SPATIALLY RESOLVED IR-MEASUREMENT TECHNIQUES FOR SOLAR CELLS

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ABSTRACT: The article gives an overview over developments in the area of characterization tools for solar cells using CCD-cameras sensitive in the IR. Additionally, the prospects for the application of these measurement systems in In-Line and Off-Line process control will be addressed. The methods discussed include Dark and Illuminated Lock-In Thermography (DLT and ILT), Carrier Density Imaging (CDI) and Sheet Resistance Imaging (SRI). The two thermography-methods allow a spatially resolved investigation of leakage currents and power losses in solar cells under dark and illuminated conditions, respectively. CDI is the first measurement technique that provides a lifetime image with good spatial resolution within a few seconds to minutes and SRI permits the same quality and speed of measurements for the sheet resistance of solar cell emitters. All these techniques apply a CCD-camera sensitive in the IR and were developed to a state applicable in routine Off-Line cell characterization. An important common feature of all of them is that an imaging method replaces scanning the sample for obtaining good spatial resolution. Thus measurement times are significantly reduced as compared to previous setups, typically by a factor of 100 or above.
Keywords: Characterization – 1: IR-measurement methods – 2: Qualification and testing – 3

1 INTRODUCTION

Over the last few years spatially resolved characterization methods using CCD-cameras sensitive in the IR have become increasingly important tools for the assessment of material quality and the detection and analysis of technological problems and failures in solar cell production. This paper is intended to give an overview over these developments and assess prospects for their application in solar cell characterization, In-Line and Off-Line.

Dark Lock-In Thermography (DLT) developed by Breitenstein et. al. [1], [2] is a versatile tool for the detection and spatially resolved characterization of so called “shunts”. The method measures the distribution of dark current over the solar cell. An advancement of this characterization technique is *Illuminated Lock-In Thermography* (ILT) [3]. This technique allows the measurement and investigation of current paths under illumination condition. Additionally a direct measure of the distribution of all power losses within the solar cell under operation conditions is obtained.

Carrier Density Imaging (CDI) [4] is a spatially resolved lifetime measurement technique that measures absolute lifetime values under low level injection conditions, that is the lifetime values relevant for solar cell performance.

Sheet Resistance Imaging (SRI) [5] is a method with high spatial resolution, that is capable of measuring the dopant dose of emitters. A sheet resistance map may be calculated from the images taken.

The latter three measurement techniques were developed over the last years in our workgroup to tools ready for a broader use. For CDI (under the name ILM) and SRI proves of principle were performed before by Bail et al. [6], [7]. An intermediate technique between Dark and Illuminated Lock-In Thermography was proposed by Rappich et al. in Ref. [8].

2 COMMON FEATURES FOR ALL TECHNIQUES

All measurement techniques discussed in this paper use a CCD-camera sensitive in the mid-infrared. The standard camera applied at our institute at the moment is able to take quadratic images of 288x288 pixels with one measurement. Thus for attaining a good spatial resolution the time consuming scanning of the sample as is necessary in other measurement techniques is overcome. With this imaging technique measurement times are reduced by a factor of 100 or more as compared to standard scanning setups. Spatial resolutions of as low as 10 µm were realized with the present setup if an appropriate microscope lens-system is employed [9]. Samples of 100x100 mm² may be investigated with a spatial resolution of 350 µm in one single measurement.

Except for the SRI-technique the methods require an amplification of the measurement signal in a Lock-In system. As sampling is done for all 288x288 individual measurement points simultaneously, the Lock-In has to work in real-time for all these measurements. This was realized with two framegrabbers working in parallel and evaluating the incoming camera images pixelwise and in real-time with a pre-defined correlation function each. For more details on the Lock-In system see e.g. Ref. [10].

3 DARK LOCK-IN THERMOGRAPHY (DLT)

Dark Lock-In Thermography (DLT) [1] became an important tool in the investigation of process-induced defects in finished solar cells. The general idea is to apply an external voltage to the solar cell under dark conditions and thus force a current through the cell. An inhomogeneous distribution of this dark current results in inhomogeneous power dissipation and heating of the cell. The latter one may be monitored by the IR-sensitive camera. Typical temperature differences are in the range of 100 µK to 10 mK. Since the Noise Equivalent Temperature Difference (NETD) of standard cameras operating in the mid-IR is around 20 mK a Lock-In system is required. To accomplish with this necessity, a rectangular voltage signal applied to the solar cell is used as excitation source. It has to have the same frequency and has to be in phase with the Lock-In. By this method sensitivities as low as 10 µK were achieved [11].

