

# Lock-in Thermography: A Versatile Tool for Failure Analysis of Solar Cells

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## Introduction

Renewable energy research is currently a major challenge. In recent years, the worldwide production of crystalline silicon solar cells has increased by approximately 30%.<sup>[1]</sup> New concepts for solar cells and new silicon feedstock are generated in the labs and on the solar cell market. Hence, the need for quality control and failure analysis of solar cells in research and industry has increased rapidly. This article demonstrates the possibilities of lock-in thermography (LIT) techniques for detailed failure analysis of solar cells. Lock-in thermography is well established for failure analysis application in integrated circuits (ICs). Special LIT techniques allow the evaluation of failure positions in ICs with good spatial resolution.<sup>[2,3]</sup> However, LIT is also a unique tool for characterization of solar cells. Currently, LIT techniques for solar cell research are fully developed and provide a wide range of applications for qualitative and quantitative analysis of solar cell parameters. In this article, a brief description of the lock-in imaging process for solar cells will be given, followed by an explanation of the different modes of LIT and their applications and results.

## Failures in Solar Cells

Silicon solar cells are large-area  $p$ - $n$  junctions usually made of  $p$ -doped wafers having a thickness of approximately 200  $\mu\text{m}$ . The  $n^+$ -doped layer, which has a thickness of approximately 250 nm, is formed by diffusion of phosphorus into the wafer. The resulting  $p$ - $n$  junction is covered by a silicon nitride layer that acts as an antireflection coating on the  $n^+$  side. The contacts to collect the current from the solar cell are made by a grid of silver lines on the frontside and a full-area aluminum contact on the backside. To avoid

a process-induced short circuit in solar cells, their edges must be isolated by a laser or by chemical etching.

Any disruption of the  $p$ - $n$  junction due to cracks and scratches that occur during the processing of a solar cell, as well as the edge, may produce failures. Many of these defects lead to unwanted leakage current. Hence, these types of failures are called process-induced shunts.<sup>[4]</sup> Multicrystalline (mc) silicon, which is used for approximately 40% of the annual solar cell world production, may contain precipitates<sup>[5]</sup> that can cause short circuits in solar cells.<sup>[6,7]</sup> These are called material-induced shunts. All types of shunts decrease the efficiency of solar cells and should be avoided. Because shunts are sites of increased current in solar cells, they produce additional heat and therefore can be detected thermographically.

This article will focus on the investigation of wafer-based silicon solar cells. However, the LIT technique is also well suited for investigating thin-film solar cells.<sup>[8]</sup>

## LIT Imaging of Solar Cells

The first attempts to image solar cell shunts were made by liquid crystal sheets,<sup>[9]</sup> which have poor spatial resolution and low temperature sensitivity. Improved temperature sensitivity was reached by dynamic precision contact thermography (DPCT),<sup>[3]</sup> which is already a lock-in method. However, the measurement times of DPCT are in the range of hours, which is quite long and not practical.

Camera-based lock-in imaging overcomes all of these problems. Figure 1 shows a schematic of a camera-based LIT setup. The system used for all images in this article is a TDL 640-XL setup (Thermosensorik GmbH, Erlangen, Germany). This system is

equipped with an indium antimonide, stirling-cooled camera head with a resolution of  $640 \times 512$  pixels, a pitch size of  $15 \mu\text{m}$ , and a maximum full-frame rate of 100 Hz. The spectral range of the camera is 1 to  $5 \mu\text{m}$ . Under steady-state conditions, that is, by applying a constant voltage to the device under test, this camera can detect temperature deviations down to 20 mK. This would be good enough to detect strong shunts under reverse bias. However, most solar cell failures appear under forward bias and exhibit temperature differences of only a few mK compared to the background. Moreover, steady-state thermography of solar cells shows very poor spatial resolution because of lateral heat spreading in the device. Therefore, lock-in techniques must be used for shunt imaging of solar cells. A detailed description of the general lock-in procedure can be found in Ref 3.

