Current and illumination dependent series resistance of solar cells

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Precise knowledge of the series resistance is essential for failure and loss analysis as well as yield prediction of solar cell devices. In this work, a method which determines the current and photogeneration dependence of the series resistance without assuming any specific current-voltage characteristic for the internal diodes is presented. This approach is of particular interest for solar cells which cannot be described by the one- or two-diode model such as organic solar cells. Furthermore, it clarifies the difference in the series resistance values that are obtained from current-voltage curves in the dark and under illumination as well as short-circuit-current and open-circuit-voltage characteristics. Additionally, it is shown how other cell parameters, such as the shunt resistance or the current-voltage characteristic of the internal diode are determined in a consistent way. Finally, it is demonstrated that our approach can be easily implemented in a new generation of solar simulators that are based on light-emitting diodes instead of conventional light sources. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4871017]

I. INTRODUCTION

The maximum power output of a solar cell is limited by a number of loss mechanisms. Among these losses, the power reduction due to the series resistance plays an important role as the magnitude of the generated currents of the individual cells has been significantly increased during the last decades. Therefore, a detailed and precise knowledge of the series resistance is essential for the simulation and prediction as well as the improvement of the power output of photovoltaic devices. Besides the well established crystalline silicon based cell technologies, promising alternatives have emerged during the last few years. In this context, a special focus has been on the investigation of the current-voltage characteristics of such new photovoltaic devices[1–4] and in particular on their series resistance.[5–9]

The current voltage characteristic (*I*–*V*-curve) is frequently described by a one-diode or two-diode model that includes a lumped resistance that represents all internal series resistances of the cell. In this case, it is well known how this parameter influences the different characteristics of the solar cell, i.e., the dark-*I*–*V*-curve, illuminated-*I*–*V*-curves, as well as, the short-circuit-current and open-circuit-voltage curve ($I_{sc} - V_{oc}$-curve).[10] However, it has been pointed out that the lateral inhomogeneity of the front contacts leads to different current density patterns when a silicon solar cell is operated under different illumination levels. This implies that the geometric structure of the front fingers leads to a lumped series resistance which is different when measured under illumination or without illumination.[10–13] One approach to deal with this issue has been to set up more complex equivalent circuit models. In these more complex models, a large number of resistors were included to properly represent the lateral inhomogeneity.[10–12] The various experimental approaches that have been proposed as well as simulation results showed a dependence of the lumped series resistance on both illumination and current density.[13–19] All of these methods rely on the applicability of the one- or two-diode model. A comparison of these methods based on a fill-factor analysis has been presented recently.[20] However, the investigation presented there also relies strongly on the applicability of the one- or two-diode model.

Besides the investigation of silicon solar cells, a large number of different solar cell technologies has been of interest. During the last few years, there was an increased scientific interest in thin film, organic or polymer materials being used for photovoltaic devices. Among these technologies, there are promising candidates for certain specific applications that cannot be covered by silicon solar cells. They feature higher flexibility, lower weight, adjustable semi-transparency, and high cost-saving potential. However, it was found that the well known two-diode model is not directly applicable for a number for these cases. The current-voltage curves of copper indium gallium selenide cells show distortions under certain operating conditions such as blue illumination.[21] Polymer solar cells exhibit an anomalous S-shape current voltage curve[1] while an improved model for organic solar cells includes a third diode or two diodes in a different arrangement than the standard two-diode model.[2,3,22,23]

Nevertheless, the reliable determination of the series resistance of such alternative solar cell technologies is of significant importance for the device characterization.[5,9] Recently, an attempt has been made to extract the series resistance without assuming any special current-voltage function form as given by the one- or two-diode model.[24] However, in Ref. 24, the series resistance has been assumed to be a constant parameter independent of current and illumination.

In the present work, a new method to determine the series resistance in dependence of external current and photogenerated current is proposed. A global equivalent circuit model is employed as the basis for our analysis. In this way,

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cells or multi-cell modules can be modelled with reasonable simulation efforts where a fully two- or three-dimensional model is not feasible. Such a model is a substantial ingredient for reliable yield and performance predictions. Furthermore, it allows a fast assessment of significant cell properties. A rapid yet precise measurement scheme as it will be proposed in this work is essential for in-line characterization.

