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Local analysis of the efficiency of solar cells based on dark lock-in thermography imaging

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Abstract

The dark forward current of solar cells strongly influences their energy conversion efficiency. If lock-in thermography is applied to a solar cell in the dark with electrical current pulse excitation, it images any inhomogeneity of the current flow in this cell. Since also the illuminated characteristic may be derived from the dark characteristic, the detailed local analysis of the dark characteristic enables the prediction of local efficiency parameters. This contribution describes the physical basics of this procedure and shows a typical example of such a local efficiency analysis.

1. Introduction

The direct conversion of solar radiation energy into electric energy by solar cells (photovoltaics, PV) is the base of one of the fastest growing industries worldwide. The solar cell technology is characterized by a steady increase of the conversion efficiency and a decline of cell and module prices. Therefore the detailed understanding of electronic loss mechanisms is a key for the further improvement of the cell efficiency. Most of today's solar cells are manufactured from large-grained block-cast multicrystalline silicon material. This material is by nature not very homogeneous. Understanding the nature of this inhomogeneity is essential for understanding the reasons of a limited efficiency of the cells. In operation a solar cell is forward-biased, whereby the internally flowing forward current, which also flows in the dark, acts as a decisive loss mechanism. The smaller the dark current, the higher is the voltage that the cell may produce, hence the better is the efficiency of the cell. Local regions of a strongly increased dark current (so-called shunts) may considerably degrade the efficiency of the whole cell, even if the area covered by these shunts is negligibly small. Since all regions of a solar cell are electrically connected with each other by a metal grid, which is used for contacting the cell and feeding out the current, it is impossible to measure current-voltage (*I*-*V*) characteristics of local regions directly. Mechanically dividing the cell into small pieces is not a solution, since this division creates additional dark leakage currents at the edges of the pieces. Hence, the dark current of the sum of all pieces is higher than it was for the former whole cell. Moreover, a non-destructive efficiency analysis is generally highly desirable.

Lock-in thermography (LT) performed in the dark is the method of choice for imaging and locally measuring dark current densities in solar cells non-destructively [1]. Here the electrical bias of the cell is square-pulsed at a typical frequency of 10 Hz from zero to a certain bias (typically between 0.5 and 0.6 V), leading to a square-shaped cell current modulation, the cell is imaged by a thermo-camera, and two-phase sin/cos-type lock-in correlation is applied to the image data. In positions of high local forward current (so-called shunt positions) the LT signal displays local maxima. The LT signal being most appropriate for quantitative evaluation is the signal component -90° phase-delayed to the applied pulses [1]. In contrast to the amplitude or phase image, which are normally used to display LT results, in the -90° signal component contributions from different local heat sources superimpose linearly. Hence, within a spatial accuracy of one thermal diffusion length, being about 2 mm for 10 Hz lock-in frequency, the -90° signal component can be interpreted to be proportional to the locally dissipated power density. This property is the base of the "Local-IV" procedure to be described in the following.

2. Method

The first version of the "Local-IV" method was described in detail already in [2], therefore here only its basic principles will be summarized. Meanwhile this method has been further developed to produce not only dark but also illuminated characteristics. Moreover, now also local I-V characteristics regarding the local series resistance can be produced, which was not possible before. These new features will be described here for the first time.

As mentioned above, the -90° LT signal image data $T^{-90^\circ}(x,y)$ (given in any units, e.g. mK) may be converted into a power density image $p(x,y)$ by applying [1]:

$$p(x,y) = \frac{T^{-90^\circ}(x,y)\,P}{<T^{-90^\circ}(x,y)>A} \tag{1}$$

Here P is the power (voltage times current) dissipated by the cell during the pulse period, A is the cell area, and $<T^{-90^\circ}(x,y)>$ is the average value of the -90° signal across the whole solar cell. This formula holds true independent of the accuracy of the temperature reading of the camera and of the local emissivity (as long as it is homogeneous), since these parameters influence the local and the average -90° signal in the same way. The "Local-IV" method relies on the fact that different current contributions are characterized by different dependencies of the current on the local voltage across the pn-junction. This local voltage may deviate from the bias voltage V_B applied to the cell, since there is a non-negligible series resistance to each position causing an inevitable voltage drop, depending on the local current density. If this voltage drop would not be considered, the quantitative evaluation would not work correctly. Since the area-related series resistance $R_s(x,y)$ (given in units of Ωcm^2) may be distributed inhomogeneous, the "Local-IV" procedure needs an R_s image of the investigated cell as an input. This image may be measured e.g. by photoluminescence or electroluminescence imaging [3, 4] or by applying the so-called RESI method [5]. Alternatively, if the evaluation is made at relatively low voltages, where a low current is flowing and the voltage drop is weak, the series resistance also may be assumed to be locally constant. In any case, the power dissipated at the local diode is:

$$p(x,y) = V_{\mathrm{loc}}(x,y)J(x,y) = \left[V_{\mathrm{B}} - J(x,y)R_s(x,y)\right]J(x,y) \tag{2}$$

