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Improved empirical method for calculating short circuit current density images of silicon solar cells from saturation current density images and vice versa

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ABSTRACT

An empirical dependence of the short circuit current density J_{sc} as a function of the dark saturation current density J_{01} is proposed, which describes this dependence down to a bulk lifetime of 1 ns. This method avoids artifacts, which appear when applying the previously proposed quadratic dependence. The parameters of the new dependence are fitted to PC1D simulations and to experimental LBIC results for various wavelengths and AM 1.5 for a typical industrial BSF-type solar cell and a PERC cell. This dependence can also be used to calculate J_{01} images from LBIC-based J_{sc} images. It turns out that this method is more reliable in BSF than in PERC cells.

1. Introduction

The local short circuit current density $J_{sc}(x,y)$ of a solar cell, which is an important local efficiency parameter in particular for multicrystalline silicon solar cells, is usually imaged by LBIC mapping at a certain wavelength, see e.g. [1]. If the mapping is performed with different wavelengths, an image of J_{sc} under AM 1.5 illumination may be obtained, see [2]. Recently, both illuminated lock-in thermography (ILIT) [3] and dark lock-in thermography (DLIT) [4] based methods for imaging J_{sc} were proposed. The basic idea of the DLIT based method is that the local dark saturation current density J_{01} is a measure of the local bulk recombination probability. Therefore this parameter should also govern bulk recombination under short-circuit condition, which governs the local value of J_{sc}. An advantage of this method is that it can be applied to J_{01} images obtained by any imaging method, even to images that have been captured in the past. In particular this method is a good extension of the "Local I-V 2" method for evaluating DLIT images, which is currently the most reliable method to image J_{01} and perform a local efficiency analysis of given inhomogeneous solar cells, see [5–7].

In the previous empirical method for imaging J_{sc} [4] it was found that and explained why the reduction of J_{sc} with increasing J_{01} is linear in J_{01} only for small values of J_{01} and gradually saturates for higher values, corresponding to lower bulk lifetimes. In this work [4] the fit of PC1D-based (see [8]) J_{01}-dependent J_{sc} values was performed up to a maximum of $J_{01}=5{*}10^{-12}$ A/cm^2. In this range, the dependence $J_{sc}(J_{01})$ could be well approximated by a quadratic function, hence by a 2nd order polynomial. However, when this method was later applied in practice and J_{01} values above $5{*}10^{-12}$ A/cm^2 appeared, this lead again to an apparent increase of J_{sc} with increasing J_{01}, which is clearly physically wrong. Therefore the goal of this contribution is to find a physically more reliable description of the $J_{sc}(J_{01})$ dependence, which does not show this non-monotonic behavior and can be used up to very high values of J_{01}. This new dependence will first be fitted to PC1D simulations of a standard industrial BSF-type and a PERC-type multicrystalline silicon solar cell. Then, on typical cells of both types, LBIC images taken at AM 1.5 and various discrete wavelengths are compared with DLIT-based J_{01} images, leading to more realistic sets of fitting parameters.

2. The method

First we simulate J_{sc} and J_{01} by PC1D [8] for a typical industrial BSF-type cell of first generation with full-area Al back contact and for a PERC cell, in both cases for widely varying values of the bulk lifetime τ_{bulk}. The used simulation parameters are the same as in [4], namely 200 μm cell thickness, $p_0=1.5{*}10^{16}$ cm^{-3}, and $T=25$ °C

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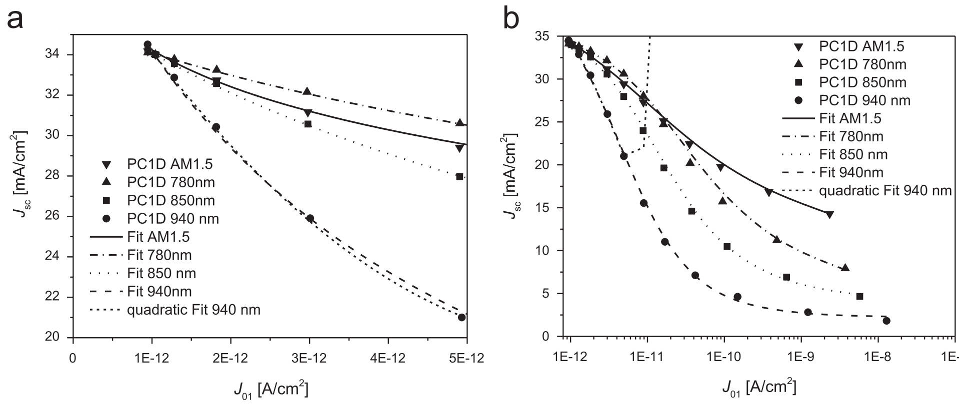

Fig. 1. Dependence of J_{sc} on J_{01} for a standard cell, (a) linear drawing up to $J_{01}=5{*}10^{-12}$ A/cm^2, (b) linear over log(J_{01}) in the whole range. Symbols: PC1D simulations, lines: Fits.

for both cells, $J^e_{01}=550$ fA/cm^2 and $S_{rear}=600$ cm/s for the standard cell, and $J^e_{01}=90$ fA/cm^2 and $S_{rear}=10$ cm/s for the PERC cell. Whereas in [4] the simulations have been performed for τ_{bulk} from 1 ms down to 1 µs, corresponding to J_{01} up to $5{*}10^{-12}$ A/cm^2, the simulations are performed here for τ_{bulk} from 10 ms down to 1 ns, corresponding to J_{01} up to 10^{-8} A/cm^2. As in [4] the values of J^e_{01} and S_{rear} are assumed to be independent of τ_{bulk}, which is only an approximation. All PC1D simulations were made for monochromatic illumination at 780, 850, and 940 nm and for AM 1.5 G (1 sun). The intensity for the monochromatic illumination was chosen so that, at a bulk lifetime of 100 µs, the monochromatic J_{sc} is equal to that at AM 1.5. In the PC1D simulations we calculate J_{01} from simulated values of J_{sc} and V_{oc} by applying a simple one-diode model with an ideality factor of unity. This is certainly not correct for very low lifetimes, where recombination in the depletion region becomes important, but is accurate in the region up to $J_{01}=1.5{*}10^{-11}$ A/cm^2, where the experimental LBIC data will be fitted.