Our approach extends previous works in the following directions. In order to keep the model as widely applicable and as general as possible a series resistance R_s is assumed that depends parametrically on the current I flowing through the external contacts, as well as, the photo-generated current I_g due to the illumination, i.e., $R_s = R_s(I, I_g)$. Second, we explicitly do not assume any specific current-voltage functional form of the internal diode itself. In particular, the presented approach is not only applicable to single- or multi-diode-models but also to I–V-characteristics of cell technologies other than silicon solar cells.

The assumptions and theoretical basis of the equivalent circuit model under investigation will be discussed in Sec. II. The applicability of our approach will be demonstrated by analyzing numerical data sets in Sec. III. Thus, it is shown that the underlying values for the series resistance $R_s(I, I_g)$ are correctly extracted by our approach without any knowledge of the internal diode characteristic. Furthermore, it will be shown to which current parameters (I, I_g) the various R_s-methods based on dark-I–V-curves, illuminated-I–V-curves, and $I_{sc} - V_{oc}$-curves correspond. A very natural and consistent explanation for the differences between these methods will be given, as discussed in Ref. 20 for the standard one-diode model.

Finally, the method is applied to both silicon and thin film solar cells. In Sec. IV, it is demonstrated how a rapid and precise measurement of the current and illumination dependent series resistance can be achieved. While there are several ways of implementing our method, the usage of LED based solar simulators is most convenient.

II. MODEL AND THEORETICAL CONSIDERATIONS

The solar cell is modeled using an equivalent circuit as shown in Fig. 1. The internal diode current-voltage-characteristic is given by the potentially unknown function $F(\bar{V})$. The I–V-curve of the solar cell is thus obtained by solving the implicit equation

$$I = I(V; R_s, R_p, I_g) = F(\bar{V}) + \frac{\bar{V}}{R_p} - I_g \,. \tag{1}$$

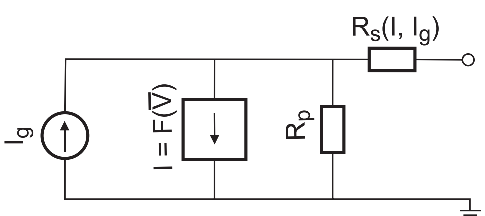

FIG. 1. Generalized equivalent circuit for a solar cell. The internal 'diode' is represented by the square and described by any current-voltage characteristic $I = F(\bar{V})$. It is therefore not restricted to one conventional diode or two diodes connected in parallel.

The internal diode voltage $\bar{V} \equiv V - I\,R_s(I, I_g)$ depends on the series resistance which is assumed to vary with the current I and the generated current I_g. The parallel resistance is given by R_p. The proposed model is reasonable assuming the following rather general properties of $F(\bar{U})$: (a) $F(0) = 0$ implying no current flows through the internal diode-device as long as there is no voltage difference at its poles, and (b) $F'(\bar{U}) > 0$ implying that an increasing voltage monotonically leads to an increasing current. The conventional one- or two-diode model would be given by

$$F_{\mathrm{1D,2D}}(\bar{V}) = \sum_{i=1}^{1\,\mathrm{or}\,2} I_{0i}\left[\exp\left(\frac{\mathrm{e}}{kT}\frac{\bar{V}}{n_i}\right) - 1\right] \tag{2}$$

with $n_{i=1,2}$ being the ideality factors. However, Eq. (1) covers a much broader range of solar cell models going far beyond the one- or two-diode model. Hence, the model discussed in this work can be applied to a vast variety of different cell technologies.

The precise determination of the individual model parameters based on measured I–V-curves is a major task when characterizing solar cells. Despite the rather general form of Eq. (1), a number of conclusions can already be drawn from this model yielding all key parameters in a very general way. The short circuit current I_{sc} is given by the solution of the equation $I_{sc} = F(-I_{sc}R_s) - I_{sc}R_s/R_p - I_g$. Typically, the series resistance is rather small such that a first order approximation in parameter $R_s = R_s(I = I_{sc}, I_g)$ is reasonable, i.e.,

$$I_g \approx -\left(1 + \frac{R_s}{R_p} + R_s \frac{\mathrm{d}F}{\mathrm{d}\bar{V}}\bigg|_{\bar{V}=0}\right) I_{sc} \,. \tag{3}$$

