LOCK-IN THERMOGRAPHY - A UNIVERSAL TOOL FOR LOCAL ANALYSIS OF SOLAR CELLS

O. Breitenstein[1], J.P. Rakotoniaina[1], M. Kaes[2], S. Seren[2], T. Pernau[2], G. Hahn[2], W. Warta[3], and J. Isenberg[3]
[1]Max Planck Institute of Microstructure Physics, Weinberg 2, D-06120 Halle, Germany, email: breiten@mpi-halle.mpg.de
[2]University of Konstanz, Department of Physics, Jakob-Burckhardt-Str. 29, D-78457 Konstanz, Germany
[3]Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstr. 2, D-79110 Freiburg, Germany

ABSTRACT: This contribution gives an overview about the present state of the art of Lock-in Thermography (LIT) applied in solar cell research. Originally introduced as a shunt imaging technique working without light irradiation, recently a number of new LIT techniques have been proposed using light irradiation to the cell. These techniques allow to image the lifetime distribution and Joule heat losses under illumination, and they allow to detect non-contacted regions in the cell. Moreover, shunts can be imaged already before contacts are made. All presently known LIT techniqes applied to solar cells are reviewed and their physical bases are explained. With these new techniques, LIT has become a universal tool for characterizing solar cells.

Keywords: Lock-in thermography, shunts, lifetime, series resistance, imaging

1 INTRODUCTION

Infrared (IR) thermography was used for detecting shunts in solar cells under reverse bias in the dark since 1990 [1]. However, the sensitivity of this direct imaging technique was not high enough to image shunts under forward bias close to the operation point of the cell, which would be most interesting. Lock-in thermography (LIT) means that the heat sources in an object are activated in a periodically pulsed manner, the object is imaged by an IR camera running at a certain frame rate, and all images captured in a certain acquisition time are sent to a computer and evaluated and averaged according to the lock-in principle [2]. The primary results of a LIT measurement are an in-phase image (0° image) and an out-of-phase image (-90° image), which represent the magnitudes of the local T-oscillation in-phase with the pulsed heat introduction and 90° delayed to it. These primary images can easily be converted into images of the phase-independent T-modulation amplitude and the phase, the latter being a measure of the time delay between the periodic heat introduction and the resulting local T oscillation [2]. The basic advantage of LIT compared to direct IR imaging is the averaging nature of this technique, which after some 10 minutes of acquisition time leads to an improvement of the signal-to-noise ratio by a factor of 100 compared to direct IR imaging. Moreover, due to the dynamic character of the measurement, lateral heat diffusion is suppressed, leading to an improved effective spatial resolution. This technique was invented in 1984 [3] and became popular for nondestructive testing in the following decade [4]. In 1999 LIT was applied for the first time to image shunts in solar cells also under forward bias [5], where temperature modulations below 100 μK have been detected by applying bias pulses in the dark. However, this technique gives no information about series resistances. Moreover, under certain conditions, the simulation of the operation of the cell by applying bias pulses in the dark may be only a poor approximation.

Recently, a number of new LIT operation modes have been proposed for solar cell investigations, which are working with irradiation of light. These techniques allow to image the lifetime distribution across the cell, which governs V_{OC}, and they give realistic information about excessive series resistances and Joule type power losses. In the following, after reviewing the physical basis for these techniques, the most important LIT techniques for investigating solar cells are reviewed and illustrated by typical examples.

