Solar Energy Materials & Solar Cells 143 (2015) 406–410

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

An empirical method for imaging the short circuit current density in silicon solar cells based on dark lock-in thermography

Otwin Breitenstein [a,*], Fabian Fertig [b], Jan Bauer [a]

[a] Max Planck Institute of Microstructure Physics, Weinberg 2, D-06120 Halle, Germany
[b] Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstraße 2, D-79110 Freiburg, Germany

ARTICLE INFO

Article history:
Received 19 March 2015
Received in revised form
30 June 2015
Accepted 17 July 2015

Keywords:
Quantitative evaluation
Photocurrent imaging
Lock-in thermography
2D device simulation
Local analysis

ABSTRACT

The most straightforward way to map the photo-induced short circuit current density (J_{sc}) in solar cells is light beam-induced current (LBIC) mapping. Recently several methods for J_{sc} imaging based on camera-based photoluminescence and illuminated lock-in thermography imaging were proposed. This letter reports an alternative method for J_{sc} imaging, which is solely based on the evaluation of dark lock-in thermography images. This method is particularly advantageous to improve the accuracy of dark lock-in thermography based local efficiency analysis of solar cells.

The local short circuit current density $J_{sc,i}$ (i=position index) is one of the basic local parameters for the efficiency of solar cells. Together with the local dark saturation current density $J_{01,i}$ and its ideality factor (a measure for injection-dependent recombination) it governs the local open circuit voltage potential $V_{oc,i}$ in the cell. In most of previous imaging methods for efficiency-related solar cell parameters [1–5] $J_{sc,i}$ is assumed to be distributed homogeneously across the cell. However, in particular in multicrystalline silicon solar cells, not only J_{01} but also J_{sc} is distributed inhomogeneously and even may limit the local conversion efficiency [6]. The classical way to create an image of J_{sc} is light beam-induced current (LBIC) mapping [7]. However, this is a sequential and therefore time-consuming method, and if AM 1.5 data should be obtained, it is experimentally expensive, since it needs an LBIC system with different wavelengths [8]. Based on an alternative one-diode model of illuminated solar cells [9], a photoluminescence (PL) based method for imaging J_{sc} was proposed [10]. However, very recent simulations have revealed that the accuracy of PL-based J_{01} imaging in local low-lifetime regions, on which this J_{sc} imaging method is based on, is insufficient [11]. The main reason is that this method strongly depends on the model of independent diodes, each of them being connected with the terminals by an individual series resistor, which does not hold for a solar cell. Hence, this PL-based method is obviously not accurate. Recently a J_{sc} imaging method based on illuminated lock-in thermography (ILIT) was proposed [12]. This method is based on measuring the bias-dependent dissipated heat due to the thermalization of the local photocurrent in the depletion region under weak reverse bias, well before avalanche multiplication takes place. Eventual ohmic shunts may be corrected by using an additional dark lock-in thermography (DLIT) image taken at the cell bias of the ILIT measurement. Manipulation of the thermalization power density across the pn-junction was used already earlier for imaging local avalanche multiplication factors [13]. This ILIT method should work well, it is robust to series resistance variations and is easily applicable to arbitrary excitation spectra, since the excitation needs not to be pulsed [14]. As for other light-induced methods such as PL imaging and LBIC, the accuracy of these results is directly influenced by the homogeneity of the illumination intensity, which may, however, be corrected if known.

In this letter another method for imaging J_{sc} is proposed, which is based solely on the evaluation of DLIT images. The advantage of this method, compared to PL-based J_{sc} imaging, is that it should be more accurate. Its advantage to the existing ILIT method is that the new method appears as a by-product improving the accuracy of DLIT-based local efficiency analysis [5,15] without needing any new measurements. Since this is a dark measurement, is also not influenced by the inhomogeneity of an illumination system. In particular, it can be applied afterwards to measurements performed in the past.