The lock-in imaging process for solar cells is explained in Fig. 1. The lock-in process requires a periodic signal from the solar cell. As shown in Fig. 1, this can be achieved by applying a pulsed voltage to the cell or by illuminating the cell with pulsed light; both methods are described in detail later. The voltage or light pulses are applied with the lock-in frequency,  $f_{\text{lock-in}}$ , provided by the computer, which triggers the power supply or light-emitting diode (LED) array, respectively. The lock-in frequency depends on the frame rate,  $f_{\text{fr}}$ , of the camera and must fulfill the relationship:<sup>[3]</sup>

$$f_{\text{lock-in}} \leq \frac{f_{\text{fr}}}{n}$$

Here,  $n$  is the number of frames evaluated in each lock-in period. Because two-phase correlation is being used, and, according to the sampling theorem, at least two samples per period are necessary,  $n \geq 4$  holds.

Hence, the maximum usable lock-in frequency is a quarter of the frame rate of the camera, but of course, a lower  $f_{\text{lock-in}}$  can be used by increasing  $n$ . In Fig. 1,  $n = 15$  is used. In the first half of each lock-in period, a certain power is applied to the solar cell, which is denoted by the “heating power” diagram in Fig. 1. The single frames taken by the camera in each lock-in period are then processed in the personal computer (PC). The frames are weighted in two channels to obtain the lock-in signal in phase with the pulse, which is called the  $S^{0^\circ}$  image, and the signal  $-90^\circ$  phase shifted to the pulse, which is called the  $S^{-90^\circ}$  image. The weighting factors,  $K$ , for each channel must be symmetric functions, respectively, because their sum must be zero after a certain number of lock-in periods. In this case, the weighting is done for the  $S^{0^\circ}$  image by a sine function and for the  $S^{-90^\circ}$  image by a  $-\cos$  function, as seen in Fig. 1. The weighted images are stored in separate image memories and summed up to complete the lock-in process, which is shown schematically in Fig. 1. The results are an  $S^{0^\circ}$  image and an  $S^{-90^\circ}$  image that are used to calculate the amplitude image,  $A$ :<sup>[3]</sup>

$$A = \sqrt{(S^{0^\circ})^2 + (S^{-90^\circ})^2}$$

and the phase image,  $\Phi$ :<sup>[3]</sup>

$$\Phi = \arctan\left(\frac{-S^{-90^\circ}}{S^{0^\circ}}\right) \quad (-180^\circ \text{ if } S^{0^\circ} \text{ is positive})$$

## General Aspects of LIT of Solar Cells

The lateral resolution of thermography images always depends on the diffusion of the thermal waves in the material. The thermal diffusion length scales