2 THE HEAT DISSIPATION MECHANISMS

Fig. 1 schematically shows the dominant elementary power sources in an illuminated solar cell in operation under a forward bias of U [6]. For electrons, all arrows facing downwards are mechanisms generating heat, like recombination or thermalization processes, and all arrows facing upwards are Peltier effects, which are cooling down the sample (for holes vice versa). For example, P_{ME} and P_{BM} are the Peltier power contributions generated at the metal-emitter contact and at the base-metal contact, which both may be positive or negative, depending or the direction of the current flow. P_{th} is the thermalization heat of the photogenerated carriers in the base. P_{pn+} is the thermalization heat for photogenerated minority carriers diffusing from the base into the emitter. This contribution could also be called a Peltier heating, since it is the opposite process of P_{pn-}, which is the Peltier cooling occuring at the pn junction if a forward current flows. P_{base} and P_{dr} are the recombination heats for carrier recombination in the base and in the depletion region. It turns out that e.g., if a current I is flowing under forward bias U in the dark, the dissipated heat splits into the recombination heat contributions and Peltier cooling contributions at the contacts and the pn junction, only the sum of all being the product P = I*U [6]. Note that, in addition to the power sources shown in Fig. 1, Joule heat is an important additional power source. The most important sources of Joule heat are ohmic shunts and horizontal current flow in the emitter and in contact lines. Joule heat in the base usually can be neglected.

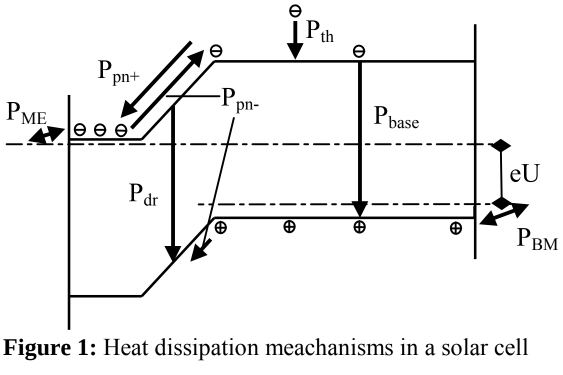

Figure 1: Heat dissipation meachanisms in a solar cell

3 LOCK-IN THERMOGRAPHY TECHNIQUES

A general rule for all thermal lock-in thermography (LIT) techniques on solar cells is that the lock-in frequency allows to choose a compromise between detection sensitivity and spatial resolution. For low frequencies, the signals are higher but the lateral heat diffusion is leading to a more blurred appearance of the images. For higher frequencies, on the other hand, the effective spatial resolution is improved, but the signal height is lower [2]. This behaviour is most pronounced for spatially homogeneous signals and least for highly localized signals. It had already been mentioned that there are 4 ways to display LIT signals, which are the 0° signal, the -90° signal, the amplitude signal, and the phase signal. The 0° signal shows the best possible spatial resolution, but it does not display homogeneous signal sources in solar cells and thus cannot be evaluated quantitatively. The -90° signal has a spatial resolution in the order of the thermal diffusion length, which is in silicon about 3 mm at 3 Hz and 1 mm at 30 Hz lock-in frequency. This is the only signal for solar cells which can be evaluated quantitatively to be proportional to the local power density [2]. The amplitude signal shows both local heat sources in good resolution and homogeneous signals, but it cannot easily be evaluated quantitatively. Nevertheless, the amplitude signal is the standard way to display LIT results. The phase signal is independent on the local IR emissivity, which makes it advantageous to image shunts below bare grid lines. Moreover, this signal shows a "dynamic compression" property, hence it displays weak local heat sources with a similar brightness as strong ones [2].

3.1 Dark lock-in thermography (DLIT)

In DLIT the operation of the illuminated solar cell is simulated by applying a forward bias in the dark. This approach relies on the validity of the superposition principle, saying that the photo-induced current is essentially bias-independent, and that the illuminated current equals the dark current minus the short circuit current I_{sc}. Then any current flowing under a certain bias in the dark would also be a loss current under illumination, which makes this technique especially useful to detect shunts. The basic advantage of DLIT is that here the image reflects only the relevant power sources, which is the reason why DLIT results can easily be evaluated quantitatively [7]. The basic limitation of this approach is that a straghtforward interpretation has to assume that the bias at the pn junction is always that at the terminals of the cell. This holds true as long as the contacts are good and the cell is investigated at a low bias, e.g. not exceeding the maximum power point of the cell (mpp, for silicon cells usually lying between 0.5 and 0.55 V), where the dark forward current is in the order of only 0.1 I_{sc}. However, for simulating open circuit voltage (V_{oc}) conditions, a forward current as high as I_{sc} has to be fed into the cell. Note that the current direction in the dark is opposite to that under illumination. Then voltage drops due to series resistances cannot be neglected anymore, and the simulation of the illuminated cell by a forward biased unilluminated one becomes unrealistic. Therefore, until now, this high current operation mode has been avoided for DLIT.

