O. BREITENSTEIN et al.: Local Electrical Parameters of Solar Cells

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# Evaluation of Local Electrical Parameters of Solar Cells by Dynamic (Lock-In) Thermography

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The local current flow through biased solar cells can be monitored by measuring the local heating at the cell surface. Based on the discussion of heat diffusion phenomena and on practical aspects, optimum strategies for dynamic local current density measurements are derived. The practical realization of dynamic contact thermography is reviewed. Local inhomogeneities of the injected current density can be measured by this technique with a spatial resolution of down to 100  $\mu$ m and a sensitivity of about 200  $\mu$ A/cm<sup>2</sup> in forward direction of a silicon cell. Moreover, local *I*–*V* characteristics can be measured thermally in a non-destructive way. The applicability of this technique is demonstrated by investigating shunts in multicrystalline silicon solar cells. Dynamic thermography is shown to be a useful supplement to LBIC and EBIC investigations, since it reveals the locations limiting the open circuit voltage and the fill factor of solar cells.

#### 1. Introduction

An inhomogeneous large-area solar cell can be considered a parallel switching of many small regions which differ in their I-V characteristics. If one or a few of these regions carry an unusually high current, they will deteriorate the I-V characteristic of the whole cell. These sites are called "shunts". They may be due to local imperfections of the material as well as of the pn-junction. The dominant quality parameters of a solar cell governing its light conversion efficiency are its short circuit current ( $J_{sc}$ , measured at zero bias), its open circuit voltage ( $V_{\rm oc}$ , measured at zero external current) and its fill factor (FF, measured at the operation point), which is the maximum output power divided by  $V_{\rm oc}J_{\rm sc}$ . Since both  $V_{\rm oc}$  and FF are influenced by the I-V characteristic, shunts may deteriorate both  $V_{\rm oc}$  and FF. Revealing the sites and currents of shunts is a nontrivial problem because of the electrically parallel switching of all regions of a solar cell. One possible approach would be to divide the sample into small parts and to measure the I-V characteristics of these parts separately. However, simply cutting the cell into pieces usually yields misleading results, because the high leakage current across the cut edges may determine the I-V characteristics of small pieces of solar cells (Breitenstein and Heydenreich [1]). Moreover, measuring a lot of separate pieces is impracticable. A better approach is to divide only the emitter of the whole cell into small mesadiodes by

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selective etching and to measure the I-V characteristics of these mesas by computer control, as it has been proposed by Sopori [2] and Häßler et al. (Mesadiode Analysis of Solar Cells, MASC [3]). Using an ensemble of 600 mesadiodes of 0.4 mm<sup>2</sup> in size on multicrystalline silicon material, Karg et al. [4] have found a strong correlation between Voc measured under standard illumination condition and the forward current separately measured at +0.5 V in the dark, but only a weak correlation between V<sub>oc</sub> and the dark reverse current at -0.5 V. This demonstrates that it is the forward I-V characteristic rather than the reverse one which governs  $V_{\rm oc}$ . This is easy to understand since in operation the solar cell is forward-biased. Obviously, the local shunts causing the inhomogeneities of  $V_{\rm oc}$  may have non-linear (non-ohmic) I-V characteristics. This mesadiode technique, however, is also destructive, very expensive and time-consuming. Recently, Baldner et al. [5] have proposed to fabricate an ensemble of numerous small solar cells on a large-area substrate by selective emitter diffusion. This mini solar cell (MSC) approach may reveal only material-induced shunts but cannot be applied to solar cell structures as they are fabricated in industry. Moreover, this technique is also very expensive and time-consuming. Therefore, the non-destructive evaluation of shunts in as-processed commercial solar cells is a challenging task for optimizing their FF and  $V_{\rm oc}.$ 

Thermography can measure lateral inhomogeneities of the current density in solar cells in an indirect way, since it reveals the distribution of the locally dissipated power, which is proportional to the local injection current for a given applied voltage. Simo and Martinuzzi [6] have correlated hot spots measured by infrared (IR) thermography under reverse bias to sites of degraded I-V characteristics measured on mesadiodes prepared after thermography. Simo and Martinuzzi have used reverse bias instead of the forward one as the thermal contrast under forward bias was too low to be received by their IR camera. However, as the results of Karg et al. [4] show, the lateral dark forward current distribution is far more correlated to  $V_{\rm oc}$  than the reverse one. Therefore, in order to reliably reveal the local positions limiting  $V_{\rm oc}$  and the FF of solar cells, thermography should be performed sensitively enough to be also used in forward direction near the usual operation point of the cells.

