Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 77 (2015) 43 – 56

Energy Procedia

5th International Conference on Silicon Photovoltaics, SiliconPV 2015

Short-circuit current density imaging methods for silicon solar cells

Fabian Fertig[a]*, Milan Padilla[a], Otwin Breitenstein[b], Hannes Höffler[a], Ino Geisemeyer[a], Martin C. Schubert[a], Stefan Rein[a]

[a]*Fraunhofer Institute for Solar Energy Systems, Heidenhofstr. 2, D-79110 Freiburg, Germany*
[b]*Max Planck Institute of Microstructure Physics, Weinberg 2, D-06120 Halle, Germany*

Abstract

Recently, several novel methods have been proposed to image short-circuit current density j_{sc} based on diverse physical principles. This work compares these methods and points out physical limitations, advantages and drawbacks of each approach. One method based on photoluminescence (PL) imaging and two methods based on dark and illuminated lock-in thermography (DLIT / ILIT) are discussed. As a versatile reference technique for j_{sc} mapping, spectrally-resolved light-beam induced current (SR-LBIC) is applied. Experimental results for crystalline silicon solar cells with varying substrate properties, rear-side passivation schemes and process-induced defects are presented. Investigated parameters are quantitative accuracy of local j_{sc}, spatial resolution, measurement time, spectral excitation dependency and calibration. Furthermore, robustness towards locally increased series resistance R_s and injection-dependent recombination is discussed along with proneness to artefacts due to local shunts, spatially varying optics and photogeneration, and fitting algorithm artefacts.

Peer review by the scientific conference committee of SiliconPV 2015 under responsibility of PSE AG

Keywords: Short-circuit current; imaging; photoluminescence; lock-in thermography

1. Introduction

It has been shown [1–3] that, especially in solar cells made from multicrystalline silicon (mc-Si), short-circuit current density j_{sc} can vary significantly across the cell and even limit local conversion efficiency η_{xy} [3]. Since the

* Corresponding author. Tel.: +49-761-4588-5482; fax: +49-761-4588-9250.
E-mail address: fabian.fertig@ise.fraunhofer.de

Peer review by the scientific conference committee of SiliconPV 2015 under responsibility of PSE AG
doi:10.1016/j.egypro.2015.07.008

latest proposed methods calculating η_{xy} from extracted diode parameters [4,5] assume j_{sc} to be constant, the spatially resolved determination of j_{sc} on solar cell level is expected to be highly beneficial for local solar cell analysis.

The objective of this work is to compare the physics of four different methods to extract maps of j_{sc} in theory and by experiment. These four methods are based on (i) photoluminescence (PL) imaging [6], (ii) illuminated [7] (ILIT) and (iii) dark (DLIT) lock-in thermography [8], and (iv) spectrally-resolved light-beam induced current (SR-LBIC) [2], all published by authors of this work.

2. Investigated methods and experimental setup

In the following, the working principles and underlying physics of each method are discussed, along with important technical details on the experimental setups.

2.1. Photoluminescence (PL)

PL signal is proportional to the product of charge carrier densities: $S_{PL} \sim n_{xy} \cdot p_{xy} \sim \exp(V_{xy})$, and, therefore, the splitting of the quasi-Fermi levels ($\triangleq$ voltage V) rather than current density j. By assuming the charge carriers in the bulk to dominate PL signal and considering the diffusion of minority charge carriers from the bulk to the space charge region (see blue arrows in Fig. 1a) by a variable "diffusion resistance", an alternative one-diode model has been proposed [9]. This model assigns an implied voltage V_{imp} in the bulk to the splitting of the quasi-Fermi levels which is larger than the *pn* junction voltage V_{pn}, which is typically considered in PL evaluation. In contrast to previous approaches of imaging diode model parameters via PL [4,10–12], the diffusion-limited carriers, meaning the carriers that are not extracted under SC conditions due to non-ideal internal quantum efficiency, are not corrected for but explicitly considered. By introducing an additional diode model parameter $j_{DL} = j_{gen} - j_{sc}$ for the difference between photo-generated and extracted short-circuit current density, the diffusion-limited carriers are considered in defining a set of equations for diode model parameter extraction [6,13]. This set of equations is iteratively solved to extract parameter values, while assuming low-level injection to hold in all four acquired images. With the assumption of spatially homogeneous j_{gen}, a spatially resolved image of j_{sc} can be calculated [6,13]. The luminescence setup applied within this work features a laser diode with a wavelength of $\lambda = 790$ nm for illumination and a one megapixel silicon CCD camera.

2.2. Illuminated lock-in thermography (ILIT)

Lock-in thermography (LIT) images can be scaled to local power dissipation [14]: $S_{LIT} \sim p_{xy} \sim j_{xy} \cdot V_{xy}$. The basic idea of the ILIT-based method [7] is to exploit the property of crystalline silicon solar cells that the illuminated current density under moderate reverse bias V_{rev}, i.e. well before junction breakdown sets in, does not differ significantly from j_{sc}. This is done by recording a difference ILIT image between short-circuit (SC) and V_{rev}. Fig. 1 illustrates selected thermal power contributions to the detected ILIT signal under SC and V_{rev} conditions. For both conditions, the constant contributions p_{th} due to thermalization of generated carriers to the band edges as well as the current-driven (for $V_{pn} \leq 0$ V) contributions p_{rec} (recombination), p_{pelt} (Peltier heating/cooling at metal contacts), p_s (series resistance, not shown in Fig. 1) exhibit the same values. By recording a difference image, they should cancel out. The only two contributions left are (i) thermalization across the *pn* junction p_{pn}, which is proportional to current *and* voltage and (ii) parallel (shunt) resistance p_p (not shown in Fig. 1). Hence, manipulating p_{pn} is the main mechanism of the ILIT-based method to extract local j_{sc}, while p_p leads to artefacts in areas of local shunting. These artefacts can be corrected by recording an additional DLIT image. Hence, in contrast to the PL-based method, the ILIT-based method does not rely on a diode model. The LIT images used for this method are recorded with two commercially available LIT systems with a lock-in frequency of $f_{lock\text{-}in} = 40$ Hz. The cameras of both systems used in this work feature Stirling-cooled InSb FPA detectors with a resolution of 256×256 pixels (system 1) and 512×512 pixels (system 2) and are sensitive in the mid-infrared wavelength range. During ILIT, the cells are illuminated with a laser diode at $\lambda = 940$ nm (system 1) or LED arrays at selectively $\lambda = 470$nm, 640 nm or 940 nm (system 2).