DLIT has proven to be very successful to detect and identify a large number of different shunts [8]. In the LIT literature the term "shunt" is understood much wider than in the former literature. In the past, the term shunts was only used for local defects having a linear (ohmic) I-V characteristic, and it was assumed that the so-called 2kT-current (i.e. the space charge recombination current) would be due to more or less homogeneously distributed recombination centers, which also govern the lifetime of the material. However, it was systematically shown e.g. by McIntosh [9] that unnaturally low lifetimes had to be assumed to explain measured recombination current values, and that measured ideality factors are larger than expected by simple diode theory. By DLIT and foregoing DPCT investigations [10, 11] we have found that many "shunts" show a non-linear (diode-like) characteristic with large values of the ideality factor. These are obviously recombination-induced "shunts", which appear if regions of high local density of states are crossing the pn junction. In fact, Konovalov has shown quantitatively that for usual multicrystalline cells the recombination current is completely due to local (non-linear) "shunts" [11]. Therefore we are using the term "shunts" not only for all local maxima with a linear I-V characteristic, but also for positions with a locally increased recombination current, with a locally increased diffusion current, as well as for local Schottky diodes [8]. Of course, the distinction between recombination-induced shunts and diffusion current induced shunts is floating, since in regions with a high density of recombination states also the lifetime is lower, leading to a locally increased diffusion current.

A typical DLIT investigation consists of two measurements performed at +0.5 V (forward bias) and at -0,5 V (reverse bias). These results are displayed side by side in the same scaling range, as shown for a typical monocrystalline cell in Fig. 2. Only if a shunt is visible in both images with a comparable brightness (see arrows), its I-V characteristic is linear (ohmic). If the brightness is higher under forward bias, this shunt shows a non-linear (diode-like) I-V characteristic.

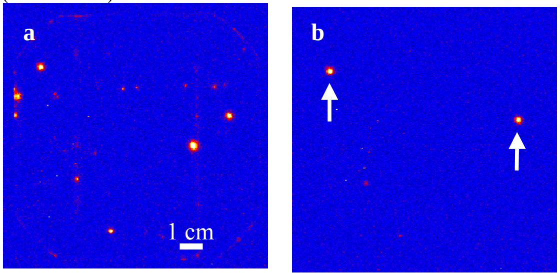

Figure 2: DLIT images for a monocrystalline solar cell, taken at + 0.5 V (a) and -0.5 V (b) at a lock-in frequency of 3 Hz, both scaled to 5 mK (arrows: ohmic shunts)

Note that DLIT can also be performed under large reverse bias (5 to 12 V), as it was done in the first thermal investigations of solar cells [1]. In this case, in addition to shunts visible at low voltage, new shunts caused by high field phenomena like local breakdowns may show. These may become important in the case of partial shading of a module, where cells may become reverse biased, leading to probably dangerous hot spots. The typical temperature signals in this case are many Kelvin, so that these shunts may also be detected by liquid crystal sheets [12], which show an inferiour spatial resolution than IR measurements, but are much cheaper to realize. Linear shunts as the most dangerous ones are visible by all these methods.

