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Quantitative Analysis of the Influence of Shunts in Solar Cells by Means of Lock-in Thermography

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Abstract

Infrared lock-in thermography not only allows to image local heat sources like shunts in electronic devices like solar cells, but it also can measure currents flowing in certain regions of the device quantitatively in a non-destructive way. After dealing with the physical basics of quantitative lock-in thermography, two types of measurements are described: 1. The quantitative measurement of the I-V characteristic of a point shunt in a solar cell, and 2. the evaluation of the influence of shunts on the efficiency of the cell as a function of the illumination intensity. The investigation of a typical multicrystalline solar cell shows that the shunts deteriore predominantly the low light level performance of the cell.

1. Introduction

Lock-in thermography has been established to be a reliable tool to locate local short circuits (shunts) in all kinds of solar cells [1]. This technique is based on the application of a periodically pulsed bias to the cell in the dark and measuring the surface temperature modulation by a sensitive IR camera according to the lock-in principle. Since the phase of the T-modulation signal is not constant, two-channel lock-in detection has to be used. In each of the channels the pixel information of every incoming image is multiplied by a weighting factor, which changes from image to image and may be positive or negative. The results are added up in two separate frame storages. In the first channel the weighting factors are approximating a sin function and in the other channel a -cos function. Thus, after the measurement the image stored in the first frame storage is proportional to the temperature modulation signal in-phase with the applied pulsed bias (0°-signal; $T^0(x,y)$), and that in the other storage is proportional to the out-of-phase T-modulation signal phase-shifted against the bias pulses by -90° (-90° signal; $T^{-90}(x,y)$). From these two images, the phase-independent amplitude image $A(x,y)$ and the phase image $\Phi(x,y)$ can be easily calculated. More details about lock-in thermography can be found elsewhere [1,2].

The aim of this paper is to show that lock-in thermography does not only permit to locate shunts, but also allows to measure their current quantitatively. Presupposition for these quantitative measurements is that the investigated cell is covered by a thin black-painted plastic film, which is sucked to the cell by a vacuum. This film serves as an efficient and homogeneous IR emitter. Moreover, the cell has to be mounted with a certain thermal insulation to the metallic support so that heat conduction to the base does not influence the T-modulation signal at the surface. Finally, the lock-in frequency has to be chosen so that the thermal diffusion length is well above the thickness of the solar cell. For lock-in frequencies below 30 Hz and typically 300 µm thick silicon cells this is generally the case. Two types of measurements will be desribed: 1. The quantitative measurement of the current-voltage (I-V) characteristic of a point shunt, and 2. the evaluation of the influence of shunts on the efficiency of a cell as a function of the illumination intensity.

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The sample used for these investigations was a multicrystalline silicon solar cell 10*10 cm^2 in size and 250 µm thick. All lock-in thermography measurements were performed with the TDL 384 M 'Lock-in' system, which is commercially available by Thermosensorik GmbH since 2000 [3].

2. Basics of the quantitative evaluation of lock-in thermograms

The basic idea of quantitative evaluation of lock-in thermography results shown here is to use the thermal signal averaged over a certain region around a heat source as a measure of the power of this source. The question is which of the signals coming out of a lock-in thermography measurement is best appropriate for this purpose? Simulations have revealed [1, 2] that only the plane integral of the -90° signal around an isolated point shunt in a thermally thin sample is exactly proportional to the power dissipated by this shunt, if the intergration boundary is choosen sufficiently distant from the shunt. With other words, we have to evaluate the component of the temperature modulation which is delayed to the applied bias pulses by -90°. The amplitude (magnitude) signal of the T-modulation is not allowed to be used for this purpose, since in this signal contributions from different neighboured heat sources do not superimpose linearly. Any arbitrary spatial distrubition of heat sources can be considered as an arrangement of many point heat sources, with the -90° signals of these heat sources all superimposing linearly. Therefore, within a sufficiently large area, the averaged -90° signal around a local shunt $\overline{T_{shunt}^{-90°}}$ in a certain area A_{shunt} is proportional to the averaged dissipated power density in this area. This also holds for a homogeneously heated region of any size, as well as for the whole solar cell area A_{cell}, where the dissipated power is known. The latter measurement gives us the proportionality factor between the thermal signal and the dissipated power. If a homogeneous current injection should be superimposed to the shunt current, the homogeneous T-signal can be subtracted from the shunt signal in order to obtain only the net current through the shunt. Since for a given bias the power is proportional to the current flowing, the above considerations finally lead to the following formula for calculating the current across a local shunt I_{shunt} [1, 3]:

$$I_{shunt} = I_{cell} \frac{\left(\overline{T_{shunt}^{-90°}} - \overline{T_{hom.}^{-90°}}\right)}{\overline{T_{cell}^{-90°}}} \frac{A_{shunt}}{A_{cell}} \tag{1}$$