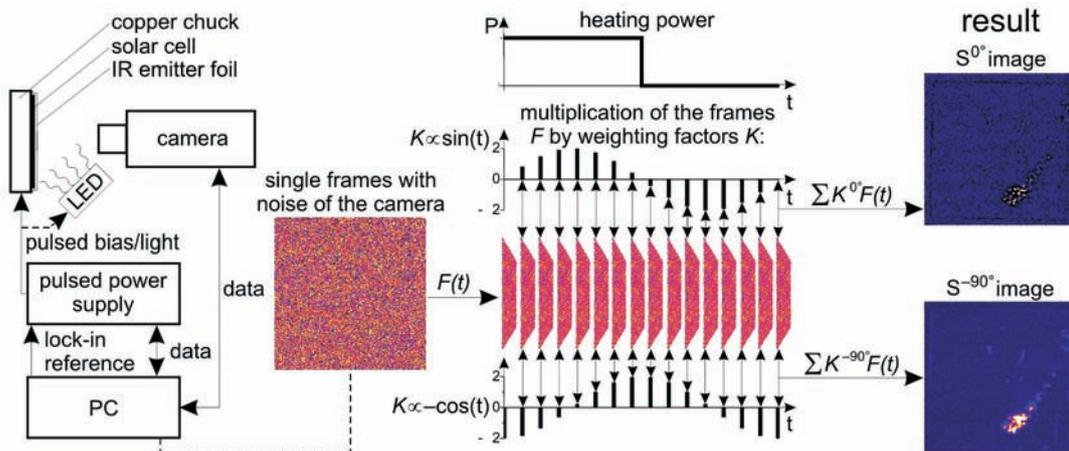


Fig. 1 Measurement setup of a camera-based lock-in imaging process (see text for explanation). The solar cell is pressed onto the chuck by a vacuum pump and is covered either by an infrared-emitting foil (dark lock-in thermography) or a transparent foil (illuminated lock-in thermography). The lock-in imaging process is shown schematically for one lock-in period with 15 frames per period.

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(continued)

with:

$$1/\sqrt{f_{\text{lock-in}}}$$

that is, the higher the  $f_{\text{lock-in}}$ , the higher the spatial resolution. The signal-to-noise ratio is determined by the measurement time, that is, the number of lock-in periods used for the measurement. The amplitude of the average noise scales with:

$$1/\sqrt{t_{\text{meas}}}$$

with  $t_{\text{meas}}$  being the measurement time.<sup>[3]</sup> After half an hour, the noise amplitude is below 0.1 mK.

The lock-in imaging process provides four images: the  $S^0$ ; the  $S^{-90^\circ}$ ; the amplitude image,  $A$ ; and the phase image,  $\Phi$ . The latter one is scaled in degrees and provides the phase shift between the signal and the lock-in reference signal, whereas the first three images are scaled in mK. The amplitude image is phase-independent and shows the shunts depending on their strength, that is, depending on the magnitude of the leakage current that flows through the shunt site. The phase image shows all local shunts independent of their strength. The  $S^0$  image has the best spatial resolution and provides the signal in phase with the sine correlation function (Fig. 1). For thermally thin samples such as silicon solar cells, the  $S^{-90^\circ}$  image, which gives the signal in phase with the  $-\cos$  correlation function (Fig. 1), is strictly proportional to the dissipated heat at the shunt position and can therefore be used for quantitative analysis of shunts.<sup>[10]</sup> The difference in the spatial resolution of the  $S^0$  and  $S^{-90^\circ}$  images is shown in the example in Fig. 1.

In addition to these four lock-in images, a topography image of the solar cell is always taken to enable comparison of the shunt positions with topological features.

## Dark LIT Methods

For dark lock-in thermography (DLIT), pulsed voltage is applied to the solar cell without illuminating it. Then, only the dark current flows in the cell. At shunt sites, an increased current causes heating of the solar cell, which can be easily detected by LIT.

DLIT is a powerful method for investigating all types of shunts. In particular, the dis-

inction between linear (ohmic) and nonlinear shunts is possible. To determine whether a shunt is linear or nonlinear, DLIT images are taken at 0.5 V forward bias (close to the maximum power point of a silicon solar cell) and at  $-0.5$  V (reverse bias). If the DLIT signals at the shunt position have the same strength in both images, the shunts are linear. If the signals differ significantly, the shunts are nonlinear.

**DLIT is a powerful method for investigating all types of shunts. In particular, the distinction between linear (ohmic) and nonlinear shunts is possible.**

Figure 2 shows a solar cell containing linear and nonlinear shunts. In the middle of the solar cell, some shunts appear (solid arrows in Fig. 2a) whose DLIT signal is strong in the forward direction but not measurable at  $-0.5$  V (Fig. 2b). These shunts are nonlinear. The shunts in the upper right corner of the cell in Fig. 2 are linear. The edge shunt (dashed arrow in Fig. 2) is also visible only in forward bias.

