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SHUNT DETECTION WITH ILLUMINATED LOCK-IN THERMOGRAPHY ON INLINE RELEVANT TIME SCALES

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ABSTRACT: The focus of this paper is on the fast spatially resolved detection of conversion efficiency limiting shunts in solar cells. These shunt producing defects can originate either from the wafer material itself or can be formed during solar cell processing. Such heat dissipating defects can be detected easily using the Lock-In Thermography technique. By improving the thermal resolution by means of lowering the Lock-In frequency the measurement time can be reduced significantly. Such fast illuminated Lock-In Thermography (iLIT) measurements allow the detection of local shunts spatially resolved within a measurement time of only one second.
For different shunting mechanisms such as material induced defects as well as processing induced shunts fast iLIT measurements are presented and demonstrate that the considered shunting types can be reliably detected within a time interval relevant for inline characterisation.
Keywords: Defects, Shunts, Inline, Thermography

1 INTRODUCTION

Solar cells may suffer from shunting as a result of poor parallel resistance causing losses in the efficiency potential due to short-circuiting the emitter and base up to a certain degree. Shunting causes a lowered fill factor FF and for significantly low shunt values even a drop in the open circuit voltage V_{oc}. While FF and V_{oc} are integral cell parameters, it is of interest to have a measurement tool available that can give locally resolved information about areas influenced by low shunt values.

Sources for low shunt values are material induced defects already present after crystallization like cracks or precipitates (e.g. SiN_x, SiC) or processing related shunts introduced for instance by non optimal firing conditions and insufficient edge isolation.

This paper focuses on the fast spatially resolved detection of material and / or processing induced shunting using the fast illuminated Lock-In Thermography (iLIT). With his technique shunting can be detected spatially resolved within a measurement time of only 1 s and thus the method is suitable for inline characterisation.

2 LOCK-IN THERMOGRAPHY

Lock-in thermography (LIT) is a tool that is able to detect weak heat sources in solar cells in a spatially resolved way. To apply the modulated reference signal needed for the mandatory Lock-in calculation, a pulsed voltage can be applied to the cell. The Lock-In technique thereby enables a better thermal signal-to-noise ratio (SNR) which can be lowered from around 20 mK for up to date infrared camera systems down to the µK range, dependant on the measurement time. Breitenstein et al. developed this technique for photovoltaic application [1].

The following equation gives the time (t) dependent development of the noise level magnitude signal σ with given camera noise σ_c and frame rate f_c:

$$\sigma = \frac{2\sigma_C}{\sqrt{f_C \cdot t}}$$

The modulated reference signal needed for the Lock-In calculation is realized for the illuminated Lock-In Thermography (iLIT) by the solar cell itself under pulsed illumination via laser or LED panels. This method was invented simultaneously by the University of Konstanz (UKN) [2] and FhG-ISE [3]. iLIT is a contactless measurement and provides a better signal compared to the conventional dark Lock-In Thermography (dLIT [4]), offering the possibility to use it as process monitoring tool even before metallisation.

In addition iLIT offers in contrast to dLIT the possibility to detect the heat dissipating loss mechanisms in a more realistic way as dLIT, as the paths of current flow are closer to real operation conditions of a solar cell under illumination. One application of iLIT therefore is an inline characterisation of heat dissipating areas (e.g. shunts) during solar cell processing.

3 MEASUREMENT SETUP

The thermography system used at UKN is based on a JADE IR camera and is now commercially available via the company InfraTec GmbH, Dresden. The camera is sensitive in the 3-5 µm range, the thermal noise σ_c is about 20 mK and the image consists of 320 x 256 pixels. The pulsed illumination is carried out via two LED panels at 880 nm (more details can be found in [2]).