Here $V_{loc}(x,y) = V_B - J(x,y)R_s(x,y)$ is the local voltage and $J(x,y)$ is the locally flowing current density. Eq. (2) can be resolved to:

$$J(x,y) = \frac{V_{\mathrm{B}}}{2R_s(x,y)} - \sqrt{\frac{{V_{\mathrm{B}}}^2}{4R_s(x,y)^2} - \frac{p(x,y)}{R_s(x,y)}} \tag{3}$$

$J(V_{loc})$ is the local I-V characteristic without the influence of R_s. It is well-known and generally accepted that this characteristic may be described in each position by the so-called two-diode model described by:

$$J(V_{\mathrm{loc}}) = J_{01}\left(\exp\frac{eV_{\mathrm{loc}}}{kT} - 1\right) + J_{02}\left(\exp\frac{eV_{\mathrm{loc}}}{nkT} - 1\right) + \frac{V_{\mathrm{loc}}}{R_{\mathrm{p}}} = J_{\mathrm{diff}}(V_{\mathrm{loc}}) + J_{\mathrm{rec}}(V_{\mathrm{loc}}) + J_{\mathrm{shunt}}(V_{\mathrm{loc}}) \tag{4}$$

J_{01} is the saturation current density of the so-called diffusion current J_{diff}, J_{02} is the saturation current density and n the ideality factor of the recombination current J_{rec}, and R_p is the parallel resistance governing the shunt current J_{shunt}, and kT/e is the thermal voltage being 25.69 mV at 25 °C. The local diode parameters must be determined for each position (x,y) separately. The extraction of these local parameters from LT images is the goal of the "Local-IV" procedure. This problem is solved by evaluating the results of four LT images taken at four different biases, three of them under forward and one under reverse bias. First all LT images are converted into power density images by applying (1). Then, by using the $R_s(x,y)$ image, which has to be known or must be assumed to be constant, these images are converted into local current density images by applying (3). This allows to calculate for all biases the local voltage images according to $V_{loc} = V_B - R_s(x,y)J(x,y)$, see (2). Now the four unknown diode parameters are obtained for each position by applying a special iterative procedure described in [2], which fits in each position (x,y) the four $J(V_{loc})$ data pairs of the four voltages where the LT images have been taken to the two-diode model (4).

Once the four diode parameters J_{01}, J_{02}, n, and R_p are calculated for each position (x,y), and $R_s(x,y)$ is known, the solar cell is completely locally characterized. Then the *I-V* characteristics of the local diode (without regarding R_s) may be calculated for each single position (x,y) or as an average over a certain selected region of the cell by applying (4). This kind of characteristic without the influence of the series resistance is in the PV community often called "suns-V_{oc}" characteristic. For a whole solar cell, it can be obtained by measuring the open circuit voltage V_{oc} as a function of the illumination intensity measured in units of "suns" (one "sun" equals 1000 W/m^2). From the suns-V_{oc} characteristic the "illuminated suns-V_{oc}" characteristic may be obtained by applying the superposition principle, saying that the illuminated characteristic equals the dark characteristic shifted in current-direction by the short circuit current density J_{sc}:

$$J_{\mathrm{illum}}(V_{\mathrm{loc}}) = J_{\mathrm{dark}}(V_{\mathrm{loc}}) - J_{\mathrm{sc}} \tag{5}$$

This principle holds because the photo-induced current is independent of the voltage, in contrast to the dark current. Under short circuit condition ($V = 0$), the dark current is zero and only the photo-induced current J_{sc} flows. If the dark current is defined to be positive, the illuminated current is negative, since it is a reverse current. Nevertheless it is usual to display also illuminated characteristics as a positive current, as it will be done also in the following.

