Infrared analysis of thin-film photovoltaic modules

Cl. Buerhop, J. Bachmann
Bavarian Center for Applied Energy Research (ZAE Bayern), Division 3,
Am Weichselgarten 7, 91058 Erlangen, Germany
E-mail: buerhop@zae.uni-erlangen.de

Abstract. Distinctive hot spot phenomena caused by electrical shunts in thin-film modules are analyzed by infrared thermography. Modelling the shunt current by an equivalent circuit and considering lateral heat transport, the detected phenomena are discussed. Defects show a characteristic intense temperature rise (>12mK) in the center and an extended sphere of influence with reduced temperature rise.

Introduction
Thin-film photovoltaic (PV) modules offer economical advantages for production by good energy output during operation. IR-imaging is a promising tool for checking the quality and reliability of thin-film modules. Measuring the infrared (IR)-radiation by applying voltage, provides spatially distributed details of hot spots caused by defects that could reduce the power yield of a solar module significantly. Possible reasons for defects are e.g. faulty cell separation or dust particles during layer deposition. The key issue of this work is to get a better understanding of phenomena observed in IR-images.

Thermography techniques monitor the temperature distribution and reveals inhomogeneities. Concerning PV-modules, spots of elevated temperature are mainly due to an increased current through the semiconductor. Because of locally reduced parallel resistance more energy is dissipated in shunting defects. In order to detect low temperature differences lock-in technique is used. The advantage is a suppression of DC-signals, resulting in an improved thermal resolution compared to the nominal sensitivity of an IR-detector. By applying power with the lock-in frequency (square wave function), the heat sources oscillate with the same frequency. The lateral resolution of an image can be controlled by the thermal diffusion length $\Lambda$. The diffusion length decreases by increasing the lock-in frequency. This makes IR-imaging an interesting visualizing technique to describe loss mechanisms in crystalline silicon solar cells [1, 2, 3], PV-modules [4] and in CdTe-modules [5].

Differing shunts in thin-film modules detected by IR-thermography will be discussed on the basis of resulting current distribution in connection with heat transport. Modeling the current through a defect (shunt) in a simple circuit model, will extract the dominating parameters. The absolute temperature differences gained by IR-imaging have to be evaluated carefully. Finally, the local temperature distribution in a shunted cell has to be linked with the simulated local current distribution.

Measurement set-up and electrical simulation

1.1. Measurement Set-up
The main component of the measurement setup is the IR-camera “Taurus SM 110k pro” from IRCAM GmbH. It is equipped with a CMT- focal plane detector with 384x288 pixels, the spectral sensitivity
ranges from 3 µm up to 5 µm and the noise equivalent temperature difference (NETD) is 20 mK. Using the lock-in technique, thermal resolutions of 395µK and 105µK are achieved. The measurements were performed by applying an external voltage to the module. The experiments have been carried out with thin-film modules and the results of an a-Si solar panel will be presented exemplarily. The module has a size of 90 cm x 29 cm, with $V_{mpp} = 16$V and $I_{mpp} = 0.75$A. This module consists of 30 cells of a width of 9 mm. The spatial resolution of the IR-image of the complete module is about 2.5 mm per pixel and 0.089 mm per pixel for the detailed images, respectively.

1.2. Equivalent circuit diagram simulation

The thermal heating in a module is mainly generated by the current flux. In order to model the current through a photovoltaic device, different currents have to be considered, the current through the active semiconductor of the cell and the current through the contacting layers. The back contact is made out of metal, e. g. Mo, while the front contact consists of TCO (transmitting conductive oxide), e. g. ZnO. The resistivity of TCO is typically in the order of $3 \times 10^{-4}$ Ωcm, while the resistivity of the metal is in the order of $10^{-6}$ Ωcm. Hence the back contact resistance is of less importance than the TCO resistance.

![Figure 1: Equivalent circuit diagram of 5 elements used for simulation. Each element consists of R1 and R2. R1 symbolizes the lateral resistance, R2 the fixed resistance of the semiconductor, $R_{sh}$ a variable shunt resistance replacing R2 in one element.](image)

In the equivalent circuit diagram a resistance network existing of two levels is made, see figure 1. Resistance R1, horizontally aligned, stands for the TCO front side contact or the lateral currents within the semiconductor layer. Resistance R2, vertically arranged, symbolizes the parallel resistance across the semiconductor. The values for R2 were fixed, whereas for one element an incremental resistance $R_{sh}$ is used instead of R2.