As an example for the usefullness of DLT in Off-Line process control Fig.1 shows an industrial solar cell, where DLT measurements revealed that the most important shunts were found on the right and left edges of the solar cell. Comparison of the DLT images of different cells fabricated under identical process conditions disclosed a weakness in the edge isolation process that was responsible for the fillfactor losses observed. The possibility of a 1:1 correlation of the IR-reflection image and thus the metalization pattern with the Thermography Image combined with zooming parts of the image as shown in Fig. 1 allows the exact correlation of point-shunt positions within the cell area with crystallographic features and the front side metallization.

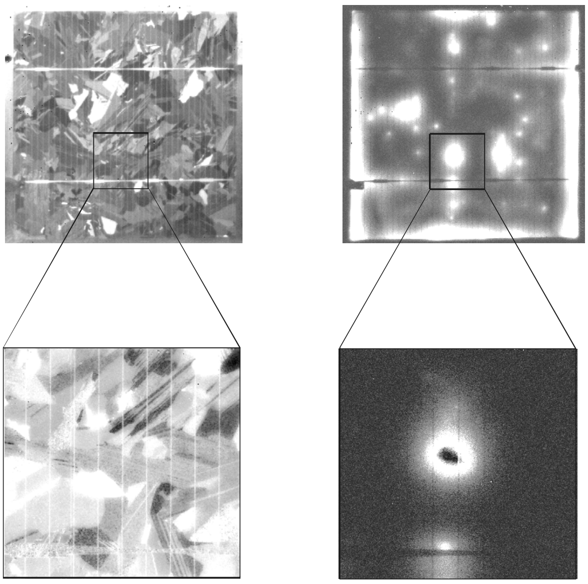

Figure 1: Dark Lock-In Thermography Image (right) and IR reflection image (left) of an industrial type solar cell.

4 ILLUMINATED LOCK-IN THERMOGRAPHY (ILT)

Illuminated Lock-In Thermography (ILT) is based on the same general idea as DLT. In ILT an optical excitation by illumination is used instead of the electrical excitation under dark conditions, which is applied in DLT. The resulting advantage of ILT is, that the measurement is conducted under realistic operation conditions of the finished solar cell. As current paths for the dark and illuminated case differ considerably, the influence of different loss mechanisms as recombination in the bulk, recombination in the space charge region and ohmic type shunts may be very different in dark and illuminated measurements. Thus, a more realistic comparison of the impact of different loss mechanisms on solar cell performance is achieved by ILT.

Additionally the measurement conditions of ILT enable a direct imaging of the distribution of power losses in solar cells. This is the advantage of Illuminated Lock-In Thermography as compared to techniques which apply a bias illumination but do the modulation with the Lock-In frequency electrically via the applied voltage (see Ref. [8]). As is explained in more detail in Ref. [12] these intermediate measurement techniques do not yield the influence of small cell areas, especially shunts, on the whole solar cell.

Thus, by using a modulated illumination as excitation source, ILT for the first time offers the possibility to quantitatively assess the spatial distribution of power losses in an illuminated solar cell under operation conditions.

The measurement under illuminated conditions allows a more detailed investigation of power losses e.g. due to individual grain boundaries in mc-silicon as is exemplified in Fig. 2.

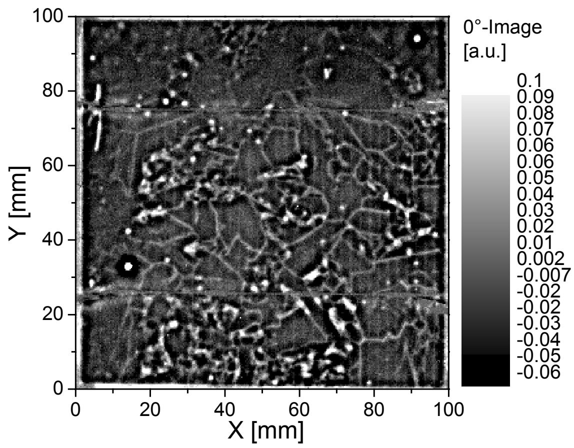

Figure 2: ILT-Image of a multicrystalline silicon solar cell (0°-Image). The power losses due to individual grain boundaries are clearly seen and may be evaluated quantitatively if the –90°-Image is used.

