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Distributed series resistance in a one-dimensional two-diode model revisited

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Abstract

The lumped series resistance R_s of large-area silicon solar cells, obtained from current–voltage (*I–U*) data according to the two-light-level method, varies along the *I–U* characteristic. Such a variation can most simply be described by the linear-response series resistance model (LR-R_s), recently developed in connection with luminescence imaging. Here, independently obtained experimental data are used to test the applicability of the LR-R_s model to R_s data based on *I–U* characteristics. After subtracting a non-distributed part from the measured R_s data, the inverse of the remaining distributed part shows a scaling proportional to the inverse of the bias-dependent diode resistance; a slope value of 1 is used as predicted by the LR-R_s model applied to a laterally one-dimensional geometry. The same experimental data have previously been interpreted based on a mathematically rather complicated model published already many years ago; just recently it was found that in some cases this model may lead to unphysical results. The present LR-R_s model based proper interpretation of the variation of the lumped series resistance along the *I–U* characteristic leads to a roughly half-by-half splitting between the distributed and the non-distributed part of R_s. This share has been observed many years for "economically reasonable" solar cells investigated by the CELLO technique. The successful usage of the LR-R_s model for *I–U* based R_s data is a strong hint that its underlying physical concepts are of general validity.

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Keywords: standard equivalent circuit ; current–voltage characteristic ; series resistance ; injection dependence ; one-dimensional solar cell modeling ; linear response theory

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1. Introduction

The conventional two-diode model is the standard description for the current–voltage (*I–U*) characteristic of a silicon solar cell. This equivalent circuit model contains the following parameters: photocurrent density (J_{ph}), saturation current density and ideality factor of first and second diode (J_{01}, J_{02} and n_1, n_2, respectively), lumped series resistance (R_s), and global parallel (shunt) resistance (R_p). Experimentally, however, it is found that the series resistance of large-area silicon solar cells changes along the *I–U* characteristic. This effect is due to R_s partly being distributed; it is known since many years (cf., *e.g.*, [1–6]). Since in the conventional two-diode model R_s is constant, this model does not hold correctly at high injection levels. There are some theoretical works in the literature describing this variation of R_s along the *I–U* characteristic (cf., *e.g.*, [7–10]), most of them making use of quite intricate mathematics. However, only recently it was shown that in cases of practical relevance this variation can be described quite simply [6] and that one of the previous theoretical approaches [9] in some cases may lead to unphysical results [6] (see also the discussion below). In previous works [11, 12], measured *I–U* data were interpreted according to the latter series resistance theory [9], so it is not clear whether their R_s description is accurate. Here, we use the previously published *I–U* based series resistance data [11, 12] to test the applicability of the newly proposed linear-response series resistance (LR-R_s) model that so far is well confirmed only for luminescence [6] and CELLO measurements [13] (and references therein).

2. Experimental

In the present work, we re-interpret already-measured data, originally published in [11, 12]. Nevertheless, here we give a brief summary about how those data were obtained and how the lumped series resistance was extracted. The measurement of the *I–U* characteristics was done on a water-cooled measurement chuck, always keeping the cell at 25 °C (even under varying illumination). To that end, the solar cell surface temperature was independently measured by an IR thermometer. Two different multi-crystalline silicon solar cells with full-area Al back surface field have been investigated: cell A is a standard industrial cell of size $(156\ \text{mm})^2$, whereas cell B is a research lab cell of size $(125\ \text{mm})^2$; further specifications can be found in [11, 12]. The cells were sucked on to the chuck by vacuum and were biased by a four-quadrant power supply. A four-probe contact scheme was used including additional sense pins contacting the middle of each front side busbar and one pin sensing the rear side contact. The *I–U* measurements were made both in the dark as well as under illumination (with light of 850 nm).

From the measured *I–U* data, the lumped series resistance data (varying along the *I–U* characteristic) were extracted as described in detail in [11, 12]. Here, we only give a brief summary of this procedure: From the low-voltage part (where R_s can be neglected), the two-diode model parameters were determined for fixed $n_1 = 1$. From a comparison with the measured open-circuit voltage (where R_s is irrelevant), for cell A the value of n_1 was slightly increased to account for an injection-dependent lifetime, and the value of J_{01} was adjusted to match this value of n_1, altogether reproducing the measured open-circuit voltage [11, 12]; for cell B, n_1 remains unity throughout.

Knowing all the two-diode parameters enables one to calculate the effective diode voltage (in the standard one-diode equivalent circuit) for the illuminated *I–U* characteristic at all lumped dark diode currents, $U_{D,calc}(I_D)$, and thus to evaluate the lumped series resistance (in mΩ) corresponding to this lumped dark diode current I_D according to

$$R_s(I_D) = \frac{U_{ext,dark}(I_D) - U_{D,calc}(I_D)}{I_D}. \tag{1}$$

Since two pairs of *I–U* data (one directly from the dark characteristic, the other calculated from the two-diode parameters that reproduce the illuminated characteristic) are used for this R_s determination, belonging to the same dark diode current, this method to obtain R_s from the measurements follows the same concept as the two-light-level method for the determination of the series resistance (cf., *e.g.*, [1, 3, 4]). For the application of the LR-R_s model (explained in the following section), the lumped dark diode current (varying over several ampere) is converted to the inverse of the lumped effective diode resistance R_D (*i.e.*, the lumped effective diode conductance G_D) by