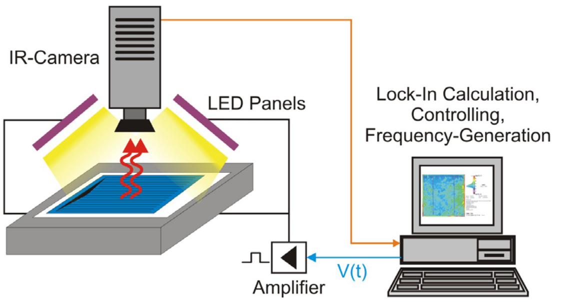

Figure 1: Illuminated Lock-In Thermography (iLIT) measurement setup at the University of Konstanz. The solar cell produces the Lock-In reference signal by photovoltaic conversion of incident IR light emitted by two LED panels.

3.1 Reduction of the Lock-In Frequency

The Lock-In frequency used for a standard iLIT measurement with the setup described above is 15 Hz. With 8 measurements (i.e. thermal images) within one Lock-In period a frame rate of the camera of 120 Hz results, which is the standard operating frequency of the used IR camera. A reduction of the Lock-In frequency increases the integrated thermal signal for a constant integration time of the camera's CCD sensor within one Lock-In period, but simultaneously decreases the spatial resolution (see Figure 2).

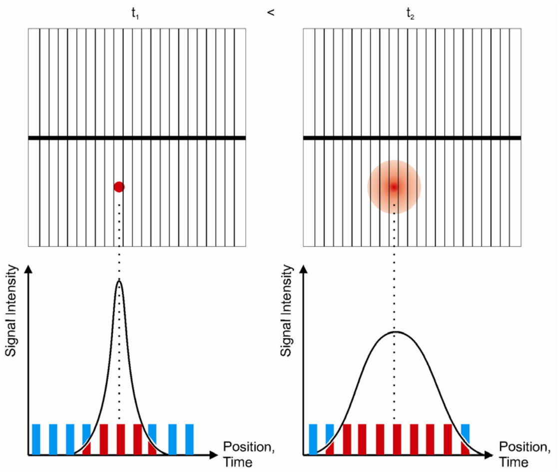

Figure 2: Thermal wave for two different times $t_1 < t_2$ propagating from a shunt position in a solar cell and measurements performed by the camera's CCD sensor for a constant number of measurements within one Lock-In period (blue and red bars).

Within one Lock-In period the integrated thermal signal is higher for t_2 (more red bars) due to a broadening of the propagating wave for a constant Lock-In periodic time. A reduction of the Lock-In frequency causes the same effect, i.e. the integrated thermal signal increases, but the spatial resolution decreases as demonstrated in the right part due to a broadening of the area which contributes to the thermal signal.

3.2 Fast iLIT Measurements

The influence of the measurement time on the noise level is demonstrated in Figure 3 where a frequency of 7.5 Hz was used for all measurements (illumination intensity 1 sun). Stronger shunts are already visible after a measurement time of 1 s, but the signal-to-noise ratio is low and thus weaker shunts are hardly visible at this Lock-In frequency.

In order to enhance the thermal resolution for very short measurement times the Lock-In frequency was lowered to 1 Hz, i.e. the measurement lasts only one single Lock-In period. Such fast iLIT measurements are shown in Figure 4 and demonstrate that strong point shunts are already visible within the very short measurement time of only 1 s.

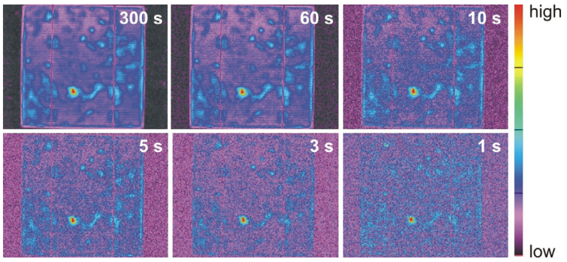

Figure 3: Conventional iLIT measurements of an industrial screen printed mc solar cell for decreasing measurement times (Lock-In frequency 7.5 Hz, illumination intensity 1 sun, V_{oc} condition, same scaling for all measurements).