By applying a forward bias larger than 0.5 V, the diffusion current becomes the dominant current in the solar cell. At sites of decreased minority carrier lifetime, the solar cell heats up, and an image such as Fig. 2(c) can be obtained. Especially in mc-silicon solar cells (such as the one in Fig. 2), the areas of increased signal strength at higher voltages correlate with areas of poor crystal quality, which contain a higher concentration of recombination-active crystal defects.

In monocrystalline solar cells, where the diffusion current usually is isotropic, DLIT images, taken at large forward bias, can be used to determine areas of high series resistance,  $R_s$ . They appear dark, because no or a lower diffusion current flows there. This tech-

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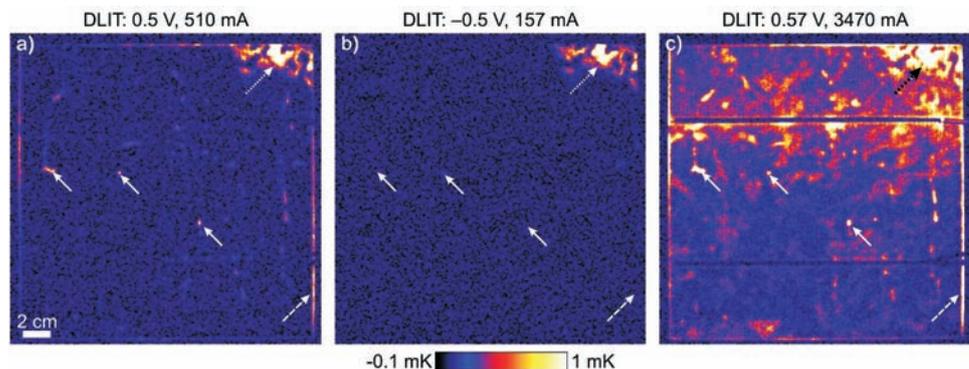
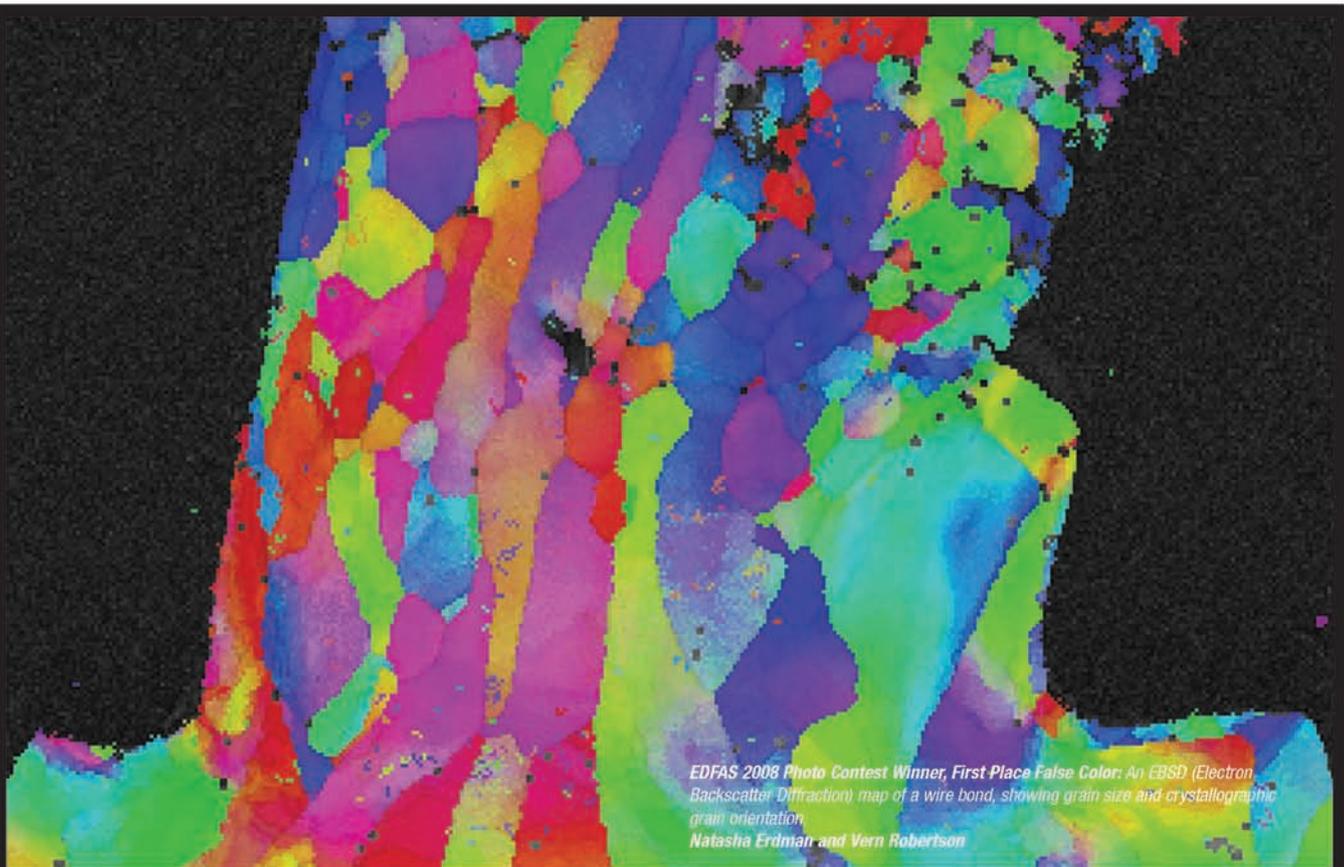


