RANGE OF LOSS MECHANISMS ACCESSIBLE BY ILLUMINATED LOCK IN THERMOGRAPHY (ILIT)

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ABSTRACT: Illuminated Lock-In Thermography (ILIT) was introduced as a further development of Dark Lock-In Thermography (DLIT) in 2004 and allows to measure under conditions considerably closer to real operation conditions of solar cells. Recently, a number of different modes were developed, that differ in the measurement conditions chosen.
This contribution investigates favorable measurement conditions for the most important parameters of a solar cell. It will be shown that adapted modes of Lock-In Thermography are well suited for the investigation of linear and non-linear shunts, bulk material quality and losses due to series resistance as e.g. contact resistance and inappropriate metalization patterns. Bulk material quality is best investigated under open circuit conditions (V_{OC}-ILIT), whereas series resistance problems dominate the Thermography image under short circuit conditions (J_{SC}-ILIT). Shunts on the other hand tend to dominated the measurement at intermediate to high voltages, thus offering the possibility to distinguish between losses due to shunting and due to series resistance. Finally, good agreement between contact resistance images obtained by J_{SC}-ILIT and emitter potential maps obtained by Corescan is demonstrated.
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1. INTRODUCTION

Illuminated Lock-In Thermography (ILIT) is a patent pending [1] further development of Dark Lock-In Thermography (DLIT) [2] for the characterization of solar cells, that was recently introduced by some of the authors [3],[4]. It was shown that ILIT is the first measurement technique that gives a quantitative and spatially resolved measure of the power losses in solar cells under operation conditions [3]. A similar idea resulting in a comparable measurement setup was independently realized at University of Konstanz and published slightly later [5].
DLIT and ILIT offer a wide range of possible measurement modes. The most relevant experimental parameters, that significantly influence the cell parameters investigated and thus the resulting thermography image, are the voltage applied to the solar cell and the change of illumination intensity and voltage with time within the Lock-In period.
Originally, ILIT was mainly used under open-circuit conditions (V_{OC}-ILIT) to investigate material quality and to measure on unfinished solar cells during the cell process. Additionally, it was used at the maximum power point (MPP) for investigating the influence of different loss mechanisms on cell performance. Meanwhile different measurement modes have evolved which are primarily tailored to the investigation of losses in series resistance [6-9].
In this paper we will demonstrate that - by choosing appropriate measurement conditions - ILIT not only allows to investigate the most relevant loss mechanisms in solar cells, notably series resistance, parallel resistance, recombination and dark saturation currents but also to distinguish between them.
The next section will give a brief overview of the most relevant parameters characterizing loss mechanisms in a solar cell and advantageous measurement conditions to determine them. After that, each measurement mode will be discussed in more detail.

2. LOSS MECHANISMS AND THERMOGRAPHY MODES – AN OVERVIEW

As was shown before [3],[4] the most relevant measurement mode for a realistic evaluation of the influence of different loss mechanisms on overall cell performance under operation conditions is Illuminated Lock-In Thermography (ILIT) with a voltage of V_{MPP} applied to the cell during the illuminated half of the Lock-In period and no voltage applied during the un-illuminated half of the Lock-In period (V_{MPP}-ILIT). The out-of-phase image of the temperature distribution (or –90°-Image) obtained in this mode is directly proportional to the distribution of the overall power dissipation in the solar cell under operation conditions. An illumination source, that has a small spectral mismatch with AM1.5G is advantageous for this kind of measurement.
On the other hand, different measurement conditions may be favorable, if specific parameters like dark saturation current or parallel resistance are to be investigated and the overall influence on solar cell performance is not the prime interest of the measurement. Table 1 summarizes the most important cell parameters and measurement modes that are particularly suited for the investigation of each parameter. Additional information is given on how to distinguish features observed for a particular cell parameter from other loss mechanisms. The measurement modes discussed may be extremely helpful for investigating particular problems in solar cell processing. However, it should be emphasized that the thermography images obtained from these modes do not display a realistic distribution of overall losses in the cell under operation.