In the following section dynamic (lock-in) thermography will be discussed as the strategy optimum for thermally evaluating lateral inhomogeneities of the forward current of solar cells. The possibility of capturing local I-V characteristics thermally (LIVT) is discussed in Section 3. The set-up in practice for carrying out dynamic precision contact thermography (DPCT) as well as LIVT will be presented in Section 4, and representative experimental results will be given in Section 5.

## 2. Dynamic (Lock-in) Thermography

The simplest approach to investigate spatial inhomogeneities of the current density of solar cells thermally would be to use stationary thermography at constant bias. However, if the sample were mounted in thermal insulation, the lateral heat conductivity, which is especially high in silicon solar cells, would tend to smear out the thermal contrasts. This leads to a poor spatial resolution, which, however, can be improved by mounting the sample with a defined heat resistance across its back to a heat sink. Such a mounting, on the other hand, reduces the thermal contrast. Let us assume a silicon cell of thickness  $d_{\rm Si}$  and a thermally insulating layer of thickness  $d_{\rm ins}$  between the sample and an ideal heat sink, a linear shunt going in *y*-direction along the sample surface.

Then we have both lateral heat flow in z-direction through the cell in x-direction and vertical heat flow through the insulating layer. For calculating the temperature profile T(x) between the cell and the heat sink we consider that the differences between the lateral heat flows at positions x and  $x + \Delta x$  just equals the vertical heat flow in this region

$$d_{\rm Si}\lambda_{\rm Si}\left(\frac{\partial T(x)}{\partial x} - \frac{\partial T(x + \Delta x)}{\partial x}\right) = \frac{\lambda_{\rm ins}}{d_{\rm ins}} \Delta x T\left(x + \frac{\Delta x}{2}\right) \tag{1}$$

 $(\lambda_{\rm Si} = \text{thermal conductivity of Si}, \lambda_{\rm ins} = \text{thermal conductivity of the insulator})$ . The junction  $\Delta x \to 0$  yields the one-dimensional stationary heat diffusion equation of this problem,

$$\frac{\partial^2 T}{\partial x^2} = \frac{\lambda_{\rm ins}}{\lambda_{\rm Si} d_{\rm Si} d_{\rm ins}} T \tag{2}$$

with exponential solution outside the heat source

$$T(x) = T_0 \exp(-x/x_0); \qquad x_0 = (\lambda_{\rm Si} d_{\rm Si} d_{\rm ins}/\lambda_{\rm ins})^{1/2}.$$
(3)

With a Si cell of  $d_{\rm Si} = 0.4$  mm and an insulating Teflon foil of  $d_{\rm ins} = 0.3$  mm in thickness the extinction length  $x_0$  would be about 3 mm. Assuming a spatially homogeneous injection current of 2 mA/cm<sup>2</sup>, which is a typical current density internally back-injected in a multicrystalline cell operating at an operation point of about 0.55 V, the temperature of a cell insulated from an ideal heat sink by this foil would rise by about only 1.46 mK, which is difficult to map by a conventional IR camera or any other means in dc mode.

The thermal detection sensitivity can be improved by an ac measurement instead of a dc one, namely by applying a pulsed bias of a certain frequency f to the sample and by evaluating only its surface temperature modulation. An ac measurement is advantageous as it is not affected by temperature drifts, it reduces the 1/f noise of the temperature detection system, and allows the integration of the result over a number of individual measurements according to the lock-in principle. Moreover, a dynamic measurement inherently improves the spatial resolution since the time-dependent solution of the thermal diffusion problem is more strongly confined to the heat source than the stationary one (see below). Dynamic thermographic measurements in lock-in mode employing pulsed irradiation-induced heating were used by, e.g., Busse et al. [7] to detect local inhomogeneities of the thermal properties of materials. In our case we may assume thermally homogeneous properties of the material. However, we are more interested in monitoring inhomogeneities of the heat generation process arising from an inhomogeneous injection current. While Busse et al. used an optical sinusoidal excitation, in our case a square wave bias excitation should be preferred to maintain the cell at a well-defined position of its I-V characteristic. Nevertheless, the time-dependent solution of the heat diffusion problem for a periodical heat supply can be attained in good approximation within the framework of the thermal wave concept valid for sinusoidal heating, as reviewed by, e.g., Carslaw and Jaeger [8]. For the simple one-dimensional case discussed above the lateral thermal wave (assuming a cosinusoidal heating power at x = 0) also shows an exponential amplitude profile [8],

$$T(x, t) = T_0 \exp\left(-x/\Lambda\right) \cos\left(2\pi f t - x/\Lambda - \pi/4\right); \qquad \Lambda = \sqrt{\frac{\lambda_{\rm Si}}{\varrho c \pi f}} \tag{4}$$