For a typical solar cell, the shunt resistance R_p is large while the function $F(\bar{V})$ representing the internal diode is rather flat at $V \approx 0$, i.e., $R_s/R_p \ll 1$ and $R_s F' \ll 1$. Thus, the short circuit current I_{sc} is predominantly given by the photo-generated current I_g and some corrections according to Eq. (3). It will be shown that even if these corrections are small, they, nevertheless, might lead to some significant changes when the other cell parameters are to be determined in a quantitative way. The open circuit voltage—being the solution of $V_{oc} = [I_g - F(V_{oc})]\,R_p$—cannot be given in the general case as it strongly depends on the functional form of $F(\bar{V})$. In case of the one-diode model with $F = F_{1D}$, an explicit solution of the implicit Eq. (1) can be found in terms of the Lambert W-function which also allows for the direct extraction of the series resistance.[6,25]

In addition to the special points at $V = 0$ (short circuit current) and $I = 0$ (open circuit voltage), the first derivative of the I–V-curve is of interest. It is given by

$$\frac{\mathrm{d}V}{\mathrm{d}I} = R_s(I, I_g) + I\frac{\mathrm{d}R_s}{\mathrm{d}I} + \left(\frac{\mathrm{d}F}{\mathrm{d}\bar{V}} + \frac{1}{R_p}\right)^{-1} \tag{4}$$

$$\approx R_p + R_s + I\frac{\mathrm{d}R_s}{\mathrm{d}I} \quad \text{for} \quad R_p\frac{\mathrm{d}F}{\mathrm{d}\bar{V}} \ll 1 \tag{5}$$

$$\approx R_s + \left(\frac{\mathrm{d}F}{\mathrm{d}\bar{V}}\right)^{-1} + I\,\frac{\mathrm{d}R_s}{\mathrm{d}I} \quad \text{for} \quad R_p\,\frac{\mathrm{d}F}{\mathrm{d}\bar{V}} \gg 1. \qquad (6)$$

Typically, the internal diode characteristic is rather shallow around the short circuit operation point ($V \approx 0$) such that the approximation Eq. (5) can be applied for $I \approx I_{\rm sc}$. This means that for small series resistance and large shunt resistances, i.e., $R_s/R_p \ll 1$, the slope of the I–V-curve is mostly determined by R_p as long as the dependence of $R_s(I,I_{\rm g})$ on the current is rather smooth. On the other hand, one can expect the diode characteristic $F(\bar{V})$ to be rather steep for large voltages, i.e., $V \gtrsim V_{\rm oc}$. In this case, Eq. (6) is valid which implies that the slope of a measured I–V-curve at large voltages beyond $V_{\rm oc}$ is mostly determined by R_s. However, typically this gives only an estimate of the series resistance as the precise functional form of $F(\bar{V})$, and $R_s(I,I_{\rm g})$ is neglected. Another R_s-determination method based on a single I–V-curve has been proposed in Refs. 20 and 26 and relies on the evaluation of the integral of the I–V-curve. However, this method is accurate only if a one-diode model is assumed.

A broad variety of measurement approaches yielding the series resistance is based on cell measurements at different illuminations. In the following, this scheme is applied to the model Eq. (1). For each set of parameters $\{R_s, R_p, I_{\rm g}\}$, there is a unique relation between the external voltage V and the external current flow I. Considering the voltage at a given illumination as a function of the current, i.e., $V_{I_{\rm g}} = V_{I_{\rm g}}(I)$, one finds for any two different illumination levels characterized by $I_{\rm g1}$ and $I_{\rm g2}$ the following two relations:

$$I_{1,2} + I_{\rm g1,2} = F\left[\bar{V}_{I_{\rm g1,2}}(I_{1,2})\right] + \frac{\bar{V}_{I_{\rm g1,2}}(I_{1,2})}{R_p}\,.$$

Thus, the pairs of values $\{I_1 + I_{\rm g1}; V_{I_{\rm g1}}(I_1) - I_1\,R_s(I_1, I_{\rm g1})\}$ and $\{I_2 + I_{\rm g2}; V_{I_{\rm g2}}(I_2) - I_2\,R_s(I_2, I_{\rm g2})\}$ are solutions to exactly the same equation. This implies that

$$V_{I_{\rm g1}}(I_1) - I_1\,R_s(I_1, I_{\rm g1}) = V_{I_{\rm g2}}(I_2) - I_2\,R_s(I_2, I_{\rm g2}) \qquad (7)$$

as long as $I_1 + I_{\rm g1} = I_2 + I_{\rm g2}$. Practically, this condition on the currents $I_{1,2}$ can always be fulfilled by selecting the appropriate values $I_{1,2}$ on the two I–V-curves corresponding to the two illuminations $I_{\rm g1,2}$ that are under consideration. The result (7) can be applied to the special case where $I_1 = 0$. It follows directly that

$$R_s(I_2, I_{\rm g2}) = \left.\frac{V_{I_{\rm g2}}(I_2) - V_{I_{\rm g1}}(I_1 = 0)}{I_2}\right|_{I_2 = I_{\rm g1} - I_{\rm g2}}, \qquad (8)$$

where $I_2 = I_{\rm g1} - I_{\rm g2}$ has to be determined from the short circuit current by application of Eq. (3).