3.2 Illuminated lock-in thermography (ILIT)

According to Fig. 1, dark lock-in thermography relies on detecting the depletion region recombination heat P_{dr} and the base recombination heat P_{base}, both diminished by the Peltier cooling at the pn junction P_{pn-} and at both contacts P_{ME} and P_{BM} [6]. The Peltier effect at the metal emitter contact is negligible, compared to all others, because of the high doping concentration of the emitter. If a cell is illuminated, in addition to these sources the thermalization heat P_{th} and the pn junction thermalization heat P_{pn+} add up. Moreover, since the net current flow reverses, the Peltier cooling P_{BM} converts into Peltier heating, and the voltage drops at all series resistances invert their sign. Depending on the bias and on the current flow, also ohmic shunts and Joule heat due to lateral current flow are visible in ILIT, just as in DLIT, but for the illuminated case. In 2004, ILIT using pulsed light irradiation was developed independently at Fraunhofer ISE Freiburg [13], where it originally also was called "Illuminated Lock-in Thermography" but abbreviated ILT, and at University of Konstanz [14], where it originally was called "Light-modulated Lock-In Thermography" (LimoLIT). In these publications DLIT was called "Dark Lock-in Thermography" (DLT [13]) and "Voltage-modulated Lock-In Thermography" (VomoLIT [14]). Meanwhile, the authors of this contribution have agreed to call LIT without light irradiation generally DLIT and all techniques employing light irradiation "Illuminated Lock-In Thermography" (ILIT).

Depending on the electrical loading of the solar cell, several kinds of ILIT have to be distinguished. If the cell is kept under open circuit condition, which is the most simple variant since it does not need any contacting of the cell, this measurement is called **V_{oc}-ILIT**, since the cell is under V_{oc}-condition. In this case, all Joule losses are minimum, since no net current is flowing. However, nevertheless certain lateral currents are flowing as will be discussed below, since the magnitudes of all currents indicated in Fig. 1 may be inhomogeneous. For example, the photoinduced current leading to P_{pn+} corresponds to the local short circuit current density J_{sc}, hence, depending on the exciting wavelength used, it depends more or less on the local lifetime. The lower the exciting wavelength is, hence the closer to the emitter the light absorption absorption occures, the lower is this influence. Also the depletion region recombination current leading to P_{dr} is inhomogeneous, since P_{dr} is governed by the non-linear shunts. If V_{oc}-ILIT is performed not under full (1 sun) illumination intensity but under reduced intensity, so that a forward bias close to mpp establishes, this measurement is equivalent to DLIT performed at mpp. The advantage of this technique compared to DLIT is that it can be performed on non-contacted cells [14]. The disadvantage is that, in addition to the heating at the shunt sites, the more or less homogeneously distributed heat sources P_{th} and P_{pn+} are superimposed in the image as an essentially homogeneous background. It has been found, however, that even the relative shunt signals of V_{oc}-ILIT are larger than in DLIT [14]. This is because in DLIT the Peltier cooling contribution P_{BM}, which also shows a maximum in shunt position, partly compensates the recombination heating at recombination-induced shunts.

This behaviour changes if V_{oc}-ILIT is performed at full (1 sun) illumination intensity. Then the dark forward current current is dominated by the diffusion current, hence for a homogeneous cell all minority carriers would be back-injected into the base. In an inhomogeneous cell, however, this back-injection is very inhomogeneous. In fact, the local diffusion current density is proportional to the local lifetime in the base, which may vary locally by more than an order of magnitude. Also here, as discussed above, the photo-induced current is flowing into the emitter nearly homogeneously, but it is back-injected into the base and recombines there very inhomogeneously, depending on the local lifetime. This mechanism basically governs the thermal signal for V_{oc}-ILIT at 1 sun. Under this condition, the V_{oc}-ILIT signal is governed not anymore by shunts but by inhomogeneities of the lifetime. Therefore there is a very good (anti-) correlation between such a V_{oc}-ILIT measurement at 1 sun and LBIC (Light Beam Induced Current) imaging, as Fig. 3 shows. In DLIT performed at mpp, usually no correlation can be found to the LBIC image. Hence, V_{oc}-ILIT is the technique of choice for determining the factors governing V_{oc}, which basically is the lifetime in the base. Note that by this technique only local lifetime variations can be imaged, but no absolute values of the lifetime can be obtained.

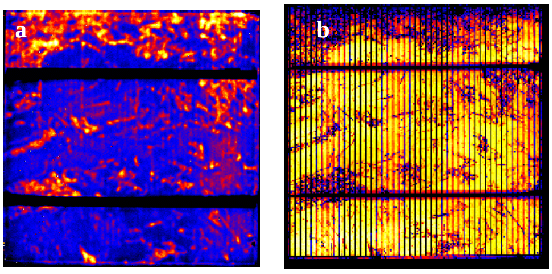

Figure 3: Voc-ILIT image (a, measured at 1 sun) and LBIC image (b) of a multicrystalline cell.