 $(\rho = \text{density}, c = \text{specific heat}, f = \text{bias pulse frequency}, \Lambda = \text{extinction length})$ . Even without any heat drain across the back of the sample, the strong natural damping of the thermal waves causes an inherent frequency-dependent spatial resolution of dynamic thermography measurements. Note that eq. (4) only holds for cosinusoidal heating instead of the actually used square wave one, which also contains higher harmonic components. However, since finally from all thermal waves only that of the basic frequency is selected by a selective amplifier (see Section 4) we only have to consider this spectral component. Eq. (4) shows that the spatial resolution of dynamic thermography improves with increasing frequency proportional to  $1/\sqrt{f}$ . Similarly, for dc thermography it improves with decreasing insulator thickness proportional to  $\sqrt{d_{\text{ins}}}$  (see eq. (3)). Since the stationary thermal contrast is proportional to  $d_{\rm ins}$  and the dynamic temperature contrast is proportional to 1/f (owing to the heat capacity of the sample), in both cases the spatial resolution changes with the square root of the thermal contrast. Thus, by choosing  $d_{\text{ins}}$  or f, respectively, a compromise can be attained between the spatial resolution of the measurement and its detection sensitivity. In order to attain the same extinction length of 3 mm as that of the stationary case discussed above also for dynamic onedimensional heat diffusion in silicon, according to eq. (4) we have to choose a frequency of about 3 Hz. Again, assuming a homogeneous injection of  $2 \text{ mA/cm}^2$  at 0.55 V, the temperature modulation amplitude under quasi-stationary conditions (i.e. with a constant cooling rate of the sample across its back equal to its averaged heating rate, leading to a constant averaged temperature) can be estimated to be about 1.14 mK for f = 3 Hz. However, it should be much easier to measure this temperature modulation than the equivalent dc temperature contrast of the stationary case owing to the advantages of the ac measurement mentioned above. Thus, dynamic (lock-in) thermography should be preferred to stationary one to detect spatial inhomogeneities of the forward current density of solar cells.

Note that eq. (4) as well as eq. (3) solely hold for one-dimensional lateral heat diffusion as this occurs for an infinitely long linear shunt or at the edge of a spatially extended heat source in a thin wafer. For a point-like heat source (point shunt) the heat generated would spread into the three-dimensional space of the sample (or the twodimensional one of a thin wafer), theoretically causing an infinite local variation of the temperature in shunt position with a finite power dissipated at the shunt [8]. In reality, of course, the finite volume of heat generation and the finite spatial resolution of the temperature measurement yield a finite temperature value measured in shunt position. For IR-based measurements the spatial resolution of the temperature measurement is governed by the parameters and quality of the infrared optics and the IR detector used. For contact temperature measurements, the size of the contact area between sample and temperature sensor is decisive. These factors, rather than  $d_{ins}$  or f, finally govern the spatial resolution of the thermal detection of point shunts, which may be as good as 100 µm for contact measurements [9].

#### 3. Local I–V Characteristics Measured Thermally (LIVT)

Dynamic local thermal measurements allow one not only to map the forward current density but also to study its bias dependence. Hence, local I-V characteristics can be measured thermally in a non-destructive way (LIVT [9]), yielding information about the nature of local inhomogeneities (shunts), previously localized by lock-in thermography.

The principle of this technique is based on the proportionality of the value of temperature variation and the local dissipated power in the same area,

$$p \sim \delta T \sim j U$$
, (5)

where U is the amplitude of voltage pulses applied to the sample, p is the local power density, j is the local current density, and  $\delta T$  is the measured temperature modulation. For carrying out LIVT measurements the surface temperature modulation is measured in one and the same position. During the measurement cycle a series of voltage pulses of a certain amplitude is applied and the relevant temperature modulation is measured. Thus, for the area chosen one can calculate the current density according to eq. (5),

$$j = \frac{p}{U} \sim \frac{\delta T}{U} \,. \tag{6}$$

Varying pulse amplitude U enables the whole I-V characteristic to be measured at a certain point of the surface. On the basis of the exponential fit of the I-V characteristic to  $I_0 \exp(eU/nkT)$ , important electrical parameters as, e.g., the so-called *n*-factor can be measured locally.