It is important to note, that the results Eqs. (3) and (8) are independent of the specific shape of the internal diode characteristic F. Thus, this result extends previous approaches in three significant ways: (a) Even without assuming a one- or two-diode model, the current and generation dependence of the series resistance can be determined from experimental data; (b) The relation (8) clearly states the current I and the generated photocurrent $I_{\rm g}$ to which the calculated series resistance corresponds; (c) The quantitative accuracy of our result depends on the knowledge of the photo-generated current $I_{\rm g}$ instead of the short circuit current $I_{\rm sc}$. This knowledge can be acquired by iteratively applying Eqs. (3) and (8).

The result (8) shows that a current and photocurrent dependent series resistance can be determined for the entire parameter space of $(I,I_{\rm g})$ only if a number N of I–V-curves at various intensities characterized by $\{I_{\rm g1}, \ldots, I_{\rm gN}\}$ is measured. Such a complete data set is necessary when the values $R_s(I, \{I_{\rm g1}, \ldots, I_{\rm gN}\})$ are to be determined. The current values I for which each $R_s(I, I_{\rm g})$ is given are determined by all possible differences $I = I_{\rm g,k} - I_{\rm g,l}$ with $I_{\rm g,k}$ and $I_{\rm g,l}$ being among $\{I_{\rm g1}, \ldots, I_{\rm gN}\}$. Thus, the more I–V-curves are measured the more values $R_s(I,I_{\rm g})$ can be extracted.

Three often applied methods to calculate the series resistance are based on (a) comparison of a dark-I–V-curve with an illuminated I–V-curve; (b) comparison of two illuminated I–V-curves; and (c) comparison of an $I_{\rm sc} - V_{\rm oc}$-curve with an illuminated I–V-curve. Each of these methods yields one or more values for the series resistance. Based on the result (8), it can easily be shown what the corresponding parameters for the current I and generated photocurrent $I_{\rm g}$ are. It becomes clear why all these methods might lead to different values of the series resistance as soon as R_s depends on I or $I_{\rm g}$. In case (a) or (b) where two curves are measured, one obtains only two values for R_s since only two illuminations can be analyzed, i.e., $R_s(I = I_{\rm g1} - I_{\rm g2},\ I_{\rm g2})$ and $R_s(I = I_{\rm g2} - I_{\rm g1},\ I_{\rm g1})$. For example, if a dark curve and an illuminated curve at 1 sun are measured, one finds $R_{s,\rm dark}(I = -I_{\rm sc,1sun})$ and $R_{s,\rm illum}(I = +I_{\rm sc,1sun})$. It is impossible to extract the complete relationship $R_s = R_s(I,\ I_{\rm g})$. In case (c), one can use all the information for different illuminations that are contained in the $I_{\rm sc} - V_{\rm oc}$-curve. However, the complete I–V-characteristic is given for a single illumination only, i.e., for $I_{\rm g}$. This implies that the series resistance can be extracted for many different values of current I but for one generation current $I_{\rm g}$ only. For example, if the I–V-curve is measured at 1 sun and the $I_{\rm sc} - V_{\rm oc}$-curve between vanishing illumination and 1 sun, then one finds $R_s(I = I_{\rm sc,1sun} \ldots 0, I_{\rm g=1sun})$.

While the voltages at $V_{I_{\rm g1}}(I_1 = 0) \equiv V_{\rm oc,g1}$ and $V_{I_{\rm g2}}(I_2)$ in Eq. (8) are explicitly known from experiment, the difference in generated photocurrents $I_2 = I_{\rm g1} - I_{\rm g2}$ that also enters Eq. (8) is not directly accessible. In most cases, the relation $I_{\rm g} \approx -I_{\rm sc}$ is a rather good approximation as shown in Eq. (3). However, this approximation for $I_{\rm g}$ cannot be applied for the particular case where $I_2 = -I_{\rm g2}$ with $I_{\rm g1} = 0$ in Eq. (8). This is due to the fact that the inverse relation $V = V(I)$ at $V \approx 0$ is very sensitive to small deviations in current I, i.e., $0 = V_{I_{\rm g2}}(I_2 = I_{\rm sc2}) \neq V_{I_{\rm g2}}(I_2 = -I_{\rm g2}) < 0$.