For all Thermography measurements the –90°-Image is directly proportional to the local (within one thermal diffusion length) power dissipation in the solar cell. This direct proportionality is not given for the 0°-Image, which on the other hand, offers a higher spatial resolution and is thus advantageous if small sized structures are to be investigated. Therefore, for a quantitative evaluation of the detrimental effects of small sized grains or grain boundaries the –90°-Image has to be taken. This is exemplified for a different industrial solar cell in Fig. 3. By optical inspection we find an area of small grains approximately in the middle of the cell. The ILT image reveals, that the power dissipation is significantly increased in this area of the cell (Fig. 3). In order to calculate the detrimental effect of this area on the whole cell, the ILT-data for this area is hypothetically replaced with the data obtained in a "high performance" area (white box on the left hand side of Fig. 3. Integrating the ILT-data, which is proportional to the power losses in the cell for the original data and the "improved data" gives the overall losses for the two cases which may be calibrated by means of ILT-data obtained under J_{SC}- or V_{OC}-conditions (see Ref. [13] for more details). With this procedure we find that the cell displayed in Fig. 3 could by improved by 12.5% relative under 914 nm monochromatic illumination conditions if the marked area of high power losses could be avoided. Simulations with PC1D using a baseline model similar to the structure of this cell type show that this increase in efficiency corresponds to an increase between roughly 6% and 12.3% relative under AM1.5G illumination assuming that the power losses in this area are essentially due to increased bulk recombination or dark saturation current respectively.

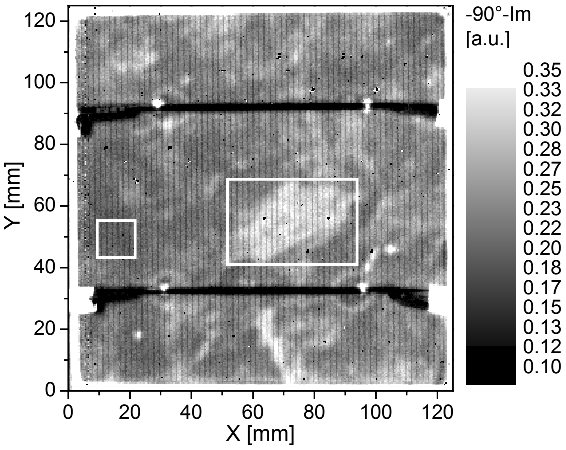

Figure 3: -90° ILT-Image of an industrial solar cell taken at a bias voltage of 479 mV (V_{MPP}=479.9 mV). The area of high power dissipation framed by the white box in the middle of the cell contains many small sized grains. The white box to the left marks the "high performance" reference area.

With its improved characteristics ILT has greatly expanded the characterization means of Lock-In Thermography as compared to standard DLT.

At present ypical measurement times for both DLT and ILT are around 5 to 30 minutes. Thus the main focus of their application will be in Off-Line process-control and detection of weaknesses in the production chain. Nevertheless, applying DLT with a high inverse voltage might be used In-Line to identify and separate out cells that may potentially cause hot-spots in the finished module [1]. Additionally ILT offers the possibility to measure unfinished solar cells at any production step after formation of the pn-junction.

5 CARRIER DENSITY IMAGING (CDI)

Carrier Density Imaging (CDI) is the only lifetime measurement technique that combines a fast measurement within seconds or a few minutes with a good spatial resolution. Additionally, it measures values most relevant for solar cell performance, that is absolute lifetime values under low-level-injection conditions.