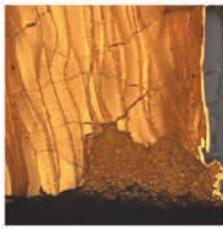
Fig. 2 Amplitude DLIT images of an mc-silicon solar cell at (a) +0.5, (b)  $-0.5$ , and (c) +0.57 V. Nonlinear shunts are marked by solid arrows, and linear shunts are marked by dotted arrows. The nonlinear edge shunt is marked by a dashed arrow.



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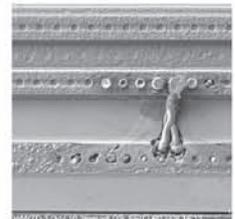
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\* The significance of the photo is to indicate that the cracks on gold plating are initiated from the alumina substrate.

\*\* Roots of ESD. This is ESD damage/short between Emitter/Collector regions on a device. Silicon has migrated from an emitter region shorting out to a collector region.

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nique cannot be used for mc-silicon solar cells, because areas of high lifetime in these cells also appear dark, so it is hard to distinguish between series resistance effects and areas of high lifetime.<sup>[11]</sup> Another DLIT method is imaging the solar cell ideality factor.<sup>[10]</sup> Neither method is demonstrated here.

To investigate the breakdown behavior of solar cells, new DLIT techniques have recently been developed.<sup>[12]</sup> By taking DLIT images at certain reverse biases at different temperatures, respectively, physical parameters such as the temperature coefficient (TC) and the slope of the reverse current at breakdown sites can be imaged. This is achieved by subtracting either two images at the same voltage but different temperatures or two images at the same temperature but different voltages. By relating the current differences to the average current values, physically relevant values of the TC (given in percent change per Kelvin) and the slope (given in percent change per volt) are obtained, independent of the magnitude of the local shunts.<sup>[12]</sup>

Figure 3 shows a  $S^{-90^\circ}$  DLIT image at a high reverse bias at room temperature, a TC-DLIT image, and a slope-DLIT image of an mc-silicon solar cell. The DLIT image (Fig. 3a) shows the breakdown sites in the solar