* Corresponding author.
E-mail address: breiten@mpi-halle.mpg.de (O. Breitenstein).

http://dx.doi.org/10.1016/j.solmat.2015.07.027
0927-0248/

Based on PC1D simulations (this is a standard software for performing 1-dimensional solar cell simulations [16]), assuming an ideality factor of $n_1=1$ for the first diode (the influence of the second diode is negligible here), it will be shown that local variations of J_{sc} can be described by local variations of J_{01}, which may be imaged by evaluating DLIT images taken at various biases [5]. Homogeneous optical properties of the solar cell under test have to be assumed here, which is realistic for most multicrystalline Si solar cells having acidic texturized surfaces. The influence of the gridlines is neglected here, but the influence of the busbars is regarded for calculating the average J_{sc}. The final method needs two fitting parameters, which may be obtained by fitting results of this method to that of established methods like LBIC.

Two 200 μm thick model cells are simulated here by PC1D, which represent an industrial standard multicrystalline cell of first generation (net base doping concentration $p_0=1.5*10^{16}$ cm^{-3}, 50 Ω/sqr emitter, front recombination velocity $S_{front}=10^5$ cm/s, emitter fraction of saturation current density J_{01}^e = 550 fA/cm^2, full-area Al back contact, rear recombination velocity $S_{rear}=600$ cm/s), and a modern PERC cell (Passivated Emitter and Rear, $p_0=1.5*10^{16}$ cm^{-3}, special *P* doping profile, $S_{front}=2000$ cm/s, J_{10}^e = 90 fA/cm^2, $S_{rear}=10$ cm/s). In both cases a parallel resistance of $R_p=\infty$ was assumed, the front and rear surfaces were assumed to be optically rough, and a single layer ARC and typical values for internal reflectances were assumed. These two different model cells have been chosen in order to check the possible influence of the cell parameters on the results. For both model cells an ideality factor of 1 is assumed and the bulk lifetime τ_b is varied between 1 μs and 1 ms. Here S_{rear} was assumed to be independent of τ_b, which is only an approximation. Four different illumination modes are simulated, which are AM1.5G and monochromatic illumination at 780, 850, and 940 nm wavelength. For all monochromatic illumination modes the intensity was chosen so that, for both cell types, at a bulk lifetime of 100 μs the value of J_{sc} of the monochromatic illumination equals that of AM 1.5G illumination. Table 1 shows the used illumination parameters and the resulting total generation current densities J_{gen} after PC1D simulation (cumulative photogeneration) for both model diodes.

For an illuminated silicon solar cell with assumed homogeneous optical properties and a certain thickness, the equivalent current density of all generated carriers J_{gen} is independent of the bias and the local lifetime properties. It slightly depends on the illumination condition (wavelength), since here the intensities were chosen that J_{sc} is the same for all illumination conditions at $\tau_b=100$ μs. Then, neglecting ohmic shunts, the local short circuit current density $J_{sc,i}$ is J_{gen} minus the local diode recombination current density at short circuit $J_{rec,sc,i}$

Table 1
Cell types, PC1D illumination conditions, and fitting parameters *A*, *B*, and *C*.

Cell type, illumination	J_{gen}[mA/cm^2]	*A*	*B*[cm^2/A]	*C*[A/cm^2]
PC1D standard sim., AM 1.5G	35.3	1.95*10^9	1.1*10^{18}	7.0*10^{-4}
780 nm	34.6	1.143*10^9	3.27*10^{17}	6.33*10^{-4}
850 nm	35.0	1.853*10^9	3.93*10^{17}	9.5*10^{-4}
940 nm	36.8	5.0*10^9	2.4*10^{18}	2.22*10^{-3}
PC1D PERC sim., AM 1.5G	35.6	1.9*10^9	1.25*10^{18}	5*10^{-5}
780 nm	35.4	1.1*10^9	3.0*10^{17}	5*10^{-5}
850 nm	35.6	2.1*10^9	9.0*10^{17}	1*10^{-4}
940 nm	36.1	5.2*10^9	3.3*10^{18}	3*10^{-4}
Exp. DLIT$-J_{sc}$ vs LBIC, AM 1.5G	–	2*10^9	2*10^{20}	–
780 nm	–	7*10^8	1*10^{19}	–
830 nm	–	1.2*10^9	7*10^{19}	–
940 nm	–	3.5*10^9	2.5*10^{20}	–