The initial idea [7] was to take advantage of the free carrier absorption of low-energy photons in silicon. If two measurements are done, one with illumination and one in complete darkness, the difference between the two IR-transmission images is just proportional to the excess free-carrier density generated by the illumination. If the photon flux density of the illumination source is known or measured once in the setup phase, the absolute minority carrier lifetime may be calculated from the difference of the two transmission images. Instead of the absorption by free carriers the IR-emission of free carriers may be used for CDI measurements as well [14]. In fact the sample always emits and absorbs radiation. The measurement modes of Emission- and Absorption-CDI provide measurement conditions that ensure that one of the two processes dominates over the other. With the application of an appropriate illumination source and a Lock-In system instead of taking just two transmission images, a sufficient sensitivity is attained to measure all kinds of samples relevant in solar cell processing. This includes as-cut and emitter diffused samples without any additional surface passivation as well as cast multicrystalline silicon from the very bottom of an ingot.

Off-Line CDI-measurements allow a quick assessment of technological problems. This greatly facilitates their detection and removal. An example for this kind of application is presented in Fig. 4. The figure shows a FZ-wafer with a thermally grown oxide processed during the starting phase of the clean-room in the new building of Fraunhofer ISE. Routine MW-PCD measurements without spatial resolution demonstrated that a contamination problem was present, but the source was unknown. The CDI Image taken within a few seconds revealed that the low lifetime is due to a contaminated carrier system.

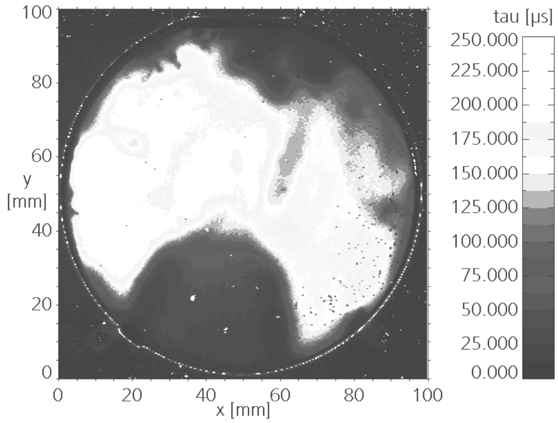

Figure 4: CDI Image of FZ-sample with thermal oxide and contamination problem due to a carrier system.

Three different methods for further reduction of measurement time were proposed [15],[16]: One is based on a statistical evaluation, the second one on emission measurements at increased temperatures and the third one applies a flash as illumination source instead of the semiconductor laser.

The method of using the Emission-CDI mode with slightly increased sample temperature demonstrates a significant reduction potential in measurement time as compared to standard measurement conditions (for more details see Ref. [17]). This is exemplified in Fig. 5: A sample with an average effective lifetime of about 18 µs was measured at three different temperatures with a measurement time of 1s only. The left part of the image displays the result obtained at a sample temperature of 40°C, the middle part at 59°C and the right third of the image visualizes the result obtained at a sample temperature of about 100°C. We find a significant increase in signal to noise ratio with sample temperature. For this lifetime range temperatures of about 60°C allow CDI measurements at a measurement time of 1 s with sufficient sensitivity.

The method of Flash-CDI uses a flash instead of the semiconductor laser as illumination source. With this change in the setup an initial illumination of roughly 100 suns may be realized, which allows for a drastic reduction in measurement time. First experiments with the Flash-CDI resulted in measurement times of below 100 ms. An example is displayed in Fig. 6.

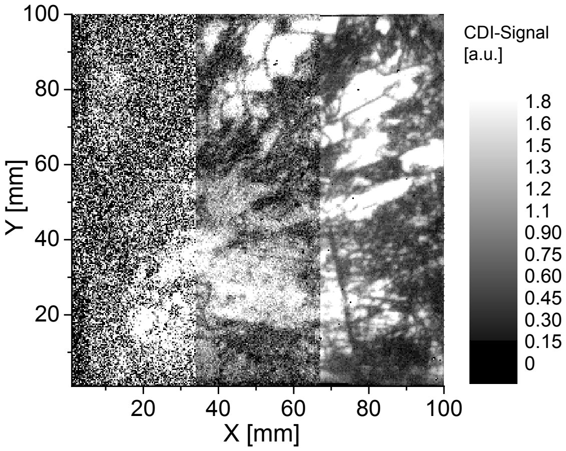

Figure 5: Emission-CDI measurement of an mc-wafer with an average lifetime of about 18 µs. The measurement time was 1 s. The image is assembled from three measurements. The left hand part of the image represents a measurement at a sample temperature of 40°C, the middle part at 59°C and the right part corresponds to a measurement at 100°C.