3. BULK MATERIAL QUALITY AND FIRST DIODE

Power losses due to first diode current are especially prominent at relatively high (around V_{OC}) forward voltages for both ILIT and DLIT measurements. In ILIT direct recombination of carriers generated in the base is

Parameter	Intention	Method suggested	Comments
J_{01} / τ_{eff}	Detect	ILIT @ V_{OC}	J_{01} is the direct measurand
R_P	Detect	ILIT or DLIT @ $\approx V_{MPP}$	Linear and non-linear shunts detected
	Distinguish from J_{0X}	ILIT or DLIT @ $\pm \approx V_{MPP}$	Only linear shunts will result in similar signal in forward and reverse bias
R_S	Detect	ILIT @ J_{SC} or R_S-ILIT @ J_{SC} / V_{MPP}	Diode currents / bulk recombination effectively suppressed at low voltages
	Distinguish from J_{0X}, R_P	Compare ILIT @ J_{SC} to ILIT @ V_{OC} / V_{MPP}	Several methods of comparison proposed herein and by Breitenstein et al. (see e.g. [7])
J_{02}	Detect	ILIT or DLIT @ $\approx V_{MPP}$	So called non-linear shunts, J_{01} may dominate at too high voltages
	Distinguish from R_P, R_S	See rows on R_P and R_S	
Overall power losses		ILIT @ V_{MPP}	Directly proportional to spatial distribution of power losses; irradiation with AM1.5G desirable

Table 1: Overview of different loss mechanisms and suggested measurement conditions. J_{01} and J_{02} are first and second diode currents, R_P parallel resistance and R_S series resistance.

Possible (direct meaning that the carriers do not cross the pn-junction). It has to be noted, that with a laterally homogeneous irradiation, as in our setup, this direct recombination is a “local” loss mechanism being proportional to the irradiation intensity and thus almost homogeneously distributed over the cell area. As defined in [3] “local” means laterally within one diffusion length from the place of electron-hole generation. Thus the recombination rate for this direct recombination is essentially constant over the cell area and cannot be detected as inhomogeneity in ILIT. On the other hand a fraction of the electron-hole pairs are separated by the pn-junction (this is the light generated current). Then, the electrons are relatively free to move laterally in the emitter and/or front side metalization. Under V_{OC}-conditions they may eventually be re-injected in the base as dark saturation current J_{01}. This is a non-local mechanism since gradients in the electrochemical potential in the emitter may cause electrons to travel laterally over distances considerably larger than their diffusion length in the base. As $J_{01} \propto L_{eff}^{-1} \propto \tau_{eff}^{-1/2}$ depends strongly on material quality and minority carrier lifetime, this dark saturation current and the resulting power dissipation in the cell is inhomogeneously distributed and may be detected by ILIT.

Additionally, it has to be considered, that - especially under V_{OC}-conditions - inhomogeneous bulk lifetime causes the emitter potential to be different in areas of high and low material quality. This results in differences in the thermalization-losses as carriers cross the pn-junction in areas of different material quality. For investigating J_{01} and thus bulk recombination ILIT measurements are preferred over DLIT for two reasons: (i) the generation of electron-hole pairs is homogeneous over the area of the solar cell and (ii) measurement conditions are closer to operation conditions.

An example of an ILIT image on a mc-cell under V_{OC} conditions is shown in figure 1. The image is almost completely dominated by J_{01}, areas of high J_{01} and thus low bulk lifetime appear bright, whereas low J_{01} and thus high bulk lifetime results in low ILIT signal (dark colors). More examples and detailed comparison with QE measurements may be found in [4].

