Solar Energy Materials & Solar Cells 159 (2017) 8–19

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Quantitative local current-voltage analysis and calculation of performance parameters of single solar cells in modules

J. Bauer*, F. Frühauf, O. Breitenstein

Max Planck Institute of Microstructure Physics, Weinberg 2, 06120 Halle, Germany

ARTICLE INFO

Article history:
Received 6 July 2016
Received in revised form
24 August 2016
Accepted 27 August 2016
Available online 8 September 2016

Keywords:
Current-voltage analysis
Modules
Si solar cells
Electroluminescence
Lock-in thermography
Single cell analysis

ABSTRACT

Quantitative characterization of single cells already embedded in modules is performed by a combination of electroluminescence imaging and dark lock-in thermography. Electroluminescence imaging is used to determine the terminal voltages of single cells in modules, and dark lock-in thermography imaging enables the use of quantitative analyses of single solar cells with the software Local I-V 2. This combination yields spatially resolved images of the performance parameters of single cells. To check the reliability of the method also the directly measured voltages of the single cells in a module have been used for Local I-V evaluation and are compared to the results of Local I-V evaluation from voltages determined by EL. The accuracy of the voltage determination in our experiments is about $\pm 1\%$ compared to directly measured voltages, leading to an accuracy of the cell parameters such as J_{01}, U_{oc}, efficiency, power, FF, and so on of about $\pm 2\%$ using the voltages determined by EL for the Local I-V analysis. With the method introduced it is possible to quantitatively identify the performance of single solar cells in modules reliably and non-destructively, thereby tracking quantitative changes of the cell performance due to degradation processes with high sensitivity and spatial resolution becomes possible.

1. Introduction

Solar cells can be investigated and characterized with a lot of standard methods, for example electro- and photoluminescence (EL/PL), lock-in thermography (LIT), light beam induced current (LBIC), and so on, all giving a map of a method-dependent parameter of the whole solar cell, see e.g. [1–6]. These images can be used for qualitative and in many cases even for quantitative analyses of solar cells. For the characterization of solar cells embedded in modules in principle the same methods can be used. Imaging methods for modules become more and more important for quality and reliability control of photovoltaic modules in terms of degradation, power yield, and hot spots. Different approaches to image loss mechanisms in solar modules have been published recently. Especially EL has been used due to its simplicity for imaging the degradation of cells in modules e.g. due to cracks and broken grid fingers [7–9], potential induced degradation (PID) [10–12], so called "LeTID" (light and elevated temperature induced degradation) [13], so called "snail trails/tracks" [14], and long term stability of modules [15]. Thermography (in steady-state and lock-in modus) imaging is used mainly to detect hot spots due to their nature of increased temperatures [16,17]. Also the analyses of power losses due to PID using thermography images was shown recently [18]. To detect cracks, shunts and other defects in modules often a combination of EL imaging and infrared (IR) thermography is used, since EL has a much better spatial resolution compared to steady-state thermography and even to LIT [19–21]. Note that luminescence imaging and LIT perfectly supplement each other, since luminescence images the local diode voltages quantitatively and LIT images the local diode currents. Most of the above mentioned methods for modules are only qualitative investigations, even if they give spatially resolved images of the modules. Another attempt for non-destructive quantitative analysis of cells in modules was done by evaluating EL images [22]. Here the individual cell parameters such as the ideality factors $n_{1,2}$, and the dark saturation current densities $J_{01,02}$ of single cells in a module have been estimated by investigating the relationship between individual cell parameters of solar cells connected in series, the voltage dependent EL intensity, and the current-voltage (*I-V*) curve of the complete module [22]. However, this approach does only lead to global cell parameters and not to spatially resolved parameters of each single cell. For quantitative spatially resolved analyses of solar cells in modules the individual cell voltage, i.e. the terminal voltage, is necessary to know.

If it is required to apply a voltage to a cell in a module, for instance for EL and LIT measurements, the voltage can only be applied indirectly via all the other cells to the cell under test. In today's standard photovoltaic modules (60 or 72 cells per module)

* Corresponding author.
E-mail address: jbauer@mpi-halle.mpg.de (J. Bauer).

http://dx.doi.org/10.1016/j.solmat.2016.08.029

all cells are connected in series. Hence, the current through all the cells is the same and equals the module current I_{mod}. Unfortunately, the often made simplification that the individual cell voltages U_i (i=number of cells in the module) results from the module voltage U_{mod} divided by the number of cells N in the module does only hold if all cells would have exactly the same current-voltage characteristic, which is not the case in reality. Instead, U_i of each cell is adjusted individually (*so*-called floating voltages) and is determined by the *I-V* characteristic of the cell, because each cell shows a different voltage at I_{mod}. Hence, for characterizing a single cell in a module, the individual cell voltage at different working points, i.e. different I_{mod} has to be determined. This can be done by the approach reported by Köntges et al. [23] and Potthoff et al. [24] using the maximum EL signal of each cell in the module for determining the individual cell voltages.

The aim of our work is to get quantitative, spatially resolved data of the performance parameters of single solar cells in standard 60-cell modules using EL and dark lock-in thermography (DLIT) imaging. For this purpose we use the approach by Köntges and Potthoff, see [23,24], to get the single cell voltages at different working points and measure DLIT images at the same working points to apply the quantitative Local I-V evaluation of DLIT images [25–27] to single cells in a module, which is described in Sections 2.2 and 3.2.