The rather high noise level in these first experiments is due to reflections of IR radiation emitted by the flash. The IR-fraction of the flashs spectrum could however be effectively filtered in an actual industrial setup. Thus a significant increase in image quality is expected. Flash-CDI leaves the concept of a measurement under low-level injection conditions. The effect on the predictability of cell performance in an industrial environment has still to be investigated .

6 SHEET RESISTANCE IMAGING (SRI)

Sheet Resistance Imaging (SRI) is an optical method that takes advantage of the IR-absorption of free carriers and measures the carrier density in the emitter and thus the sheet resistance of emitters with a very high spatial resolution. The advantage of the optical measurement is, that extremely high resolutions of the images may be realized without distortions from probe size and geometry as is commonly the case for electrical measurements (e.g. four-point probing) on inhomogeneous samples. At the moment, specially prepared reference-samples are required for a good measurement result. This hinders an In-Line application, but ideas to overcome these problems exist [5]. Disregarding this problem for the moment, an optimization for In-Line process control should be attainable as SRI is a contactless measurement technique and measurement times in the non-optimized setup used at the moment range from approximately four to ten seconds per wafer.

SRI proved to be very helpful in the analysis of inhomogeneities in different diffusion furnaces. Due to the very fast measurements a wide variety of diffusion parameters may be tested and the homogeneity of the resulting emitters investigated. Thus, an optimization for the homogeneity of emitter sheet resistance becomes feasible, which up to now, applying four-point-probing for controlling the sheet resistance, is either extremely time-consuming or could only be done with very few measurement points per wafer. In many cases this is not enough to reveal e.g. a drastic increase of emitter sheet resistance towards the edges of the sample.

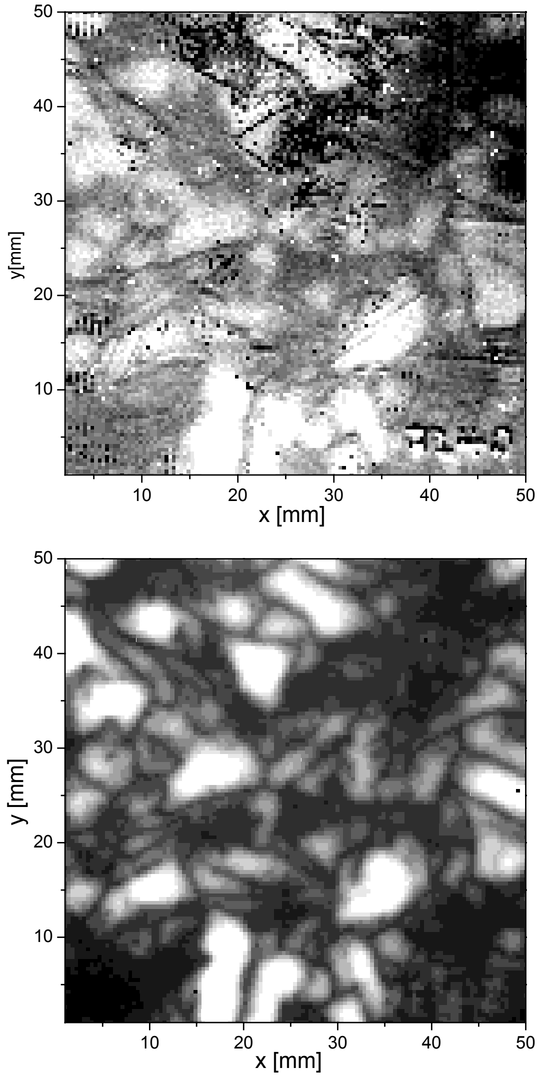

Figure 6: Flash-CDI image (upper image) with a measurement time of 16 ms only and standard CDI image of the same sample for comparison (lower image). The comparatively high noise level in these first experiments with Flash-CDI is due to IR-reflections of the flash that could effectively be filtered in a state-of-the-art setup.