An example of a typical selection of these evaluation areas is given in Fig. 1. Note that the area $A_{hom.}$, where the homogeneous signal is measured, does not appear in eq. (1). Since for a homogeneous current flow also the thermogram is homogeneous, the -90° signal in such a region $T_{hom.}^{-90°}$ is proportional to the power density everywhere. Therefore this value is allowed to be directly subtracted in the numerator of (1). For measuring the current-voltage (I-V) characteristic of a shunt in the dark, several -90° lock-in thermograms have to be taken at different values of the pulsed bias V in the dark and evaluated according to (1). Note that for this type of measurement it is essential to switch a well-defined bias on and off instead of applying a sin-shaped bias, since we are interested in the behaviour of the cell at a certain bias. If standard sin/cos lock-in correlation is used in the system the higher harmonics do not disturb [1].

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The practical limitation of the technique described above is given by the noise level in the lock-in thermography results, which makes the measurement for decreasing bias increasingly inaccurate. Therefore the I-V characteristic can always be measured only in a limited bias range. There is a simple technique available to increase this range to lower biases if only highly localized (point-like) heat sources are condsidered. In this technique only the thermal amplitude signal in the position of the heat source $\Delta T(0)$ is evaluated, which shows a considerably better signal-to-noise ratio than the averaged -90° values appearing in (1). Note that the amplitude signal in the position of a point heat source shows a distinct maximum, which is much stronger pronounced than that of the -90° signal [1]. For an isolated local shunt it can be assumed that also the amplitude signal in shunt position is proportional to its power, hence to the shunt current multiplied by the applied bias. Hence, dividing the amplitude signal in source position by the bias leads to a value, which is at least proportional to the locally flowing shunt current. This technique has been called LIVT (Local I-V characteristics measured Thermally [4]). Its limitation is that the results are only qualitative, hence they are accurate up to an unknown factor. This factor can easily be obtained by comparing LIVT results with that according to (1) at the highest bias, where the signal-to-noise ratio is highest for both techniques.

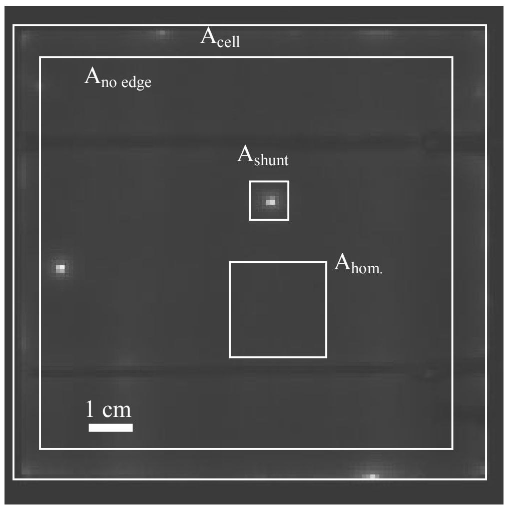

***Fig. 1:** Lock-in thermogram of a multicrystalline solar cell showing two point shunts in the area and many weak shunts in the edge region. The averaging regions used in eqs. (1), (2), and (3) are indicated*

If e.g. only the influence of all shunts in the edge region of a solar cell has to be evaluated, a special averaging area $A_{no\ edge}$ can be chosen slightly smaller than A_{cell} (see Fig. 1). In this case the following formula holds for the current of a hypothetical cell of the same size having no edge shunts:

$$I_{no\ edge} = I_{cell} \frac{\overline{T_{no\ edge}^{-90°}}}{\overline{T_{cell}^{-90°}}} \frac{A_{cell}}{A_{no\ edge}} \tag{2}$$

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It is also interesting to estimate the hypothetical current which would flow in a cell of the same area having no shunts at all, hence if the whole cell would be as good as the homogeneous "no shunt" region $A_{hom.}$. This current can be estimated by applying the following formula:

$$I_{no\ shunts} = I_{cell} \frac{\overline{T_{hom.}^{-90°}}}{\overline{T_{cell}^{-90°}}} \qquad (3)$$

Also here, just as for eq. (1), the complete I-V characteristic for a solar cell with no edge shunts or without any shunts can be estimated by measuring lock-in thermograms at different biases and applying eqs. (2) and (3), respectively, for each -90° thermogram.

3. Results

Lock-in thermograms of the solar cell shown in Fig. 1 have been measured under 0.30, 0.35, 0.40, 0.45, 0.50, 0.52 and 0.55 V forward bias, which was pulsed at a frequency of 3 Hz. Fig. 2 shows the I-V characteristic of the shunt indicated in Fig. 1, which was calculated by using (1). It is obvious that this shunt shows a strongly non-linear I-V characteristic. This property is important for the correct interpretation of the influence of this shunt to the light-to-electrical energy conversion efficiency of the cell.