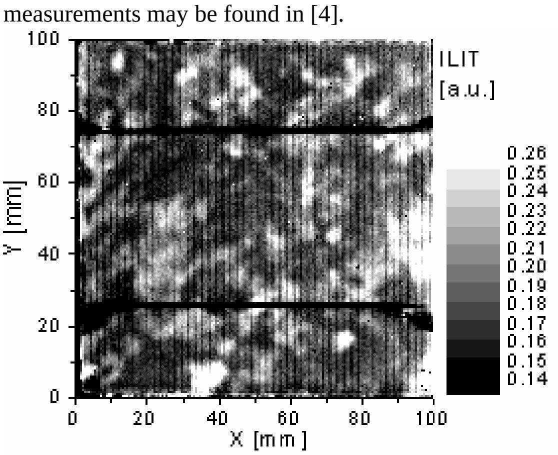

Fig.1 : ILIT -90°-Image of a multicrystalline cell, V_{OC}-conditions. The measurement is dominated by J_{01}.

4. LINEAR AND NON-LINEAR SHUNTS

So called “ohmic” or “linear” “Shunts” often occur underneath the front side metalization or at the cell edges. They result in a low parallel resistance (R_P) and are often point-like features. DLIT was originally developed for the investigation of this kind of defects and is an excellent method for detecting them. Performing a measurement at a forward bias around V_{MPP}, say 0.5V, and a second measurement under the same reverse bias allows to distinguish between linear shunts and other loss mechanisms, since only ohmic shunts result in a similar signal under forward and reverse bias. The drawback is that DLIT tends to heavily overestimate the impact of shunts underneath the front side metalization (see e.g. [3]), which may be avoided by using ILIT instead. In ILIT, typical voltages applied are again around V_{MPP}. As in DLIT a comparison to a measurement with the same voltage applied in reverse direction is used to distinguish linear shunts from e.g. dark saturation currents. Figure 2 (left) shows an ILIT Image of Cz-cell 1 at 502 mV that features dark saturation currents J_{01}, linear (ohmic) shunts and shunts with non-linear characteristics. By subtracting two times the image taken at 500mV reverse voltage from this image a new image (figure 2 - right) is obtained. Ohmic shunts disappear and comparison with figure 2 (left) allows to distinguish between ohmic and non-linear shunts. The main non-linear shunts were identified by this analysis and are marked with arrows in the left image of figure 2. The factor of two is most likely due to series resistance effects: In DLIT switching from $+V_{MPP}$ to $-V_{MPP}$ results in both the direction of the current and voltage to be changed. In ILIT on the contrary the direction of the current is the same at both voltages. Thus the voltage difference between contacts and shunt position causes the absolute value of the voltage at the shunt to be larger than V_{MPP} in forward direction, but smaller in reverse direction. For an ohmic shunt this difference in absolute voltage at the shunt position may well explain the differences observed in the thermography images. Of course it can not be completely excluded that there is a slight diode like behavior of a particular shunt besides its dominant ohmic nature. Finally, it should be noted that the difference image could be realized in one ILIT measurement if the reverse voltage is chosen slightly higher than the forward voltage.

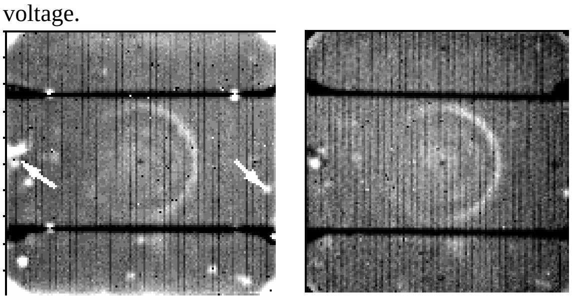

Fig. 2: ILIT –90°-Image of a Cz solar cell at 502 mV (left). Same image but with two times the image taken at –500 mV subtracted (right).

5. SERIES RESISTANCE

Series resistance (R_S) mainly arises from contact resistance, emitter sheet resistance and disruptions, constrictions, etc. of the grid. R_S may be observed by ILIT as the heating caused by current flowing through a resistor. Favorable measurement conditions are at or close to short circuit (J_{SC}-ILIT). Under these conditions loss mechanisms like shunts or dark saturation currents are effectively suppressed as the emitter potential is close to 0. Thus most of the power is dissipated by thermalization of the minority carriers in the base and while crossing the pn-junction. These processes result in a quite high, homogeneous background signal.