Fig. 1 shows PC1D simulations of $J_{sc}(J_{01})$ for the standard BSF-type cell as symbols (a) with a linear scale up to $J_{01}=5{*}10^{-12}$ A/cm^2 and (b) over the logarithm of J_{01} in the full simulation range. The results for the PERC cell look qualitatively similar, except that here the J_{01} values already start in the low 10^{-13} A/cm^2 range. In Fig. 1(a) and (b) the result of a quadratic fit of $J_{rec,sc}(J_{01})$ for the 940 nm data in the range below $J_{01}=5{*}10^{-12}$ A/cm^2 is also shown. We see in (a) that this fit is quite good in this fitting range, but (b) shows that for higher J_{01} the values of J_{sc} drastically increase again. The goal of this paper is to find a better empirical description of $J_{sc}(J_{01})$, which holds over the whole definition range of J_{01} and shows a monotonic dependence on J_{01}.

The short circuit current represents the quantum efficiency of a solar cell, where the diffusion length L_d of the minority carriers, depending on the bulk lifetime τ, enters as a crucial parameter. Similarly, the dark saturation current density is directly related to the diffusion length. Let us first look for the two limiting cases of the bulk thickness being much larger and much smaller than L_d and L_α, respectively. These two limiting cases should also be met by our empirical formula for $J_{sc}(J_{01})$. In a first simplified approach for bulk thickness larger than L_d and L_α we find $J_{sc}\sim \mathrm{IQE}=1/(1+L_\alpha/L_d)$ (see [9]) and $J_{01}=(eDn_i^2)/(N_A L_d)$ (see [10]), leading to:

$$J_{sc}(J_{01}) \sim \frac{1}{1+\frac{J_{01}L_\alpha N_A}{eDn_i^2}} \tag{1}$$

Here L_α is the absorption length, D the diffusion constant, n_i is the intrinsic carrier concentration, and N_A the bulk doping concentration. This dependence is constant for low values of J_{01} and approaches zero for large J_{01}. However, it has to be considered that (1) only covers the bulk contribution of J_{sc}. There is also an emitter and depletion region contribution of J_{sc}, which does not depend on the bulk lifetime. Hence in reality even for very large J_{01} (low bulk lifetime), J_{sc} is expected to drop to a finite value, which should depend on the excitation wavelength governing L_α. In the second limiting case, where bulk thickness d smaller than L_d and L_α we find $J_{sc}\sim 1-c1/\tau$ (here $c1$ is a constant) and $J_{01}=(en_i^2 d)/(N_A\tau)$ (see [11]), leading to:

$$J_{sc}(J_{01}) \sim 1-c2J_{01} \tag{2}$$

Here $c2$ is another constant. This dependence drops linearly for low values of J_{01}, where it should be valid. The derivation of a strict analytical relationship between J_{sc} and J_{01}, which is applicable to real solar cells and includes the spectrum of the light, the inhomogeneity of the cell, its optical properties and contributions from emitter and space charge regions, would be very complex. Thus, our proposal is a phenomenological expression, which contains only four free parameters A, B, C, and n, but nevertheless yields a very good representation of the numerical and experimental data. We have found that the $J_{sc}(J_{01})$ dependence can be well fitted by:

$$J_{sc}(J_{01}) = C-\frac{AJ_{01}}{\left[1+\left(\frac{AJ_{01}}{B}\right)^n\right]^{\frac{1}{n}}} \tag{3}$$

For low values of J_{01} this dependence drops linearly with J_{01} as in (2), whilst for very large values it approaches a finite value as in (1), regarding its discussion. The parameter A (dimensionless) in (3) describes, as in [4], the slope of the dependence in the linear part for low J_{01} values. This parameter describes the limiting case of small J_{01} after Eq. (2), where it corresponds to the parameter $c2$. The parameter B (in units of A/cm^2) describes the saturation value of the reduction (drop) of J_{sc} for large J_{01}. According to Eqs. (1) and (3), $B\sim eDn_i^2/(L_\alpha N_A)$ holds, assuming $n=1$ (the factor A in the nominator and the denominator cancel for large J_{01}). The parameter n (dimensionless) describes how fast the dependence saturates (large n means fast saturation and small n means slow saturation), and the offset parameter C (in units of A/cm^2) describes the J_{sc} value for an assumed J_{01} of zero. These parameters hold globally for certain types of cells (e.g. standard or PERC) and certain illumination conditions. Note that, for varying light intensity or reflection properties, the parameters A, B, and C scale linearly with the light intensity, but parameter n does not. This becomes clear by considering the limiting cases for low and high J_{01}, leading after (3) to $J_{sc}^{low}=C$ and $J_{sc}^{high}=C-B$, which both must be proportional to the illumination intensity, and also the slope factor A should be proportional to the drop amount B. As a good approximation it can be assumed that these parameters scale with the global mean value of the short circuit current density of the cell. The lines in Fig. 1 show the fitting results for all illumination