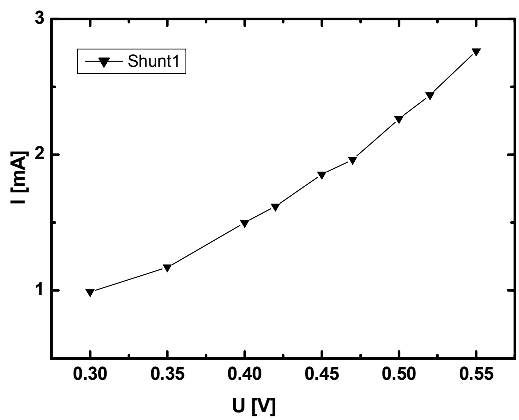

Fig. 2: *Dark I-V characteristic of the point shunt indicated in Fig. 1 measured by applying eq. (1)*

Fig. 3 shows the dark current-voltage (I-V) characteristic measured for the whole solar cell, the characteristic calculated for this cell without the edge shunts (but including the two point shunts) predicted by eq. (2), and that without any shunts, predicted by eq. (3). From these I-V characteristics the efficiency of the cells can be calculated as a function of illumination intensity [3] with the results shown in Fig. 4. We see that in all cases the efficiency drops with decreasing illumination intensity. However, both the edge shunts and the two point shunts are leading to a steeper drop of the efficiency with reducing illumination intensity. Therefore, these shunts do influence the efficiency of solar cells only litte at full illumination intensity, but are increasingly dangerous if the illumination intensity reduces. In the present case the

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loss in efficiency due to the shunts is negligible at full illumination intensity, and it is only about 0.5% at 100 W/m^2. However, in other cases we have shown [5] that ohmic edge shunts may degrade the efficiency of solar cells at 100 W/m^2 by about 2.5 %.

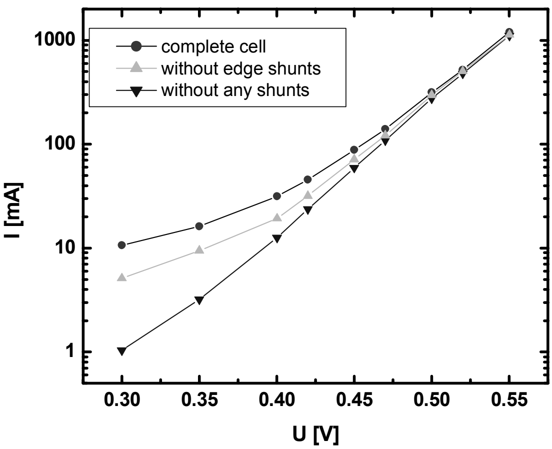

Fig. 3: *Dark I-V characteristics of the complete solar cell and predicted characteristics of this cell without edge shunts and without any shunts.*

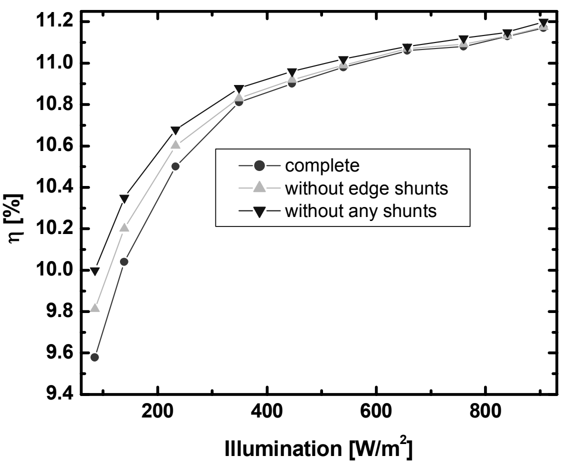

Fig. 4*: Efficiency as a function of illumination intensity for the complete cell, for this cell without edge shunts, and without any shunts.*

4. CONCLUSIONS

It was shown that lock-in thermography allows to perform a quantitative analysis of the spatial distribution of the dark forward current density of solar cells. Thus it is possible to measure thermally the I-V characteristic of point shunts in a non-destructive way. The accuracy of this method has been proven recently by a comparison with local emitter potential mapping (PRAMP [6]) in another example. Both independent measurements lead to the same current values within an accuracy

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of 10 % [7]. As a second type of quantitative analysis of lock-in thermograms, a hypothetical solar cell without any shunts can be modelled, whereby the influence of shunts on the energy conversion efficiency of a solar cell can be estimated as a function of illumination intensity.

Acknowledgements

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