2. Experimental and methods

For our investigations we use a standard 60-cell module made of PERC (passivated emitter and rear cell [28]) solar cells, which are specially treated to show a light- and elevated temperature-induced degradation effect. The module was degraded according to [13]. For our purposes we benefit from the fact that some cells show a strong degradation and other cells show no measureable degradation, hence a large variation in cell performance can be expected, and a large variation in cell voltages, which in turn is a good test for our investigation method. For testing our method we measure the cell voltages directly at the module as well. To be able to do so, the module was locally opened carefully on the rear side at the middle busbars between two cells, respectively, and contact wires have been soldered at these positions onto the middle busbars. The single cell voltages $U_{i,\ meas}$ have been measured with a multimeter with an error of about $\pm$0.2 mV. A similar approach was used by Köntges and Potthoff et al. in [23,24]. For applying voltage and current to the module the junction box was opened and four wires, two for the plus and minus contact, respectively, have been soldered onto the module contacts in the junction box. This allows four-point probing of the module preventing errors due to voltage drops caused by the external wiring, which might cause failures of the module voltage measurement.

Following the method published in [23,24] one needs the maximum EL signal of each cell to determine its terminal voltage, i.e. the voltage which can be measured at the metal contacts of the cell. For the quantitative DLIT analysis of the solar cells [25,26] DLIT images at three different voltages are needed. Here we restrict on forward bias investigations, since the Köntges/Potthoff method [23,24] works only under forward bias. Hence, if there should be ohmic shunts in the cells, they will be identified as J_{02}-type shunts with a large ideality factor. We performed EL imaging, DLIT imaging, and steady-state thermography imaging of the module, using a Si-CCD Sensovation CoolSamba HR-400 camera with a pixel resolution of 2048 × 2048 for EL imaging, and the Lock-in Thermography system PV-LIT by InfraTec equipped with an InSb detector camera (Image IR 8300) with a resolution of 640 × 512 pixels for the thermography measurements. For the voltage determination using the EL images, steady-state thermography images were needed to determine the temperatures of all cells as exact as possible, since during the high voltage (high current) measurements the cells get significantly warmer than the surrounding. As a consequence the current is rising until the thermal equilibrium to the surrounding is reached. To limit this effect, we operated the power supply in constant current mode to get approximately the desired U_{mod}, see details below in Tables 1,2. The accuracy of the current limit was better than $\pm$ 10 mA. The integration time for each EL image was 180 s.

Table 1
Global module parameters for cell voltage determination from EL images.

U_{mod} [V]	I_{mod} [A]	T_{mod} [K]	n_i [cm^{-3}] from [32]	C eq. (9)	R_{mod} eq. (4) [Ω]
33.85	0.627	297.2	7.76×10^9	3.46×10^{-7}	0 (per def.)
35.55	1.606	298.5	8.66×10^9	4.31×10^{-7}	0.242
37.27	3.800	302.0	1.16×10^{10}	7.70×10^{-7}	0.226
38.47	6.705	306.7	1.69×10^{10}	1.65×10^{-6}	0.224

Table 2
Global module parameters for DLIT measurements.

U_{mod} [V]	I_{mod} [A]	T_{mod} [K]	ΔT_{mod} EL–DLIT [K]
33.84	0.627	296.5	0.7
35.80	1.606	297.2	1.3
37.44	3.804	298.7	3.3
39.05	6.705	301.7	5

DLIT was performed by imaging the back sheet of the rear side of the module at 1 Hz lock-in frequency for 1 h for each image. Therefore the LIT images contain the shadow of the junction box at the top. In the efficiency analysis only the non-shadowed part of the corresponding cells could be analyzed. All LIT based images are shown mirrored for a better comparison to the front side EL images. It is important to note that EL is done by applying a constant current to the module and DLIT is done by applying a pulsed current to the module. Hence, different power is consumed by the module at the same current limit and different temperatures are reached in thermal equilibrium to the environment, regarding a fixed current limit. Therefore it was important to measure the temperature as exactly as possible to be able to correct the cell voltages for the temperature differences between the EL and the DLIT measurements (see details in Section 3.2). We managed to measure the temperatures of each cell with an error of about $\pm$0.2 °C by IR imaging. We measure the module voltage with an error of about $\pm$0.01 V. Please note that the temperature change of the module depends strongly on the lab conditions such as air temperature, air flow (maybe due to an active air conditioning) and the lab size. We performed our measurement in an air conditioned lab with a nominal fixed temperature of about 20 °C, this gave us the opportunity to repeat measurement under nearly the same conditions.

Overall we took EL images, the corresponding thermography images for EL, and DLIT images at four different module voltages U_{mod}, please see Tables 1,2 for details. For EL a background image was taken at zero bias with the same integration time and subtracted from each EL image to get rid of bad pixels and background illumination. All measurements have been performed in a dark lab to minimize effects of the surrounding. The cells are named from 1 to 60 according to the scheme in Fig. 1(a).

2.1. Cell voltage determination by EL

The local EL signal $\Phi(x,y)$ of a solar cell depends on the local voltage $U(x,y)$ and the local calibration factor $C(x,y)$: