Solar Energy Materials & Solar Cells 135 (2015) 35–42

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Advanced large area characterization of thin-film solar modules by electroluminescence and thermography imaging techniques

A. Gerber *, V. Huhn, T.M.H. Tran, M. Siegloch, Y. Augarten, B.E. Pieters, U. Rau

IEK5-Photovoltaik, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany

ARTICLE INFO

Article history:
Received 13 June 2014
Received in revised form
10 September 2014
Accepted 15 September 2014
Available online 8 October 2014

Keywords:
Thin-film solar cells
Electroluminescence
Thermography

ABSTRACT

This paper shows that the combination of both dark lock-in thermography (DLIT) and electroluminescence (EL) imaging techniques is especially suitable for in-depth shunt analysis of industrial $Cu(In,Ga)Se_2$ (CIGS) thin-film modules and for the quantitative analysis of the local electrical cell properties, such as the internal junction voltage or the series resistances of the front and back contact. First results obtained for amorphous silicon (*a*-Si:H) based thin-film solar modules reveal that the quantitative EL analysis method is applicable to amorphous silicon technology as well. Using the consistent modeling of EL and DLIT images using a SPICE based model with input data generated from EL and DLIT measurements, we demonstrate that we can obtain properties of solar modules like the spatial voltage distribution, the resistances of the front and back contact, and the shunt resistance of local defects. We furthermore discuss two newly developed techniques, namely voltage-modulated lock-in thermography at the maximum power point (MPP-LIT) of an illuminated cell or module as well as differential EL analysis of illuminated cells and modules.

1. Introduction

In the steadily growing photovoltaic industry, there is a massive demand for fast and reliable large area analysis methods for the in-line quality management of fabricated solar modules. The most popular imaging methods to investigate the influence and properties of electrical losses within a large area PV module are the electroluminescence (EL) [1] and the lock-in thermography (LIT) [2] imaging techniques which are complementary [3,4]. The EL image reveals the distribution of the voltage drop over the junction within the cells. In contrast, LIT is sensitive to the local temperature, and thus to the spatial distribution of dissipated electrical power, revealing interconnection losses and more inherent properties of defects like shape, size, and local power dissipation. Most of the classical work on LIT is concerned with silicon wafer solar cells [5–10] but increasingly the method is applied to thin-film solar cells as well [11,12]. Generally, two different modes of LIT are used: The application of an external voltage to the non-illuminated device is denoted as dark LIT (DLIT), in turn, the application of a periodic illumination is denoted as illuminated LIT (ILIT) [1]. Since the lock-in method is a modulation technique, a wide variety of voltage or illumination bias conditions combined with either voltage modulations (VoMo-LIT) or illumination modulations (LiMO-LIT) are possible [7,10].

The present paper gives a short overview of both imaging techniques with respect to their usability for loss analysis and shunt detection for thin-film modules, as well as their potential suitability for industrial applications. We show that EL imaging is a promising tool for fast in-depth failure analysis of industrial sized $Cu(In,Ga)Se_2$ (CIGS) thin-film modules. First results on in-house fabricated amorphous silicon thin-film modules reveal that from EL experiments, we can determine the internal junction voltage of amorphous silicon based solar cells [13].

Furthermore, we demonstrate that from the consistent modelling of EL and dark lock-in thermography (DLIT) images using a SPICE based model [14] we can obtain properties of solar modules, such as the spatial voltage distribution, the resistances of the front contact, of the back contact, and the shunt resistance of local defects. These properties enable us to investigate the impact of different kinds of electrical defects on the module performance under various conditions—e.g. high and low illumination conditions. Finally, two new techniques are discussed, both investigating the properties of cells or modules under homogeneous illumination.

2. Theory

Both imaging techniques capture the emission of radiation emitted by a solar cell, however, the spectral ranges of the electroluminescence and the thermal (infrared) radiation differ. In case of

* Corresponding author. Tel.: +49 2461 611819; fax: +49 2461 613735.
E-mail address: a.gerber@fz-juelich.de (A. Gerber).

http://dx.doi.org/10.1016/j.solmat.2014.09.020
0927-0248/

CIGS solar modules the EL emission at room temperature is typically in the spectral range between 700 nm and 1100 nm, whereas for example, the infrared radiation (black body radiation) of a 100 °C hot-spot peaks, according to Wien's law at $\lambda_{max} \approx 7.4\ \mu m$.

Electroluminescence can be interpreted as the reverse operation of a solar cell, i.e., converting electric energy into electromagnetic radiation. The relation between the spatial EL intensity $\phi_{EL}(\mathbf{r})$ and the local internal junction voltage $V_j(\mathbf{r})$ is described by the opto-electronic reciprocity relation [15]

$$\phi_{EL}(E,\mathbf{r}) = Q_e(E,\mathbf{r})\phi_{bb}(E)\exp\left(\frac{qV_j(\mathbf{r})}{kT}\right). \quad (1)$$

Here, Q_e denotes the local external quantum efficiency of the solar cell, E is the photon energy, $\phi_{bb}(E)$ is the spectral photon density of a black body, and kT/q is the thermal voltage. As an approximation, the spatial variation of the external quantum efficiency is neglected and treated as spatially independent $Q_e(E,\mathbf{r}) = Q_e(E)$ [17].

