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Linear-response description of the series resistance of large-area silicon solar cells: Resolving the difference between dark and illuminated behavior

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Abstract

Directly from luminescence images it can be shown that, for constant average injection (lumped dark current) and for not-too-large lateral voltage differences, besides the sign, the current flow direction doesn't play any role for the voltages present, so the series resistances in the dark and under illumination are the same. This fits to the results of a linear-response based series resistance description, treating lateral voltage differences on large-area silicon solar cells in linear order in the series resistance as deviation from the case of zero resistance. In this approach it is found that for constant lumped dark current, emitter and grid of a large-area solar cell can be described as a passive network. Therefore, no difference occurs in the voltage distribution caused by inward and outward currents except for the sign. This contradicts several literature works reporting a smaller lumped series resistance of silicon solar cells in the dark than under illumination. However, we show that this contradiction is just a result of the series resistance definition applied in the respective works or that it can be the result of unsuitable measurement conditions. In a numerical modeling of a large-area silicon solar cell as a 1D distributed structure, using exactly the same parameters as Araújo *et al*. [IEEE-TED 33 (3), 391–401 (1986)] but calculating the lumped series resistance from the integrated Joule losses, we obtain completely different results than Araújo *et al.*: Under short-circuit condition, the series resistance stays constant, and there is no difference between the open-circuit and dark series resistance; the latter show the same dependence on the diode current density.

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Keywords: series resistance; injection dependence; lateral voltage offsets; lumped Joule losses; solar cell modeling; linear-response theory; luminescence-based series resistance imaging; dark series resistance; illuminated series resistance

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1. Introduction

The equivalent lumped series resistance R_s of a solar cell has at least one, if not two physical meanings: First, it allows to express the sum of all ohmic heating losses (Joule losses) in the solar cell as

$$P_s = R_s I_{ext}^2 , \quad (1)$$

and second, under certain conditions (cf. [1]) it provides the voltage difference between the external contacts and the effective internal voltage related to replacing the whole solar cell by an effective ideal diode (or two diodes in case of the two-diode model) according to the equivalent circuit. The latter role of the series resistance – providing the local voltage – is of importance for all local solar cell efficiency analyses, carried out *e.g*. in any optimization procedure related to changes in solar cell manufacturing.

Various series resistance measurement prescriptions, related to different R_s concepts, can be found in the literature. One of the latter has been introduced to treat the well-known variation of the lumped series resistance with the operating conditions (cf., *e.g*., [2] and references therein) directly in the framework of the equivalent circuit. In this modeling, the external-current-density dependent series resistance $r_s(J_{ext})$ is defined by the following expression for the effective diode voltage of the equivalent circuit [J_{ext} is the external current density, here taken as positive for inward (dark) current and negative for outward (photo-)current, and U_{ext} is the terminal voltage]:

$$U_D = U_{ext} - r_s(J_{ext})\, J_{ext} . \quad (2)$$

In the literature, several works report a smaller lumped series resistance of silicon solar cells in the dark than under illumination. For example, based on the above-given expression for the diode voltage, Eq. (2), and a numerical modeling of a large-area silicon solar cell as a 1D distributed structure, Araújo *et al*. [2] have explicitly displayed $r_s(J_{ext})$ for the dark, open-circuit, and short-circuit cases in dependence on the external current density; always their dark value is the lowest of all. However, we have found that there is no such difference between the series resistance behavior in the dark and for the open-circuit case. In this contribution we want to resolve this contradiction, and we provide a consistent description via an appropriate replacement for the standard equivalent circuit model.

Nomenclature

LR-R_s Linear-response series resistance

2. Experimental and theoretical basics: the LR-R_s method

Parts of the basics of the LR-R_s method have already been published [3–5]; here we present it in a consistent manner. After considering the lumped series resistance $R_{s,cell}$ for a fixed dark current, we explain how to obtain the distributed series resistance $R_s^{distr}(x,y)$ from an auxiliary function $R(x,y)$ and discuss its dark current dependence.

2.1. The lumped series resistance

The most reliable measurement of the lumped series resistance of a solar cell is obtained by the comparison of two illuminated *I–U* curves for different illumination strengths [6]; the relative error of this method can be considerably decreased by using multiple *I–U* curves, i.e. several illumination levels [7]. In this method, those points of the *I–U* curves are compared where the solar cell is under identical injection conditions as measured by the dark current flowing. From the differences in the relevant external cell currents, ΔI_{cell}, and the corresponding voltages, ΔU_{ext}, the series resistance is determined as

$$R_{s,cell} = \Delta U_{ext} / \Delta I_{cell} . \quad (3)$$