If the local series resistance has to be regarded in I-V characteristics, which corresponds to the calculation of "real *I-V* characteristics", the current values cannot be expressed analytically anymore. Note that the local current density J also influences V_{loc} in (4). Nevertheless, for any value of V_{loc} the current density may be calculated after (4), from which, knowing R_s, the applied voltage V_B may be calculated after (2). In the software code "Local-IV 2", where this procedure is implemented, this calculation is performed for a representative number of V_{loc}-values, and the resulting J-V_B data pairs (which are not equidistant in V_B) are re-sampled in a lookup-table to obtain the current values of any arbitrary V_B. The "Local-IV 2" software allows to display images of the two-diode parameters, of the total dark current, or of any of the three current components J_{diff}, J_{rec}, or J_{shunt} at any of the three forward biases. Moreover, it calculates images of local solar cell parameters, like the local open circuit voltage V_{oc}, the local fill factor *FF* (which is a measure of the losses at the maximum power point of the cell), and the local efficiency η. These cell parameters are hypothetical, since they stand for a whole cell that would have the properties of the image position (x,y). Finally the software allows to display suns-V_{oc} and "real" *I-V* characteristics (including the influence of R_s), either in the dark or under illumination, for any position (*x,y*) or for a selected region. Since this region may also be the whole cell, the procedure enables the simulation of suns-V_{oc} or I-V characteristics of whole solar cells, based on their local analysis.

3. Results

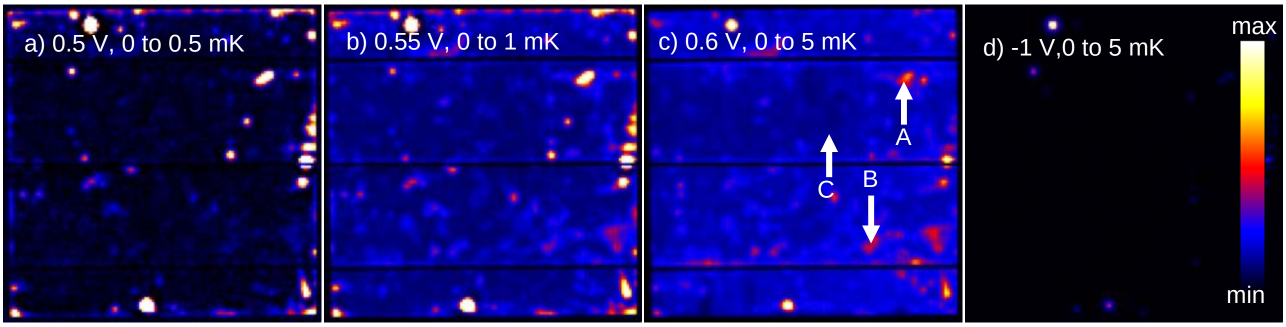

Fig. 1. *Four LT amplitude images of a solar cell measured at 10 Hz; the applied biases and used T-modulation amplitude scaling limits are indicated. The color bar also holds for Fig. 2*

In Fig. 1 four typical LT images of a typical multicrystalline silicon solar cell taken at different biases are shown which serve as the starting data of the evaluation. These images reflect the local current densities at these biases. The color bar at the right holds for all images shown here. It is visible that not only the magnitude but also the local distribution of the current strongly depends on the bias. At 0.5 V the recombination current dominates, which obviously flows mostly at the edges and in some local positions of the cell, which are called "non-linear shunts". With increasing forward bias the current becomes more homogeneous but some cloud-like structure remains. At a bias of 0.6 V the diffusion current dominates, which depends on the local silicon material quality. In good quality regions the diffusion current density is small and in bad quality regions it is larger. Position A in Fig. 1 marks a typical non-linear shunt, position B a bad material quality region, and position C a good material quality region. Under reverse bias (-1 V) only some weak ohmic shunts are visible, which are not important for this cell.

