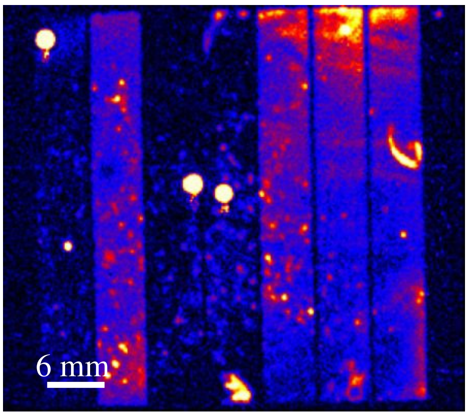

Fig. 1: LIT image (amplitude, a.u.) of a shunted CIS mini module. Due to severe shunting in three of the seven cells, the bias in these three cells is significantly lower than in the other cells

Fig. 1 shows a LIT image of a Copper-Indium-Sulfate (CIS) mini module imaged from the active layer side before encapsulation [5]. Here the surface is covered by a TCO layer which, together with the underlying cell, shows a sufficiently high IR emissivity to enable LIT investigation. This module consists of seven cells connected in series. The bright spots are all local shunts, which are sites showing a locally increased forward current. Of the seven cells, only in four of them the cell area appears bright. This is a consequence of the fact that these four cells are only weakly shunted, whereas the three other cells are more heavily shunted. For the same current flowing through all cells, the more heavily shunted cells exhibit a lower bias than the other cells. Since the current flow through the area is strongly bias-dependent, only for the four less shunted cells the forward bias is large enough that an appreciable areal current is flowing. This is a general property of wafer-based modules and most thin-film technologies: a single strong shunt in a cell short-circuits the whole cell. This problem is weakened in the CSG technology (Crystalline Silicon on Glass [6]), where, due to an interdigitated contacting scheme, the electric conductivity along the cell stripes is much lower than in current direction parallel to the contact pads [7]. For a quantitative interpretation of LIT results on solar modules the individual local cell bias in the considered position must be known. Then, if the series resistance can be neglected, the LIT signal is proportional to the local current density multiplied by the local cell bias.

3 VARIOUS MODULE IMAGING CONDITIONS

As demonstrated in Fig. 1, the best way to image thin film modules is to directly image the active layer before encapsulation. Then, if the IR emissivity is high enough, the LIT signal height is maximum and the spatial resolution is not degraded. However, in all superstrate technologies (like CSG) the device side is usually metallized at the top and shows a very low IR emissivity. Then the usual way in thermography to increase the emissivity is to apply a black paint to the surface. Such a paint layer may be hard to remove after the investigation. Therefore we are successfully using a thin (23 µm) black polyethylene foil which is used for packaging purposes (rs40-B "ratioform-Stretch" by www.ratioform.de), sucked to the active module surface by a vacuum [3]. Interestingly, the LIT observation is also possible "through the glass" showing a spatial resolution much better than the glass thickness, see below.

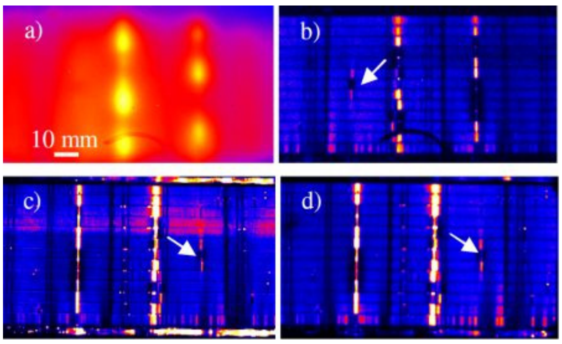

Fig. 2: Thermography on an experimental CSG solar module; (a) d.c. thermography, LIT with observation (b) through the glass, (c) from the bare active layer, (d) from the active layer with black foil

Fig. 2 shows a comparison of a d.c. thermogram of an experimental CSG module from the glass side (a) and LIT images "through the glass" (b), from the bare device side (c), and from the device side by using the black IR emitter foil (d, all images separately scaled). Since (c) and (d) were imaged from the other side of the module, these images appear horizontally mirrored to (a) and (b). The glass thickness was 3 mm. The remarkable improvement of the spatial resolution of LIT compared to steady-state thermography is visible in all LIT images. Even in (b) the spatial resolution is considerably better than 3 mm, which was expected for radiation coming from the glass surface. Especially the characteristic feature of a single shunt, see arrows in (b, c, d), is only visible in the LIT images but not in the steady-state thermogram. In the bare device-side image (c) the IR emission stems mostly from the gaps between the aluminum contact stripes, which leads to some image artifacts. The magnitude of the LIT signal in (d) was about 10 times higher than in (c).