The approximation $I_{\rm g} \approx -I_{\rm sc}$ can be optimized by Eq. (3) which allows an iterative calculation scheme of R_s. Such an iteration of Eqs. (3) and (8) can significantly improve the result if the corrections in Eq. (3) become important. This can be the case when the series resistance is rather large while the shunt resistance becomes small. The procedure involves the initial step setting $I_{\rm g}^{(0)} = -I_{\rm sc}$ and the subsequent iterative steps:

1. calculation of $R_s^{(0)}(I, I_{\rm g})$ according to Eq. (8) based on the measured current-voltage curves,

2. determination of $R_p^{(0)}$ according to Eq. (5),
3. calculation of $F^{(0)}(\bar{V})$ for all experimentally determined voltage and current values using Eq. (1) and $R_s^{(0)}$ and $R_p^{(0)}$,
4. application of Eq. (3) and determination of corrected photo-generated current $I_g^{(1)}$.

Repeating these iteration steps leads to $R_s^{(1)}$, $R_p^{(1)}$, $F^{(1)}$, and so on. It results in a rather precise determination of cell parameters contained in model Eq. (1).

According to our findings, the measurement of an entire set of I–V-curves is essential for the experimental determination of the current and photocurrent dependent series resistance. Thus, a very rapid and precise practical implementation of this method can be achieved by using LED-based illumination sources as they allow a fast adjustment of the illumination intensity. Experimental results obtained by application of this technique are shown in Sec. IV.

III. APPLICATION TO NUMERICAL DATA

Before demonstrating the experimental applicability of our method, the usefulness of the approach is shown by applying Eqs. (3) and (8) to numerically generated test data. In a first step, the I–V-characteristic of model Eq. (1) is generated as a starting point. Here, a given series resistance $R_s = R_s(I, I_g)$ which explicitly depends on the current I flowing through the contacts and the generated photocurrent I_g is employed. It is shown that our approach is capable to identify this functional dependence $R_s = R_s(I, I_g)$ with a very high accuracy. To this end, the I–V-data is analyzed in a second step using Eqs. (3) and (8). The resulting series resistance is then compared to the known input parameters used in the first step. In this manner, it is demonstrated that a precise knowledge of the dependence of R_s on current I and generated photocurrent I_g can be obtained without any assumptions regarding the internal diode characteristic $F(\bar{V})$.

As model system, $F(\bar{V}) = F_{2D}(\bar{V})$ is chosen but with a variable ideality factor, i.e., $n_2 = n_2(\bar{V})$ in Eq. (2). Thus, the example shows that the approach proposed in this work is applicable to the general case where the ideality factor is non-constant. This extension of the two diode model plays a significant role when solar cells with defects are considered.[27] The numerical I–V-curves are shown in Fig. 2 with the inset showing the variation of n_2. The remaining parameters were set to $R_p = 300\,\Omega\mathrm{cm}^2$, $n_1 = 1$, $i_{g=1\mathrm{sun}} = 35\,\mathrm{mA/cm}^2$, $i_{01} = 2 \cdot 10^{-12}\,\mathrm{A/cm}^2$, and $i_{02} = 2 \cdot 10^{-8}\,\mathrm{A/cm}^2$. The functional dependence of the series resistance $R_s(I,I_g)$ as a function of current I and generated photocurrent I_g is shown by the lines in Fig. 3. Based on this parameter set, fourteen I–V-curves with $I_g = \{0 \cdot i_{g=1\mathrm{sun}} \ldots 1.3 \cdot i_{g=1\mathrm{sun}}\}$ have been calculated of which four are plotted in Fig. 2.

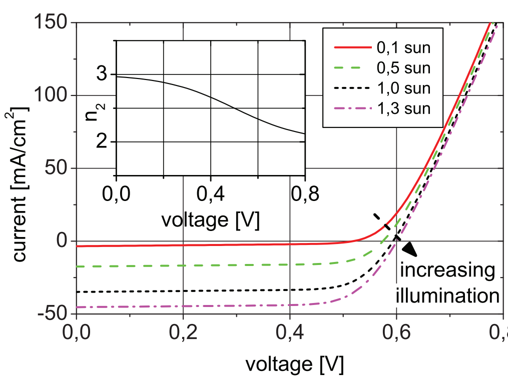

FIG. 2. Numerical data: The I–V-curves used as input data were obtained for a non-constant ideality factor $n_2 = n_2(V)$ shown in the inset. The series resistance $R_s(I,I_g)$ has been assumed to depend on current I and photocurrent I_g as shown in Fig. 3.