Due to its high spatial resolution (down to 50 µm with the present setup) SRI is excellently suited for the detailed investigation of selective emitter structures. Fig. 7 shows the sheet resistance image of a section of a 100x100 mm² wafer with selective emitter structure taken with SRI at a spatial resolution of approximately 50 µm and a measurement time of 4 s only. The selective emitter structure is clearly displayed.

Fig. 8 displays a linescan of emitter sheet resistance perpendicular to the selective emitter structure of Fig. 7. Comparison of measurements with SRI and two different setups for four-point probing reveals, that the results of the electrical measurement of this inhomogeneous structure with four-point probing significantly depends on the size and orientation of the probe relative to the structure in emitter sheet resistance. Thus results obtained by four-point probing on similar samples have to be treated with utmost care. On the opposite, SRI is free of such kinds of problems as it is a pure optical and contactless measurement. Additionally SRI-images of the emitter sheet resistance have an excellent quality and are even suitable for assessing the width of the heavily doped regions and the sheet resistance value in the lightly doped areas of the structure shown in Fig. 7 and 8.

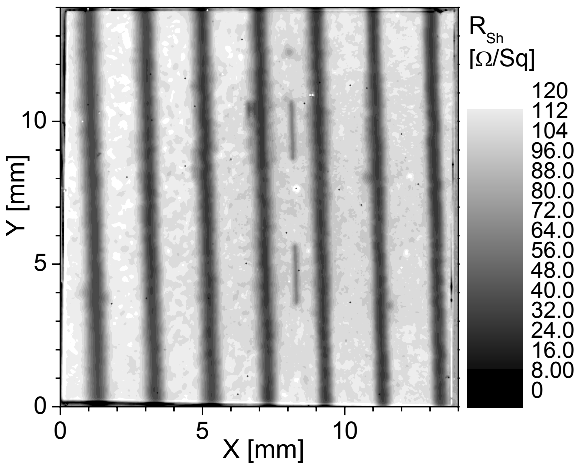

Figure 7: Sheet resistance image taken with SRI on a wafer with selective emitter structure before metalization. The image was taken at 4 s measurement time with a spatial resolution of 50 µm.

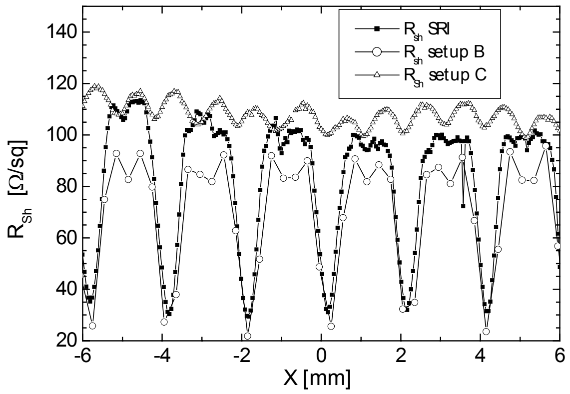

Figure 8: Linescan through the center of the selective emitter structure shown in Fig. 7. Setup B is a four-point probe with square-array and alignment of the two probes, that are used for current and voltage respectively, perpendicular to the selective emitter structure. Setup C is a Wenner-Array (linear array) aligned in parallel with the selective emitter structure.

7 CONCLUSION

This paper describes four recently developed spatially resolved IR measurement methods for the characterisation of solar cells and precursor. Dark- and Illuminated Lock-In Thermography measure the distribution of current and power losses in solar cells under dark and illuminated conditions respectively. Carrier Density Imaging gives a spatially resolved image of carrier lifetime under conditions that match the operation conditions of solar cells. Finally, Sheet Resistance Imaging provides maps of the emitter sheet resistance of solar cells.

Common to all of them is the high spatial resolution, which is e.g. 350 µm if a 100x100 mm² wafer is to be investigated with one measurement. All methods discussed are characterized by very short measurement times, since spatial resolution is achieved by an imaging technique rather than by scanning the sample. A more detailed discussion of the measurement techniques and possible applications may be found in Ref. [16].

The development of these IR measurement techniques has greatly improved the options for solar cell characterization in research labs and thus helped in the understanding of loss mechanisms in solar cells. These techniques may significantly improve the possibilities for industrial process-control, In-Line and Off-Line. For Off-Line application all methods described herein may be incorporated in one single measurement setup with one CCD-camera and different measurement modes.

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