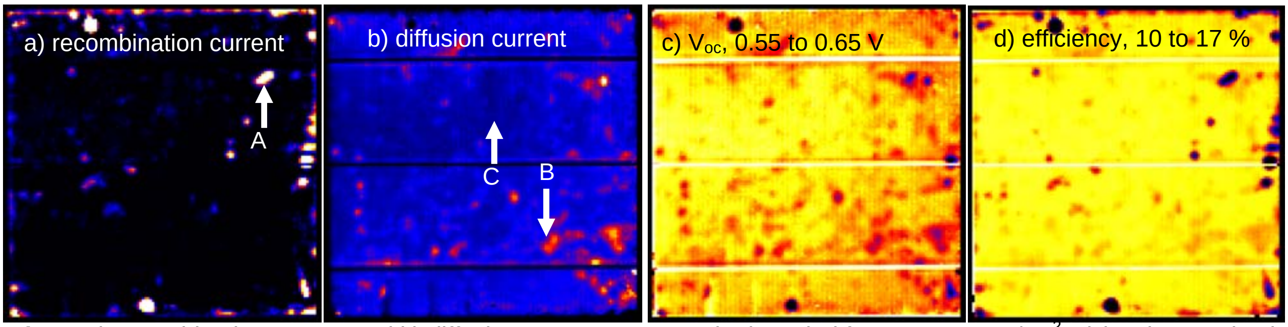

Fig. 2. *a) recombination current and b) diffusion current at 0.55 V, both scaled from 0 to 10 mA/cm^2, c) local open circuit voltage (V_{oc}) and d) local efficiency of the investigated solar cell*

The images of Fig. 1 have been evaluated by the "Local-IV 2" procedure leading to images of all two-diode parameters, which in turn allow to display various current contributions, local cell parameters, and local I-V characteristics. Fig. 2 shows resulting images of the recombination current a) and the diffusion current density b), both scaled from 0 to 10 mA/cm^2 and calculated for a bias of +0.55 V, which is close to the working point of the cell. Due to their different physical origins, these two current contributions are distributed very differently. While the recombination current a) is flowing only at the edges of the cell and in some local shunt positions, the diffusion current b) flows more homogeneously but also shows some local maxima, however, in positions different to that in a). In c) and d) images of the local open circuit voltage (V_{oc}) and of the local efficiency are shown. Again, it has to be remembered that these are hypothetical values, that would hold only if the whole cell would have the property of the local image pixel. The importance of such local cell parameter images lies in the fact that they may show which defects are especially degrading a certain cell parameter, and (in positions of good parameters) they may show how good a cell could be if it had only the properties of this position. It is visible that the diffusion current (b) degrades mainly the local V_{oc} (c) whereas the recombination current (a) has a strong influence on the local efficiency (d). While the whole cell showed a V_{oc} of 625 mV and an efficiency of 15.2 %, the maximum local V_{oc} is 631 mV, and the maximum efficiency is 16.0 %. This shows which improvement would be possible if all regions would perform like the best regions in this cell.

In Fig. 3 a) dark I-V characteristics of regions A, B, and C are shown, together with illuminated characteristics b) constructed from a) by assuming a homogeneous short circuit current density of 31.8 mA/cm^2. The scatter dots in a) are the current values measured by LT. It is visible that the diffusion current, dominating in positions B and C, rises much steeper than the recombination current dominating in position A. This is the reason why the recombination current mainly influences the fill factor and thus the efficiency, whereas the magnitude of the diffusion current, which is the main difference between B and C, mainly influences the open circuit voltage.

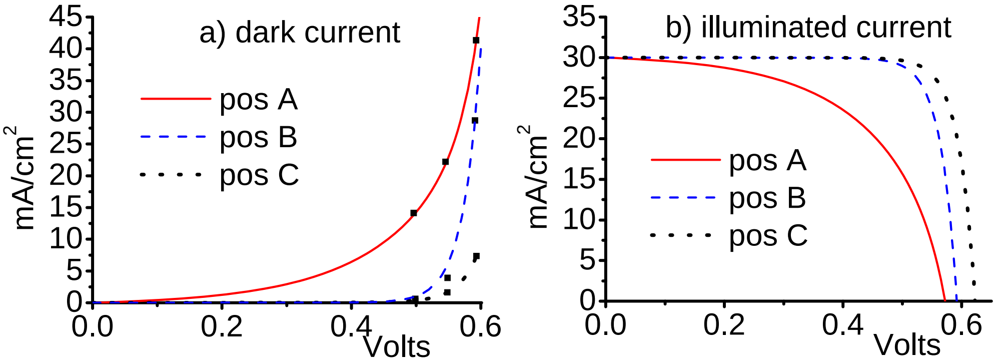

Fig. 3. *a) Local dark current-voltage (I-V) characteristics and b) illuminated characteristics of positions A, B, and C*

4. Conclusion

This investigation has shown that lock-in thermography (LT) enables a detailed quantitative analysis of solar cells. The LT-based analysis of local I-V characteristics introduced here is a valuable tool for a deeper understanding of efficiency-limiting factors of solar cells. It allows to localize the regions which are responsible for the degradation of different cell parameters, and it shows which defects are most detrimental for the various cell parameters. After this localization step is performed, detailed physical investigations have to be made for identifying the physical origins of the defects leading to the observed parameter degradation.

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