A uniform current is applied to the network. In the simulation a thin-film solar cell is fractionized in n elements parallel to the interconnects, with one element having the length of 1 mm. Thus, the 225 calculated elements represent a cell length of 225 mm. The calculations of the partial currents $I_1$, $I_2$, … $I_n$ were done using the software MatLab and the results were rechecked with the simulation tool PSpice.

Results

3.1 Experimental Results

A typical amplitude lock-in image and the corresponding I-V-curve of the investigated a-Si thin-film module are shown in figure 2. The individual unit cells the module is made of are clearly visible ranging from the left to the right side. The bright white area visible on the right side of the module is probably due to thickness fluctuations which indicate non-uniform processing parameters but is not of importance for this work.
The focus of this investigation lies on the bright spots within the module, showing areas with increased temperature. The increased temperatures indicate multiple shunts which have impact on the cell. The homogeneously heated cell areas show an average temperature rise of about 1.2 mK. The temperature rise of the shunted spots range from 6.6 mK for small defects (D3) up to 26 mK and 34 mK for larger ones, (D1 and D2) respectively. These temperatures are averaged values across the pixels containing the shunts. The temperature in a defect may be much higher because the shunt size is much smaller than the pixel size. For example, shunt D2 shows a temperature increase of 150 mK in a higher resolved image, shown in figure 3a. Shunts showing temperature rises above 12 mK are associated with a sphere of influence. In this surrounding area the temperature rise is reduced, visible by the long, dark regions, e.g. of spot D2 in figure 2. The minor defect D3 does not exhibit such an influence on the neighborhood. The line scans in figure 3 illustrate the differing temperature profiles of the selected defects D1, D2, and D3. The lateral temperature distribution visualizes that strong defects D1, D2 impact the temperature of the shunt surrounding. The temperature increase affects approximately 4-5 pixels, respectively 7.5-10 mm, which is in the order of the lateral thermal diffusion length of $\Lambda=16$ mm (if the metallic back contact is considered as the dominant factor for the heat transport). The temperature rise close to the defect is low for D1 and D2 ($\Delta T > 400 \mu K$) compared to the homogeneously heated area of ($\Delta T = 1.2$ mK) near defect D3 (figure 3b).

Defect D1 in figure 3a is composed of two single defects, one revealing probably a bad break line, the other might be originated during layer depositing process. Defect D2 in figure 3a illustrates descriptively a poorly performed laser cut.

### 3.2. Simulation Results

In order to get a better understanding of the IR-images and the current flow, simulations with different values for $R_1$, $R_2$, and $R_{SH}$ have been carried out. The examination of the resistance $R_2$ yields, that the current through the shunt $R_{SH}$ rises with increasing $R_2$. The calculated influence a defect with varying
shunt resistance $R_{SH}$ on the current distribution in a thin-film solar cell is demonstrated in figure 4. Reducing the shunt resistance $R_{SH}$ in the model from 1Ω to 0.01Ω, enhances the current through the defect drastically and simultaneously enlarges the sphere of influence.

![Figure 4](image)

**Figure 4**: Calculated current through the shunt resistance $R_{SH}$ in thin-film cells, $R_1=0.02\, \Omega$ and $R_2=10\, \Omega$ are taken constant. The lower the resistance of the defect $R_{SH}$ the larger is the influenced neighbourhood.

The simulation makes clear that a low shunt resistance $R_{SH}$ caused by a defect forwards the current flow through the defect, if the lateral resistance enables a cross flow. The resulting current is not homogenous. The maximum current is obtained in the center of the defect and drops instantaneously in order to approach asymptotically the current value of a shunt-free cell. The current reduction around the shunt is more pronounced the higher the shunt current is. The resulting power dissipation across the semiconductor becomes also a function of the local position, too. Considering a defect as a point heat source, lateral heat diffusion into the surrounding has to be taken into account. The periodically pulsed heat sources used in lock-in technique are advantageous, because the lateral diffusion is determined by the lock-in frequency, e.g. $\Lambda(1\, \text{Hz})=5\, \text{mm}$.

**Conclusion**
Lock-in thermography of thin-film modules enables the distinction of weak and strong electrical shunts caused by fabrication defects. They distinguish significantly in terms of signal intensity and sphere of influence. Experiments reveal that intense defects with $\Delta T>12\, \text{mK}$ have a significant sphere of influence. The temperature difference between the sphere of influence and the unaffected cell is larger than $400\, \text{mK}$.

Future work will focus on the refinement of the circuit model to include more realistic, non-linear resistances, taking account for diode-like resistance of the semiconductor. This implies the demand of calculating the temperature profile with a FEM-program in order to consider position-dependent power. Localizing defects facilitates their characterization and the quality control of thin-film modules.

**References**
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