If ILIT is performed with pulsed light under short circuit conditions of the cell (**J_{sc}-ILIT**), linear and non-linear shunts and also recombination in the bulk should have a negligible influence, since the bias is very small. Then the dominating local heat sources are Joule heat of lateral current flows and the thermalization heat at the pn junction P_{pn+} (see Fig. 1). In J_{sc}-ILIT, inhomogeneities of the lateral current flow in the emitter can be made visible most effectively by displaying the 0°-image instead of the amplitude image [13]. Fig. 4 (a) shows such an image taken at the edge of a cell, where the grid lines are ending. The current crowding in the emitter at the tips of the grid lines is clearly visible. Fig. 4 (b) shows another cell under 1 sun illumination showing excessive heat dissipated in the bus bars close to the 4 current feed-in points (see white marks). If ILIT is performed with a resistor load to obtain mpp, this "**mpp-ILIT**" image reflects all energy losses appearing in real operation.

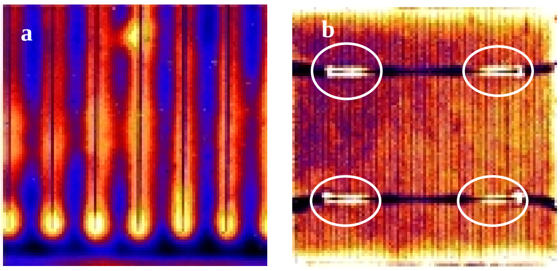

Figure 4: (a) 0° image of a J_{sc}-ILIT measurement (detail), (b) J_{sc}-ILIT amplitude image of a whole cell.

If all regions of a solar cell should be well-contacted, the bias in all regions should be close to zero, if the cell is kept at short circuit under illumination. However, if there should be regions of increased contact resistance between the emitter metallization and the cell, in these regions a considerable forward bias develops. This mechanism is used in the Corescan technique to detect non-contacted regions by mechanically probing the local bias under illumination of a cell under short cicuit [15]. If such a local bias develops, in this position the pn junction thermalization heat P_{pn+} reduces, hence a lower thermal signal is expected. In Fig. 5 (a) such a measurement is shown for a sample having problems with the emitter contact. Indeed, there are dark regions visible which, by independent Corescan measurements, have been identified as non-contacted regions. Hence, J_{sc}-ILIT is able to detect non-contacted regions in solar cells. However, as Fig. 5 (a) shows, these regions are surrounded by a bright halo. This halo is due to Joule heat dissipated in the emitter by the lateral current flowing out of the non-contacted region. Hence, the interpretation of J_{sc}-ILIT in terms of non-contacted regions is not straightforward; dark regions are certainly regions of high series resistance, but bright regions are not regions of low series resistance. In fact, the average thermal signal across a whole non-contacted region equals the thermal signal in well-contacted regions, since in both cases the whole light energy irradiated to a certain region is converted into heat.

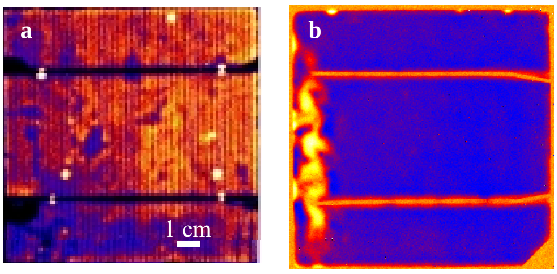

Figure 5: (a) J_{sc}-ILIT of a multicrystalline cell showing non-contacted regions, (b) R_s-ILIT image of a monocrystalline cell containing a non-contacted region.