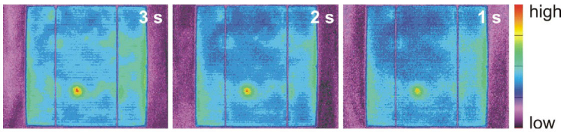

Figure 4: Fast iLIT measurements of the same solar cell as shown in Figure 3 but with a Lock-In frequency of 1 Hz (same measurement conditions as for Figure 3).

Besides point shunts originating e.g. from material induced defects such as precipitates penetrating the space charge region or over-firing of the front side metallisation, shunting of the cell edges is often observed due to an insufficient edge isolation during the cell process. Figure 5 shows an example for this kind of shunting which can be detected reliably with the fast iLIT measurement as well.

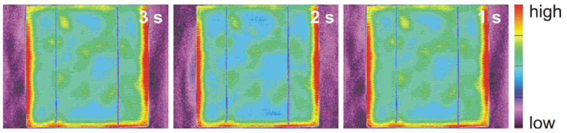

Figure 5: Fast iLIT measurements of an industrial screen printed mc solar cell (same conditions as for the measurements shown in Figure 4).

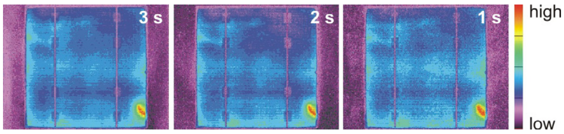

Figure 6: Fast iLIT measurements of an EFG solar cell (same conditions as for the measurements shown in Figure 4).

As an example for a material and / or process induced shunt fast iLIT measurements of an EFG solar cell are presented in Figure 6. A crack causing a strong shunt can clearly be identified at the lower right cell edge after a measurement time of 1 s.

3.3 Illumination Intensity

The illumination intensity used for the Lock-In reference signal generation has an influence on the measurement. With lowering the illumination intensity, the influence of recombination active areas compared to the strength of the shunting signal is less pronounced. This is due to the comparably higher conductivity of parallel resistances as well as the reduced bias dependence of shunts compared to recombination.

Therefore, lowering the light intensity allows for detection of shunts more selectively. It was found that lowering the intensity allows the detection of stronger shunts in very short measurement times even for a standard Lock-In frequency of 15 Hz.

3.4 Process Monitoring

To check if e.g. Al contamination at the cell's front side can be detected with fast iLIT, a wafer was intentionally contaminated with Al metallisation paste at the front side before firing. The structure has no front grid and no Al contact at the back side.

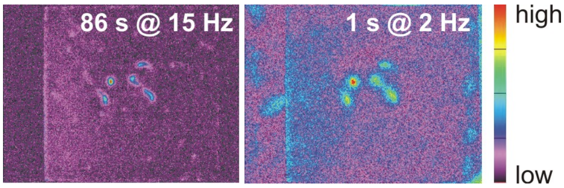

Figure 7: iLIT (left) and fast iLIT (right) measurements of a pn-structure (no front and back side metallisation) with an intentionally Al-contaminated front side after firing.

For a standard Lock-In frequency of 15 Hz and lowered illumination intensity the detrimental effect of the Al contamination causing a shunt is clearly visible. Even for the 1 s fast iLIT measurement, the occurring shunts can clearly be detected (Figure 7, right).

4 SUMMARY

Fast Lock-In Thermography measurements have been carried out on industrial solar cells. The aim of this work was to demonstrate that most relevant types of harmful shunts can be detected reliably in very short measurement times down to 1 s relevant for inline processing control. The presented measurements show that besides point shunts, shunting caused by cracks as well as shunting at cell edges can be identified reliably within an inline relevant time frame.

The influence of an Al contamination at the front side could be detected within 1 s even without an Al back contact or a front grid present. This result proves that fast iLIT can be used for process monitoring inline even before metallization.

5 OUTLOOK

It was demonstrated that with the fast iLIT technique measurement times of 1 s are sufficient to reliably detect different types of shunts. In combination with the latest generation of camera systems showing even better signal-to-noise ratios compared with the one currently in use at UKN, inline detection of shunts should be possible even more easily and reliably.

6 ACKNOWLEDGEMENTS

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