The camera signal $S_{cam}(r)$ of each pixel can be expressed as the integral over the product of the camera's energy dependent spectral sensitivity Q_{cam} and of the measured EL signal ϕ_{EL} [16,17]

$$S_{cam}(\mathbf{r}) = \int Q_{cam}(E)\phi_{EL}(E,\mathbf{r})\, dE. \quad (2)$$

From Eqs. (1) and (2) we can derive the local internal junction voltage $V_j(\mathbf{r})$

$$\frac{kT}{q}\ln\{S_{cam}(\mathbf{r})\} = V_j(\mathbf{r}) + V_{off}. \quad (3)$$

Therefore, we can derive the internal junction voltage $V_j(\mathbf{r})$ directly from the camera signal, except for an unknown spatially independent offset voltage V_{off}. The EL signal does not contain losses from series resistances and thus the sum $\sum_{n=1}^{N}\overline{V}_{j,n}(J)$ of the averaged internal junction voltage $\overline{V}_{j,n}(J)$ of each sub-cell ($n=1\ldots N$) at a given current density J equals the open circuit voltage V_{oc} of a module determined from separately measured illuminated J_{sc}/V_{oc} curves. This allows us to determine the value of V_{off} according to [17,18]

$$V_{oc}(J_{sc}) = \sum_{n=1}^{N}\overline{V}_{j,n}(J_{sc}) = \frac{kT}{q}\sum_{n=1}^{N}\ln\{S_{cam}(J_{sc})\} - N\,V_{off}, \quad (4)$$

by adjusting the sum in Eq. (4) to the module open circuit voltage V_{oc} (measured at the respective short circuit current density ($J=J_{sc}$)).

In contrast to the EL signal, the local infrared emission of a solar module is the sum of all local heat sources. The infrared signal contains the dissipation in the series resistances of the front and back contact, the junction, and the contact resistance between the cells, the electrodes as well as in the electrical active defects (shunts). This makes it rather complex to separate these effects in order to gain quantitative results. The application of a lock-in technique helps to enhance the signal to noise ratio and also reduces thermal blurring caused by the heat wave propagation, however, blurring effects are generally not negligible. Recent work focusing on the quantitative analysis of DLIT images of thin-film solar modules concentrate on the comparison between simulated power images including the thermo-electric Peltier effect and experimental data to infer cell parameters [11,19].

In general, the infrared emission of radiation is proportional to the local variation of the device temperature $\delta T(\mathbf{r})$ and therefore proportional to the dissipated local electrical power density p, leading to a generalized approach similar to Eq. (1)

$$\phi_{IR}(\mathbf{r}) \propto \phi_{bb}(T+\delta T(\mathbf{r})) \propto p(\mathbf{r}), \quad (5)$$

where $\phi_{bb}(T+\delta T)$ is the photon density of black body at the temperature $T+\delta T(\mathbf{r})$, and $p(\mathbf{r})$ is the local power density. The camera signal can be expressed similar to Eq. (2) by

$$S_{cam}(\mathbf{r},E) = \int Q_E(E)\,\phi_{IR}(T+\delta T(\mathbf{r}))\, dE. \quad (6)$$

Throughout this paper we use the DLIT technique for qualitative defect analysis, i.e., we investigate the size and strength of local defects within the absorber layer and the interconnection lines (laser lines).

3. Results and discussion

For the EL measurements we used a temperature-controlled silicon based 10 mega pixel CCD camera from Apogee. The camera and the samples were kept in a light-tight box. The LIT measurements were performed using a Velox 327k SM-thermocamera from IRcam GmbH, which is equipped with a cadmium-mercury-telluride detector with a resolution of 640 × 512 pixel. For the experiments we used non-encapsulated industrially fabricated CIGS modules with a dimension of 30 × 30 cm² and in-house fabricated amorphous silicon (a-Si:H) based thin-film solar modules with a dimension of 10 × 10 cm².

3.1. Thermography and EL analysis of CIGS modules

Both imaging techniques are suitable for the investigation of shunts although they are somewhat complementary. Electrical defects within the absorber appear in a thermography image as hot spots with sharp contours, whereas in an EL image they appear as dark spots. Thermography can also be used to investigate the losses in interconnection lines between cells, for which EL is unsuitable. In contrast, an EL image reveals the local internal

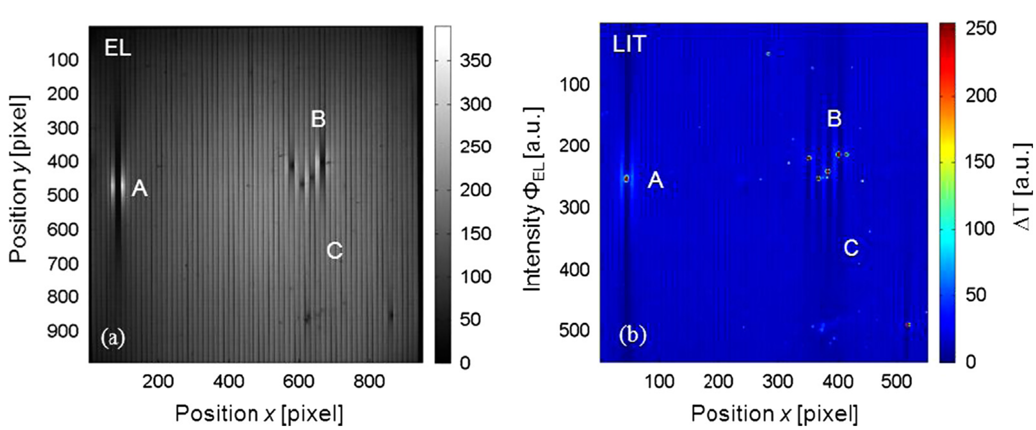

Fig. 1. Comparison of an EL image (a) and an LIT image (b) of a 30 × 30 cm² CIGS module at an injection current of 0.83 mA cm⁻². The EL image was captured within 3 s, whereas the measurement duration for the LIT image was 30 min. The letters A, B and C indicate defects of different strength.