There are some inherent limitations to this technique. The sensitivity of the temperature measurement limits the voltage range of the measurement at lower values. Therefore, depending on the I-V characteristic to be measured, only some fraction of the whole characteristic is out of noise. However, since we are mainly interested in detecting regions of high current (shunts), usually we are able to measure the most interesting part of the characteristics. Moreover, it is not trivial to interpret the LIVT of point shunts quantitatively in terms of current values. This is due to the above-mentioned dependence of the temperature response of a "point shunt" on its real extension and on the spatial resolution of the temperature measurement itself. However, if the real extension of the heat source is smaller than the spatial resolution of the temperature measurement, the values measured of the temperature modulation of different point shunts are at least proportional to their different current values. Thus different point shunts can reliably be compared with respect to their current values. Finally, there is a superposition of the temperature signal of a point shunt with that of the homogeneous injection in its surrounding. The spatial resolution of the temperature measurement, too, determines which of the two signals dominates at a certain bias. These aspects regarding the quantitative interpretation of lock-in thermography investigations on solar cells will be discussed in detail in a forthcoming publication. In spite of these limitations, however, local I-Vcharacteristics measured thermally (LIVT) provide useful additional information for the investigation of local inhomogeneities in solar cells, as it will be shown in Section 5.

### 4. Practical Realization of a Dynamic Precision Contact Thermography(DPCT) System

There are at least three possible experimental approaches to carry out lock-in thermography on solar cells: 1. using an IR camera and appropriate lock-in image processing as Busse et al. [7] did for investigating materials, 2. using mechanical sequential position scanning and IR radiation detection as known from photothermal investigations [10], and 3. using mechanical position scanning and measuring the surface temperature by a sensor in contact mode [11]. Recently, we have compared these three approaches experi-



Fig. 1. Functional scheme of the Dynamic Precision Contact Thermography (DPCT) system

mentally under comparable conditions with the result that contact thermography is by far the most sensitive approach [12]. Therefore, in the following we will review the practical realization of our Dynamic Precision Contact Thermography (DPCT) system as the simplest and most economic way to perform this type of measurement.

The functional principle scheme of the system is shown in Fig. 1. We have used a stepping motor driven "isel-EP 1090" x-y-z scanner for positioning a pearl-type NTC thermistor (Siemens/Matsushita "K19",  $\emptyset$  0.35 mm) with a spring-defined load of approximately 0.1 N on the sample surface. The solar cell is covered with a 10 µm thick polyethylene film, which protects both the cell and the sensor from mechanical violations. Moreover, it assures a reliable thermal contact with the sensor even for rough surfaces, it guarantees electrical insulation between cell surface and sensor, and it presses the cell against a thermostatted Cu-base by vacuum. In order to regularly distribute the vacuum across the cell area and to reduce the heat conductivity between the cell and the Cu-base, a 0.1 mm thick woven Cu-net is placed between the cell and the thermostatted base. The bias is fed to the emitter of the cell via two 0.1 mm thick Pt-platelets, which, owing to the vacuum applied, are also pressed against the contact stripes of the cell by the plastic film. The base of the cell is electrically connected via the copper base, which is thermostatted by flowing water from a digital *T*-controller type

HAAKE DC3 provided with a cooled water bath of type HAAKE K20. Due to the piezoresistive effect of the sensor the whole arrangement is quite sensitive to mechanical vibrations of the floor, which we tried to avoid by hanging the whole system on the wall of the laboratory. A closed box including both sample and sensor protects the sensor from draught, which would severely disturb the sensitive temperature measurement.

The core of the system is the temperature measuring bridge, which converts the minor changes of the temperature-influenced resistance of the sensor into a measurable signal. We have developed a patent-pending bridge circuit, providing a noise level equivalent to a temperature modulation at the sensor of about 10  $\mu$ K for a signal integration time of 1 s (averaging over 3 periods of 3 Hz). Using well-defined pulsed heat sources proved that at 3 Hz the temperature modulation directly at the surface is about 10  $\mu$ K at the sensor owing to the thermal resistance of the insulating plastic film together with the heat capacity of the sensor. Hence, the sensitivity of 10  $\mu$ K at the sensor corresponds to a detection limit of about 100  $\mu$ K of the surface temperature modulation. Thus, according to the estimation of the temperature modulation amplitude in Section 2 (1.14 mK for a forward current density of 2 mA/cm<sup>2</sup>), this system can resolve lateral changes of about 0.2 mA/cm<sup>2</sup> of the forward injection current density.