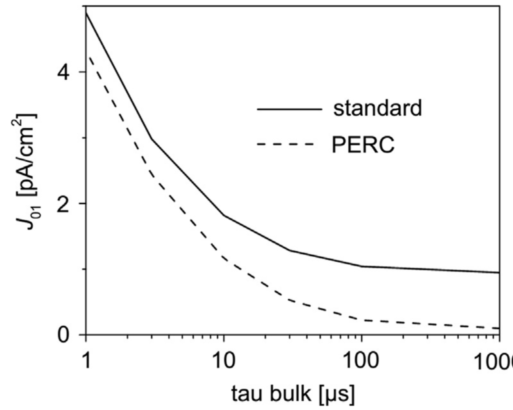

Fig. 1. PC1D simulation of J_{01} as a function of τ_{bulk} for standard and PERC cell.

$$J_{sc,i} = J_{gen} - J_{rec,sc,i} \quad (1)$$

The saturation current density J_{01} is a measure of the lifetime-dependent recombination properties. In the dark, for a given forward bias, the total diode recombination current density is proportional to J_{01} and exponentially increases with the diode bias. Hence, the total recombination probability in the dark is proportional to J_{01} and to the excess carrier concentration at the pn-junction. Under illumination and short-circuit condition the electron concentration in the bulk at the pn-junction is close to zero. Here a profile of diffusion-limited carriers in the bulk $n_{sc}(z)$ establishes, which depends on the illumination wavelength, the diffusion constant, the bulk lifetime τ_b, and the rear recombination velocity S_{rear} [17]. It can be expected that $J_{rec,sc}$, being a measure of the bulk and backside recombination rate under short circuit, depends both on J_{01} and on $n_{sc}(z)$. It will be shown below that, under short circuit condition and for near-IR illumination, recombination in the emitter is negligibly small. Fig. 1 shows the dependence of J_{01} on τ_b obtained by evaluating PC1D data of J_{sc} and V_{oc} at $T=25$ °C for the two model cells. As expected, with increasing τ_b, J_{01} decreases and reaches a saturation value, which is significantly lower for the PERC than for the standard cell.

The values of $n(z)$ are given for two positions $z=20$ and $z=100$ μm below the pn-junction in Fig. 2. While the simulated J_{01} data are nearly independent of the illumination wavelength (since in all cases the same J_{sc} was assumed, see also Fig. 3; data for 850 nm are shown in Fig. 1), $n_{sc}(z)$ strongly depends on it. In the middle of the cell ($z=100$ μm) the wavelength dependence of $n_{sc}(z)$ is stronger than close to the junction ($z=20$ μm), and for $z=100$ μm the 850 nm data are lying close to the AM 1.5G data. In all cases, in the limit of high bulk lifetimes, $n_{sc}(z)$ is nearly independent of τ_b. Note that a constant S_{rear} was assumed here. Under this condition $J_{rec,sc,i}$ can be expected to depend linearly on $J_{01,i}$. For low bulk lifetimes also $n_{sc}(z)$ decreases with decreasing τ_b. In this regime $J_{rec,sc,i}$ is expected to increase slower than linearly with increasing $J_{01,i}$.

For the two cell types considered here (standard and PERC), first J_{gen} was calculated for all illumination conditions by PC1D, see the results in Table 1. These data hold for all bulk lifetimes. As mentioned above, the intensity for monochromatic illumination was chosen that, for a bulk lifetime of 100 μs, J_{sc} for monochromatic illumination equals J_{sc} for AM 1.5G for both cells. The weak differences in J_{gen} between standard and PERC may be due to a different free carrier light absorption in the emitter (the PERC emitter is more lightly doped). Then in all cases J_{sc} was calculated for τ_b ranging between 1 and 1000 μs by PC1D, and $J_{rec,sc}$ was calculated after Eq. (1). Fig. 3 shows the results for the standard cell (a) and the PERC cell (b) as the symbols plotted over J_{01}. Here J_{01} was calculated separately for each illumination and bulk