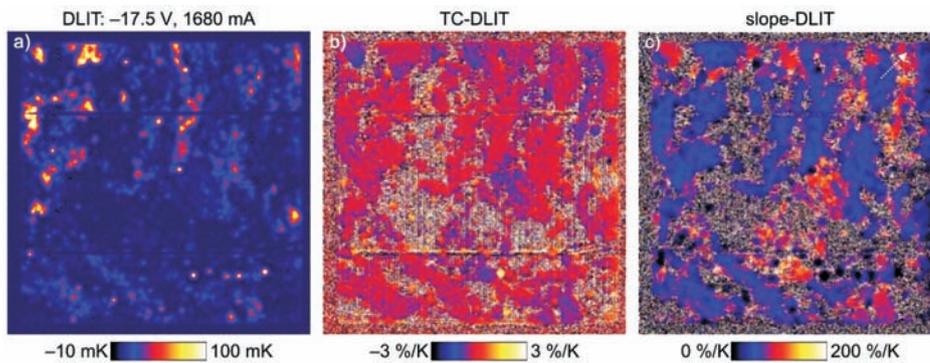


Fig. 3 (a) Reverse-bias DLIT image of an mc-silicon solar cell. (b) TC-DLIT image showing the distribution of the temperature coefficient of different breakdown sites. (c) Slope-DLIT image maps the slope of the reverse current.

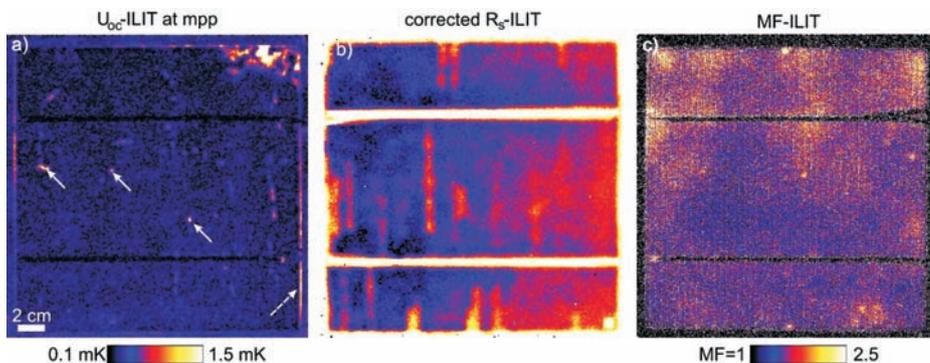


Fig. 4 (a)  $U_{oc}$ -ILIT image of the same solar cell shown in Fig. 2. (b) Shunt-corrected  $R_s$ -ILIT image of another solar cell. (c) MF-ILIT image of the same solar cell shown in Fig. 3

cell, with the brightness depending on their dissipated power. The dark areas in the TC-DLIT image (Fig. 3b) correspond to areas of negative TC, and the bright areas are regions of positive TC of the current. In the slope-DLIT image (Fig. 3c), the dark areas correspond to regions of a weak slope of the reverse current, and the bright areas show regions of a high slope. Regions without breakdown sites (Fig. 3b, c) are noisy. The TC-DLIT and slope-DLIT images show extended regions of the same TC or slope values, respectively, because, due to lateral heat spreading, an extended region around each local breakdown site leads to the observed signal.<sup>[12]</sup>

## Illuminated LIT Methods

Illuminated lock-in thermography (ILIT) is performed by illuminating the solar cell with pulsed light.<sup>[13,14]</sup> In the simplest case, the cell is not contacted, so that it is under open-circuit voltage ( $U_{oc}$ ) conditions. The value of  $U_{oc}$  depends on the light intensity used. For full solar intensity, a nominal  $U_{oc}$  of approximately 0.6 V is established, whereas at a certain reduced intensity, a  $U_{oc}$  of approximately 0.5 V can be obtained, corresponding to the nominal maximum power point (mpp) of the cell. Figure 4(a) shows such a  $U_{oc}$ -ILIT image, taken at the mpp. It is the same cell shown in Fig. 2 and also reveals the shunts. The nonlinear shunts are especially well pronounced. At full illumination intensity, the image looks similar to Fig. 2(c).