As the currents flowing at J_{SC} are high, Joule heating in series resistance of the metalization is rather prominent and often the most significant inhomogeneous features of the measurement. Examples may be found in [4].

Locally increased contact resistance may lead to locally increased emitter potential and redistribution of the current flows in the emitter and the front side metalization. This may lead to two contrary effects in the thermography images for not too large areas of high contact resistance: Firstly, the increased emitter potential in the badly contacted area results in a decrease of the potential difference over the pn-junction and thus in decreased thermalization heating and consequently decreased thermography signal in the poorly contacted area. Secondly, the redistribution of current patterns may lead to currents flowing within the emitter towards regions with lower contact resistance and only there into the metalization. This causes locally increased joule heating, in particular in a “corona like ring” around badly contacted regions and at places where significant power is dissipated at the semiconductor-metal interface due to the redistribution of current patterns.

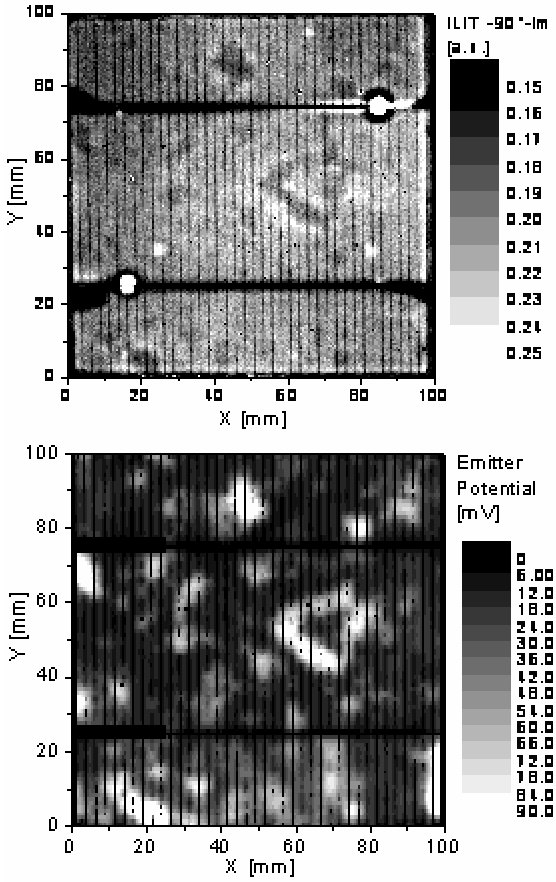

Fig. 3: J_{SC}-ILIT -90°-Image of a multicrystalline solar cell with inhomogeneous contact resistance (upper). Emitter potential map of the same solar cell measured by Corescan (lower). From [8].

Figure 3 displays a measurement showing all of these effects: The upper image shows an ILIT image taken under short circuit conditions on a multicrystalline solar cell with inhomogeneous contact resistance, the lower image displays the emitter potential map on this cell at short circuit as obtained with Corescan [10]. Excellent correlation between the J_{SC}-ILIT image and the Corescan map is found. As predicted, the areas of high emitter potential in Corescan result in a low thermography signal surrounded by a corona of higher thermography signal. Investigating the 0°-Image (not shown) reveals that the “corona” is not a homogeneous ring of increased joule heating, but that the highest power dissipation is found at the intersections of the metalization with the edges of the

poorly contacted region. This is most likely due to joule heating resulting from current crowding at the semiconductor-metal interface at these places which is caused by the extra current coming from the poorly contacted emitter region and entering the grid here.
A different method for the detection of series resistance losses was proposed by Breitenstein et al. [6],[7]. Constant illumination is used and the voltage is modulated between 0V and around V_{MPP}. A comparison between the two methods can be found in [8].