This set of numerical I–V-curves is analyzed using our R_s-approach. It is important to stress that the internal diode characteristic, as well as, the functional dependence of $R_s(I,I_g)$ do not enter the analysis. The resulting set of series resistance values is shown by the symbols in Fig. 3. It has been obtained by iterating Eqs. (3) and (8) three times. The first iteration based on Eq. (8) and assuming $I_g = I_{sc}$ leads to a poor accuracy at small currents I where $I + I_g \approx 0$. However, including corrections for I_g according to Eq. (3) improves the quality of the data analysis for these values. Thus, it can be observed that a remarkable agreement between the R_s-values used as input parameters (lines in Fig. 3) and the extracted R_s-values using our approach (symbols in Fig. 3) can be achieved. Both the current dependence as well as the dependence of R_s on the generated photocurrent are correctly reproduced. The relative error between the chosen R_s entering the I–V-curves and the obtained R_s is less than 0.5% for all values shown in Fig. 3.

The corresponding results of the most well known methods are shown[10,20] in Fig. 3 as well: (a) Comparison of dark and illuminated curve yielding $R_{s,\mathrm{dark}}$ and $R_{s,1\mathrm{sun}}$; (b) comparison of $I_{sc} - V_{oc}$-curve with I–V-curve yielding $R_{s,I_{sc}-V_{oc}} = R_s(I = I_{sc,1\mathrm{sun}} \ldots 0, I_{g=1\mathrm{sun}})$. It is obvious that with either approach, only a partial information of $R_s(I,I_g)$ can be obtained. In contrast to these simplified approaches, our method yields the complete information on $R_s(I,I_g)$ for any general solar cell that can be represented by model (1).

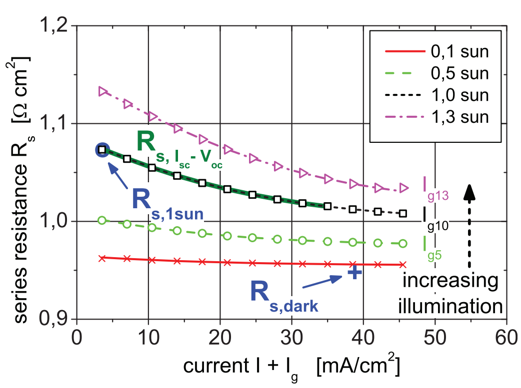

FIG. 3. Numerical data: The lines represent the functional dependence of R_s on current I for different values of generated photocurrent I_g that has been used to calculate the I–V-curves in Fig. 2. Those I–V-curves only were the starting point for the calculation of the set of $R_s(I,I_g)$-values using Eqs. (3) and (8) represented by the symbols. The underlying thick olive line beneath the 1 sun curve shows the R_s values that can be obtained from an $I_{sc} - V_{oc}$-curve compared to an illuminated curve. The individual blue symbols (+ and o) show the $R_{s,1\mathrm{sun}}$ and $R_{s,dark}$ values that can be obtained from a dark I–V-curve and an illuminated I–V-curve.

IV. APPLICATION TO A SILICON, AN ANORGANIC THIN FILM AND A DYE-SENSITIZED SOLAR CELL

The proposed approach has been applied to various types of solar cells based on crystalline silicon and amorphous silicon as well as dye-sensitized solar cells. The *I*–*V*-curves were measured at different intensities using a tunable LED-array as a light source. The LED array has been calibrated by means of a solar cell with well known power characteristic. Alternatively, these measurements can be carried out using different shadowing grids. However, the more curves are available as a data basis the better can the parameter range for $R_s(I,I_g)$ be covered. The samples were placed on a temperature stabilized chuck. For each sample, the voltage range has been adjusted such that the *I*–*V*-curves cover current values approximately between $+I_{sc,1sun}$ and $-I_{sc,1sun}$. Each individual measurement has been averaged over three repetitions such that the measurement errors are reduced. The data analysis has then been performed using an optimized computer code which automatically iterates Eqs. (8), (3), and (5).