The whole system is controlled by an IBM AT-compatible personal computer equipped with a Keithley DAS 1600 (12 Bit) ADC/DAC analogue interface card. This card provides the calibrated bias pulses, which are amplified by a self-made pulse amplifier. At choice, this pulse amplifier may provide either pulses of constant height up to 10 V, or pulses of constant current up to 3 A. The temperature modulation signal leaving the temperature measurement system is fed to a 3 Hz selective amplifier in order to filter out the 3 Hz component of the signal. This amplifier has been optimized to highly reject unwanted spectral components and to attain a short pulse relaxation time. The selective amplifier also acts as an aliasing filter integrating between subsequent digitizing events. The signal is digitized at four equal intervals during each measurement period consisting of a bias pulse and a waiting period, each of 150 ms duration. After averaging these four values over an adjustable number of measurement periods (typically three), the phase-independent *T*-modulation signal is calculated by

$$\delta T = \sqrt{\left(T(1) - T(3)\right)^2 + \left(T(2) - T(4)\right)^2},\tag{7}$$

where T(1) to T(4) are the averaged values of the signal measured at times 1 to 4. A comprehensive software written in Turbo Pascal allows the operator to choose the measurement parameters, to carry out the measurement (including LIVT at a well-defined point), and to observe the image appearing on the monitor. Note that any positioning of the sensor severely affects the temperature reading at this moment due to the interruption of the thermal contact with the sample and due to the piezoresistive effect of the sensor. Thus, after each positioning step the system has to wait for 1 to 2 s before the actual measurement can start. Since the actual measurement comprising three periods at f = 3 Hz takes one more second, capturing a 100 × 100 pixel image like those presented in the following section usually takes about 10 h.

This measurement time might be reduced if instead of our K 19 sensor a thin film sensor without any piezoresistive effect were used, allowing a higher modulation frequency to be used, and a shorter thermal relaxation time after positioning the sensor. Another possibility to speed up this measurement would be to use an array of sensors measuring in parallel at the same time. Probably the most efficient variant would be to use a highly sensitive focal plane array (FPA) infrared camera in a lock-in thermography system. Meanwhile, such systems having a sensitivity below 1 mK are available [13], however, still very expensive.

# 5. Results of DPCT and LIVT Measurements

Fig. 2 shows lock-in thermograms of a  $100 \text{ cm}^2$  multicrystalline silicon solar cell taken at a frequency of 3 Hz using the dynamical contact thermography system described above. Fig. 2a was taken at a forward bias of +0.5 V (which is near the operation point of the cell), and Fig. 2b at a reverse bias of 1.2 V. In both cases the current was 0.14 A. The contrast scale was chosen such that the whole dynamic range of the temperature modu-



Fig. 2. Lock-in thermography results of a  $100 \text{ cm}^2$  multicrystalline solar cell: a) forward bias, 0 to 15 mK; b) reverse bias, 0 to 120 mK; c) forward bias, 0 to 1.5 mK; d) reverse bias, 0 to 3 mK