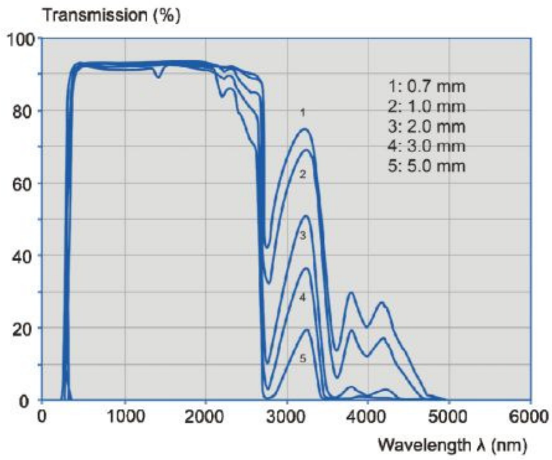

Fig. 3: Spectral transmission data of borosilicate glass [8]

The image formation "through the glass" can be explained using the fact that glass is not completely opaque to the thermal IR radiation. Figure 3 shows the IR transmittance of borosilicate (borofloat) glass [8]. A 3 mm thick sheet still has a certain transmittance in the wavelength range of 3–5 µm detected by mid-range thermal imaging cameras. For an InSb detector we have found a damping of the thermal radiation of 99 % through the glass, with only 1 % of the modulated IR signal penetrating the glass. Simultaneously thermal waves are traveling from the active layer into the glass towards its opposite surface. The IR emission due to thermal waves close to the glass surface has to penetrate only a thin layer of glass. Hence it suffers little optical damping. A rigorous treatment of this problem shows that for lock-in frequencies below 0.5 Hz most of the radiation is generated close to the glass surface, but for frequencies above 0.5 Hz most radiation stems from the active layer [9]. If the lock-in frequency used is not too low (in the example 1 Hz), the signal may be still large enough to be detected even after only a few minutes of acquisition time and shows a good spatial resolution. Note that, due to the lower heat conductivity of glass compared to silicon, the LIT signal height of thin film modules is about 10 times higher than for crystalline cells. For d.c. thermography, on the other hand, the radiation stems predominantly from the glass surface. For this d.c. imaging technique the spatial resolution is additionally degraded by thermal blurring.

4 THE TEMPERATURE DRIFT EFFECT

For thermal wave observation "through the glass" an interesting disturbing effect occurs. In Figure 4 another experimental CSG module was imaged by using various acquisition times; all images are shown in the same scaling. As Fig. 4 a) shows, the image is not dominated by noise already after 3 minutes acquisition time, but it appears very blurred. It looks rather similar to the steady-state IR image 2 a). Only after a very long acquisition time (here 50 min) the expected LIT image appears. The reason for this transition from a steady-state image to a lock-in image is the temperature drift of the glass surface. After starting to apply the pulsed bias to the device, its temperature rises and it takes some minutes until its temperature has stabilized again. Since this drift is a slow process and spreads over the whole thickness of the device, it is detected "un-damped" by the IR detector, whereas the modulated radiation is damped by a factor of 100. Therefore, if solar modules are imaged "through the glass", the influence of this drift is a factor of 100 stronger than usually. Fortunately, this temperature drift can be compensated by evaluating the thermograms taken before and after the LIT measurement [3, 10]. If this temperature drift correction is applied, LIT can be performed even through the glass of solar modules with acquisition times of only a few minutes.

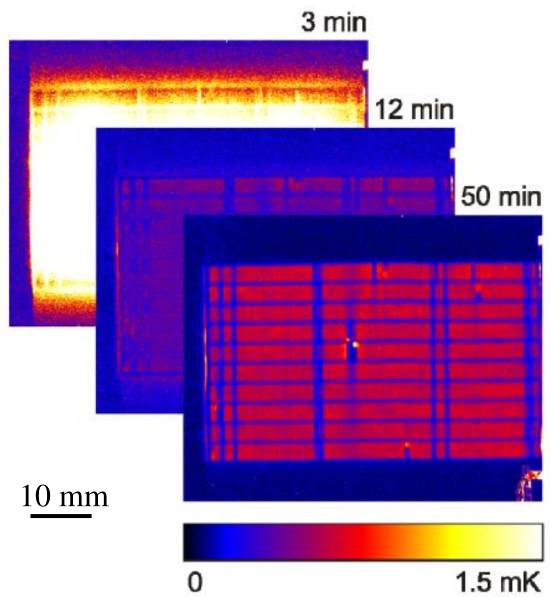

Fig. 4: Image evaluation in a LIT experiment through a 3 mm glass substrate

5 CONCLUSIONS

In this contribution it was demonstrated that the application of lock-in thermography is very advantageous compared to conventional (d.c.) thermography not only for single solar cells but also for solar modules. Both the sensitivity and especially the spatial resolution are considerably improved. Therefore special types of defects, like single shunts in CSG modules, can be localized only by LIT. It was discussed how the interpretation of LIT results of modules differs from that of single cells. Different LIT imaging conditions for modules (imaging the bare component side, component side with black foil, through the laminate, through the glass) were compared to each other. It was found that LIT imaging through the glass is possible if a lock-in frequency above 0.5 Hz is used and the temperature drift during the measurement is properly corrected.

The support of this work by the SiThinSolar project (# 03IP607) is gratefully acknowledged. The authors are indebted to I Gavilanes (previously Hahn Meitner Institute Berlin) for providing the module used for Fig. 1) and to CSG Solar (Thalheim) for fruitful cooperation.

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