In this work, the results of three different solar cell types are presented. Figure 4 shows the series resistance values for a commercially available crystalline silicon solar cell. The resulting R_s-values are based on eleven *I*–*V*-curves obtained at different levels of illumination between 0 sun and 1 sun. Of all resulting $R_s(I,I_g)$-values, only those for 0.1 sun, 0.4 sun, 0.7 sun, and 1 sun are shown in Figure 4. It can be observed that the series resistance under dark conditions is smaller than under illumination, as expected. Furthermore, a weak decrease of the series resistance when going from short circuit conditions to open circuit conditions is found. Finally, it can be concluded that a single constant value for the series resistance can lead to a rather poor description of the solar cell due to the large variations in $R_s(I,I_g)$. Depending on the operation conditions, the series resistance varies between $0.55\,\Omega\,\mathrm{cm}^2$ and $0.75\,\Omega\,\mathrm{cm}^2$.

As a second example, an amorphous silicon solar cell has been investigated. The results are presented in Fig. 5. Although there is again a trend of decreasing series

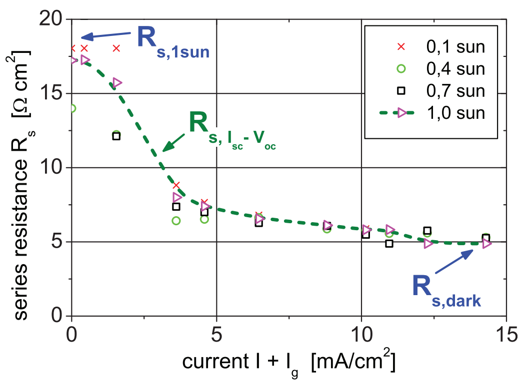

FIG. 5. Amorphous silicon solar cell: Using eleven *I*–*V*-curves of an amorphous silicon solar cell yields the set of $R_s(I,I_g)$-values represented by the symbols. The symbols and lines have the same meaning as in Fig. 4.

resistance when going to higher currents, the difference between operation under weak or strong illumination is not significant. This is in contrast to the crystalline silicon solar cell. Contacting a solar cell using individual fingers leads to a difference between the series resistance found in the dark and under illumination while this effect is not as pronounced as for homogeneous contacts. However, previous methods to determine $R_{s,dark}$ and $R_{s,illum}$ have neglected the dependence of the series resistance on the current itself. Although the $R_s(I,I_g)$-curves for various I_g values are quite similar, the resulting $R_{s,dark}$ differs significantly from $R_{s,illum}$, see Fig. 5. Therefore, the difference between these two values is not caused by the different illumination levels but by the difference in current *I*.

The third example, presented in Fig. 6, is a dye-sensitized solar cell module made of eight individual cells. The absolute R_s-values for this type of solar cell are larger than for the other two samples. Furthermore, a clear trend of R_s when going from small to large currents cannot be observed. An exception is the curve obtained for low illumination levels, i.e., for $I_{g=0.1sun}$. While $R_s(I)$ increases with increasing current for a 0.1 sun illumination rather strongly it is nearly constant for a 1 sun illumination.

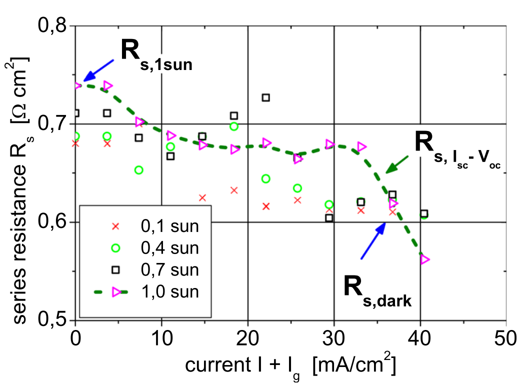

FIG. 4. Crystalline silicon solar cell: Using eleven *I*–*V*-curves of a crystalline silicon solar cell yields the set of $R_s(I,I_g)$-values represented by the symbols. The underlying thick olive line beneath the 1 sun curve shows the R_s values that can be obtained from an $I_{sc}-V_{oc}$-curve compared to an illuminated curve. The $R_{s,1sun}$ and $R_{s,dark}$ values obtained from a dark *I*–*V*-curve and an illuminated *I*–*V*-curve are indicated.