For enabling a more reliable detection of non-contacted regions, a special technique called **R_s-ILIT** has been developed [6]. This technique works with permanent irradiation of light and pulses the bias from zero to 0.5 V, which is close to mpp. It turns out that the thermal signal is especially low in non-contacted regions, if the cell is kept under short circuit (see above), but is especially high in non-contacted regions, if the cell is kept at mpp [6]. On the other hand, the Joule heat, caused by the current flowing out of a non-contacted region, is similar in both cases. Thus, by the action of the lock-in correlation procedure, which subtracts both measurement results from each other, the non-contacted regions become visible more clearly, but the influence of the Joule heating around them is suppressed. Since R_s-ILIT may produce positive and negative signals, the -90° image has to be displayed here. In R_s-ILIT well-contacted regions appear dark (negative signal) and non-contacted regions bright (less negative or positive signal). Fig. 5 (b) shows the R_s-ILIT signal of another (monocrystalline) sample, also showing a large non-contacted region at the left. It is visible that this region is displayed with a negligible dark halo around, which would point to a Joule heat contribution. Note that in R_s-ILIT also shunts become visible, since here the bias is pulsed. The influence of shunts can be compensated by performing a DLIT measurement under similar conditions and subtracting the image from the R_s-ILIT image [6].

4 CONCLUSIONS

This contribution shows that lock-in thermography meanwhile provides a whole class of investigation techniques, which allow to image not only shunts in solar cells but also inhomogeneities of the lifetime, the series resistance, and the distribution of Joule losses under realistic operation of the cell. Note that lock-in thermography is also the base of IR lifetime mapping techniques [16], which allow a very efficient investigation not only of the lifetime distribution itself, but also of its dependence on experimental parameters like the temperature or the illumination intensity. The different lock-in thermography techniques are meanwhile valuable tools for analyzing solar cells and materials.

The authors are indebted to A.S.H. van der Heide (ECN) for providing cells for these investigations and making Corescan measurements on them. This work was supported by BMU project 0329846 (ASIS) and the EC project ENK6-CT2001-00574 (RGSells).

References:

[1] A. Simo, S. Martinuzzi, Proc. 21st IEEE PVSC (Kissimee 1990), 800.

[2] O. Breitenstein, M. Langenkamp, *Lock-in Thermography - Basics and Use for Functional Diagnostics of Electronic Components*, Springer, Berlin (2003).

[3] P.K. Kuo, T. Ahmed, H. Jin, R.L. Thomas, SPIE **1004** (1988) 41.

[4] X.P.V. Maldague, *Theory and Practice of Infrared Technology for Nondestructive Testing*, Wiley, New York 2001.

[5] O. Breitenstein, M. Langenkamp, O. Lang, A. Schirrmacher, Proc. 11th Int. PVSEC (Sapporo 1999) 22-C-3-2.

[6] O. Breitenstein, J.P. Rakotoniaina, JAP **97** (2005) 074905.

[7] O. Breitenstein, J.P. Rakotoniaina, M.H. Al Rifai, Prog. Photovolt: Res. Appl. **11** (2003) 515.

[8] O. Breitenstein, J.P. Rakotoniaina, M.H. Al Rifai, M. Werner, Prog. Photovolt: Res. Appl. **12** (2004) 529.

[9] K.R. McIntosh, Ph.D. thesis at UNSW Sydney, Australia (2001).

[10] O. Breitenstein, M. Langenkamp, Proc. 2nd WCPVSEC, Vienna (1998) 1382.

[11] I. Konovalov, Ph.D. thesis at Martin Luther University Halle, Germany (2000).

[12] C. Ballif, S. Peters, J. Isenberg, S. Riepe, D. Borchert, Proc. 29th IEEE PVSC, New Orleans (2002), 446.

[13] J. Isenberg, W. Warta, Journal of Appl. Phys. **95** (2004) 5200

[14] M. Kaes, S. Seren, T. Pernau, G. Hahn, Prog. Photovolt: Res. Appl. **12** (2004) 355

[15] A.S.H. van der Heide, J.H. Bultman, M.J.A.A. Goris, J. Hoornstra, Proc. 3rd WCPEC, Osaka (2003) 1036.

[16] S. Riepe, J. Isenberg, C. Ballif, S.W. Glunz, W. Warta, Proc. 17th PVSEC, Munich (2001) 1597.