6. SHUNTS AND SERIES RESISTANCE

Shunts, non-linear or linear, often occur underneath the front-side metalization due to over-firing of (screen-printed) front-side contacts. From a technological point of view it is therefore desirable to distinguish between shunts and losses in series resistance, notably in contact resistance. This is best achieved by comparing an ILIT-image taken under J_{SC}-conditions to an ILIT-image taken at higher voltages, e.g. under V_{OC}-conditions (V_{MPP} or around would also be acceptable). Series resistances are best observed under J_{SC}-conditions, whereas all diode type losses tend to dominate the ILIT-image at higher voltages. Figure 4 shows an example, where the comparison was performed by dividing the image obtained under J_{SC}-conditions through the image taken under V_{OC}-conditions. The cell investigated received a deliberately inhomogeneous firing of the contacts with a too low firing temperature on the left hand side of the cell. Thus a region with interwoven areas of high and low contact resistance resulted on the left hand side of the cell, whereas good contact formation was made in the rest of the cell.
In the analysis presented in figure 4, bright spots indicate relatively high local signal under short circuit conditions and thus most likely series resistance problems, whereas dark spots indicate locally higher signal under open-circuit conditions, which is most likely due to shunting or locally low bulk material quality. Thus the dark spots in the central and right part of this cell indicate shunting problems, whereas the bright spots most likely display local series resistance problems. The interwoven area of high and low contact resistance results in a dotted image as the J_{SC}-ILIT signal is very inhomogeneous due to the structure of this area.
The analysis is unfortunately not as straight forward for multicrystalline solar cells, as their thermography signal under open circuit conditions tends to have strong inhomogeneities due to the bulk material quality. Thus the effect of low contact resistance in the J_{SC}-ILIT image may easily be covered by the stronger lateral differences in the V_{OC}-ILIT image. It may be desirable to interpret the individual J_{SC}-ILIT image for contact resistance in such cases and use images which are obtained similar to Figure 4 for the investigation of point like shunts only. Another alternative might be to resort to lower voltages, but even at V_{MPP} bulk material quality may cause significant inhomogeneities in the thermography image.
If the difference between the two images is taken as comparison, then images as in figure 4 may be obtained in one measurement using a constant illumination source and applying a modulated voltage of V_{OC} and 0V in the two halves of the Lock-In period respectively. This technique is very close to the one proposed by Rappich et al. [11] and was first suggested by Breitenstein et al. [6] for modulation between 0V and V_{MPP}.

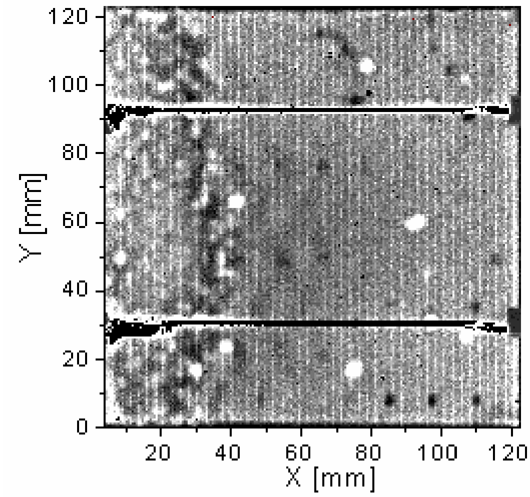

Fig. 4: Cz cell with deliberately inhomogeneous contact resistance: J_{SC}-ILIT image divided by V_{OC}-ILIT Image. Dark spots indicate shunting, whereas bright spots indicate for example series resistance problems.

7. CONCLUSION

Illuminated Lock-In Thermography (ILIT) and its different measurement modes were discussed. It was shown that a wide variety of parameters and loss mechanisms in solar cells is accessible and distinguishable by Lock-In Thermography if the measurement conditions are chosen carefully.
Appropriate experimental conditions for the detection and identification of dark saturation currents, ohmic shunts and losses in series resistance were proposed. Additionally possibilities to distinguish these loss mechanisms from each other were demonstrated.

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