ILIT overcomes the problems of DLIT concerning the imaging of  $R_s$  in mc cells. By taking an ILIT image under continuous illumination with the voltage pulsed between short circuit (0 V) and the mpp of the cell (0.5 V), the series resistance can also be imaged for mc-silicon solar cells.<sup>[11]</sup> This  $R_s$ -ILIT image still contains the shunt signals, but a DLIT image taken at 0.55 V may be subtracted from the  $R_s$ -ILIT image for qualitatively imaging the series resistance in solar cells without the influence of shunts. Such a shunt-corrected  $R_s$ -ILIT image is shown in Fig. 4(b).

Last, a method is introduced that images the multiplication factor (MF) of avalanche break-

down sites in solar cells.<sup>[12]</sup> The technique, called MF-ILIT, makes it possible to clearly distinguish between avalanche breakdown and breakdown due to the Zener effect in solar cells. Figure 4(c) shows an MF-ILIT image of the same cell as in Fig. 3. The image uses data from two measurements, taken by illuminating the solar cell with pulsed light of 0.1 sun intensity and a wavelength of 850 nm for two different constant reverse voltages. At low reverse voltages, only the photocurrent flows in the cell and heats it up isotropically. If, at higher reverse currents, avalanche breakdown occurs, the current increases at the respective sites, and the solar cell becomes warmer than at places where no avalanche multiplication occurs. The MF is the ratio of these two modulated photocurrents. In mc cells, the MF-ILIT image is typically rather anisotropic (Fig. 4c). Note that any breakdown sites not affected by the photocurrent are not shown in this image.

## Conclusions

In recent years, LIT imaging has become a versatile, powerful tool for failure analysis of solar cells. With LIT techniques, it is possible to investigate the local variation of many physical parameters that are important for characterizing solar cells. For example, the ideality factor of solar cells and other important parameters such as the series resistance can be imaged. The high-temperature resolution of the camera-based LIT techniques down to some  $\mu\text{K}$  allows the location of even very weak shunts in solar cells. The dynamic character of LIT considerably improves the spatial resolution compared to steady-state thermography. The new TC and slope-DLIT and MF-ILIT methods are useful tools for imaging the TC and slope of the current in reverse-biased solar cells, as well as the avalanche MF. Lock-in thermography is an accurate tool for finding the interesting spots on a solar cell and is therefore very important for precharacterizing solar cell samples for further investigation of the physical origin of defect sites. Lock-in thermography is a nondestructive characterization method and may even be fast enough for use in solar cell production lines.<sup>[15]</sup>

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### About the Authors



**Jan Bauer** received his diploma in physics from the University of Halle, Germany, in 2006 following an investigation of shunting precipitates in silicon solar cell material. After investigating electrical properties of nanowires at the Max Planck Institute of Microstructure Physics in Halle, Germany, he is now a Ph.D. student in the solar cell research group of that institute, working on solar cell characterization.



**Otwin Breitenstein** received his Ph.D. in physics in 1980 from the University of Leipzig, Germany, and has been at the Max Planck Institute of Microstructure Physics in Halle, Germany, since 1992, where he investigates defects in semiconductors. Since 1999, he has used lock-in thermography to detect internal shunts in silicon solar cells. In 2001, Dr. Breitenstein introduced this technique on a microscopic scale for isolating faults in ICs. He has contributed to ISTFA tutorials, authored a book on lock-in thermography, and published more than 100 articles about his research in scientific journals and international conferences.

**Jan-Martin Wagner** received his Ph.D. in 2004 from the University of Jena, Germany, where he did first-principles calculations of group-III nitrides. As a postdoctoral student at the same Institute of Solid-State Theory, he did calculations on ultrathin Si/SiO<sub>2</sub> multi-quantum-well structures as candidates for third-generation solar cells. In 2007, Dr. Wagner joined the Max Planck Institute of Microstructure Physics in Halle, Germany, where he now works on theoretical aspects of solar cell characterization.



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