lation between 0 and 15 mK at forward bias and between 0 and 120 mK at reverse bias was revealed. Fig. 2c and d show the same images as Fig. 2a and b with the contrast scale chosen ten and forty times enhanced to display more details in the interior of the cell besides the dominant shunts at the edge. In Fig. 2, point shunts both at the edges and in the interior of the cell are visible as bright spots being surrounded by bright halos. These halos are due to the lateral heat conduction of the cell. The comparison shows that at the edge of this cell the dominant point shunts under forward bias are also point shunts under reverse bias. As can be expected from the higher bias used, the amplitudes of the temperature modulation of the reverse-bias shunts are considerably larger than those of the forward-bias ones. However, there are some point shunts that appear in forward direction only (as, e.g., position (B)). In Fig. 2d in the interior of the cell there are three point shunts appearing solely in reverse direction. In particular, spatially extended injection regions outside the areas of the point shunts are displayed solely in the forward bias thermogram of Fig. 2c. These extended regions of enhanced current density, which are probably caused by a higher defect density in these regions, are not detectable in the reverse bias thermogram. Since, in a first approximation, the thermograms in Fig. 2 can be interpreted as the distribution of the current density, their data allow the quantitative estimation of the fraction of the current flowing across the edge region relative to that in the cell interior. A quantitative analysis of the data of Fig. 2a yields for the whole cell in forward direction an averaged temperature modulation amplitude of 0.378 mK, but for the inner part of the cell without the edge region an averaged temperature modulation amplitude of only 0.18 mK. Hence, in forward direction the current without the edge is roughly half of the total current and roughly the other half of the current flows across the edges. In reverse direction, on the other hand, the temperature modulation averaged over the whole area in Fig. 2b is 1.97 mK, and that without considering the edge region is only 0.207 mK. Hence, here only 10% of the total current flows within the area, and 90% flows across the edge. This shows that thermography, if carried out solely in reverse direction, may yield the dominant shunts but does not allow one to predict all shunting activities in forward direction (hence under operation conditions) quantitatively.

Local I-V characteristics measured thermally (LIVT) of special positions of the solar cell used for Fig. 2 are displayed in Fig. 3. In Fig. 2, the positions of the LIVT measurements are marked by (A) to (D). Fig. 3a presents the LIVT of a dominant point shunt at the edge (A). It shows a linear characteristic, hence this is a shunt of ohmic type. The non-linearity at high positive (forward) bias is due to the voltage drop from the current feed position to the shunt position. Shunt (B), which is only visible in forward direction, shows a non-linear characteristic, hence its physical nature is different from that of shunt (A). An exponential fit gives an n-factor of about 6.7 for shunt (B). Fig. 3c and d show logarithmical drawings of the LIVT of a bright region (C) and a dark region (D) in the interior of the cell. In both cases the reverse current is negligible relative to the forward current. These local I-V characteristics are mainly exponential, both having an *n*-factor of about 2.0 at the working point of 0.5 V. The *n*-factor of the whole solar cell measured at 0.5 V is about 2.8. This investigation clearly shows that the I-V characteristic of this large-area solar cell can only be interpreted by taking into account spatial inhomogeneities of the current flow. As also other authors frequently observed, n-factors of large area solar cells are often well above n = 2, which cannot be interpreted by classical diode theory. They should arise from the presence of local shunts



Fig. 3. Local I-V characteristics measured thermally (LIVT) of special positions in Fig. 2: a) linear shunt (A); b) non-linear shunt (B); c) bright region (C) in Fig. 2c, logarithmic drawing; d) dark region (D) in Fig. 2c, logarithmic drawing

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Fig. 4. Light-beam induced current (LBIC) image of the solar cell used for Fig. 2 and 3

as it was earlier presumed by Queisser [14]. Our investigations show that these shunts have either a linear or an exponential characteristic with a large *n*-factor, and that they may dominate the I-V characteristic of the whole cell near its operation point.

For comparison, Fig. 4 shows the local mapping of the short circuit current (lightbeam induced current map, LBIC) of the cell used for Fig. 2 and 3. This technique is a standard technique of characterizing solar cells, showing the local distribution of recombination centres like grain boundaries and dislocations in dark contrast. Physically, it is comparable to the electron-microscopic EBIC technique (imaging with the electron-beam induced current), which has a better spatial resolution than LBIC, but which does not allow one to image large areas. However, LBIC and EBIC are not very sensitive to defects or inhomogeneities of the pn-junction, which govern the local injection behaviour. Indeed, only the extended regions of increased forward current density show a correlation to dark (defective) regions in the LBIC map, but the local shunts are displayed in the thermograms only.

# 6. Conclusions

The presented results show that LBIC and/or EBIC, lock-in thermography, and LIVT favourably supplement each other for the investigation of local inhomogeneities in solar cells: LBIC and EBIC display the spatial distribution of recombination centres in the bulk, which govern the short circuit current of solar cells, lock-in thermography reveals the regions dominating the I-V characteristics, which finally govern the open circuit voltage and the fill factor of the cells, and LIVT allows detailed investigations to be carried out of the local injection behaviour in certain positions. Thus, the combination of these techniques enables a comprehensive local characterization of solar cells with respect to all factors limiting their efficiency. It should be noted that lock-in thermography should be a valuable tool to display the homogeneity of the current flow also in other electronic components like, e.g., in power devices.

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