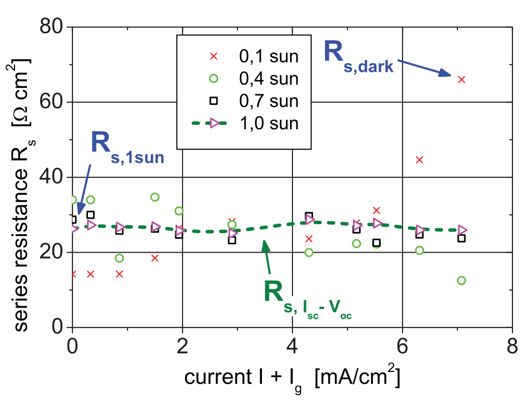

FIG. 6. Dye-sensitized solar cell: Using eleven *I*–*V*-curves of a dye-sensitized solar cell yields the set of $R_s(I,I_g)$-values represented by the symbols. The symbols and lines have the same meaning as in Fig. 4.

V. CONCLUSIONS

A new approach is presented that allows the extraction of the dependence of the series resistance on the current and the generated photocurrent. Our method does not require the knowledge of the specific functional form of the internal diode current-voltage characteristic. In particular, it is not necessary to assume the validity of the standard one- or two-diode model. This implies that our approach can directly be applied to all sorts of solar cell technologies that are based on crystalline silicon, anorganic thin films, or organic materials.

The method is demonstrated to work with very high accuracy when applied to numerically generated data sets. The numerical data set used in this work is based on a non-constant ideality factor in order to verify its applicability to more general cases than the standard one- or two-diode model. It is found that the dependence of R_s on both external current and photo-generated current are correctly reproduced even without any specific assumptions on the internal diode. However, quantitative results are found only if the estimation of the generated photocurrent based on the short circuit current is calculated by an iterative procedure which includes the corrections due to the parallel and series resistance in a self-consistent way.

Finally, the proposed approach is applied to experimentally obtained current-voltage-curves for different types of solar cells. As a result, we conclude that the series resistance must not be described by a constant value when a certain accuracy is required. Furthermore, the series resistance was found to exhibit quite different behaviour when a crystalline silicon solar cell, an amorphous silicon solar cell, and a dye-sensitized solar cell are compared. While the illumination level plays a role for crystalline silicon solar cells it is less important for the other two cell types with homogeneous contacting.

In summary, our new approach of applying a rather simple equivalent circuit model extended by a non-constant series resistance leads to a significantly better understanding of solar cell characteristics and allows for an accurate modeling of the solar cell performance. It is applicable to all sorts of equivalent circuit models going beyond the standard one- or two-diode model. As a result, the dependence of the series resistance on the external current and on the photo-generated current is obtained. Thus, various types of solar cell technologies can be compared with respect to their series resistance using a unified approach.

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[1]A. Kumar, S. Sista, and Y. Yang, "Dipole induced anomalous s-shape i-v curves in polymer solar cells," J. Appl. Phys. **105**(9), 094512 (2009).
[2]A. Wagenpfahl, D. Rauh, M. Binder, C. Deibel, and V. Dyakonov, "S-shaped current-voltage characteristics of organic solar devices," Phys. Rev. B **82**, 115306 (2010).
[3]V. A. Trukhanov, V. V. Bruevich, and D. Y. Paraschuk, "Effect of doping on performance of organic solar cells," Phys. Rev. B **84**, 205318 (2011).
[4]A. Petersen, T. Kirchartz, and T. A. Wagner, "Charge extraction and photocurrent in organic bulk heterojunction solar cells," Phys. Rev. B **85**, 045208 (2012).
[5]J. R. Tumbleston, D.-H. Ko, E. T. Samulski, and R. Lopez, "Nonideal parasitic resistance effects in bulk heterojunction organic solar cells," J. Appl. Phys. **108**(8), 084514 (2010).
[6]C. Zhang, J. Zhang, Y. Hao, Z. Lin, and C. Zhu, "A simple and efficient solar cell parameter extraction method from a single current-voltage curve," J. Appl. Phys. **110**(6), 064504 (2011).
[7]C. Chibbaro, M. Zimbone, G. Litrico, P. Baeri, M. L. Lo Trovato, and F. Aleo, "A general and precise method to evaluate the series resistance of photovoltaic cells from i-v characteristics," J. Appl. Phys. **110**(4), 044505 (2011).
[8]H. Nesswetter, W. Dyck, P. Lugli, A. W. Bett, and C. G. Zimmermann, "Luminescence based series resistance mapping of iii-v multijunction solar cells," J. Appl. Phys. **114**(19), 194510 (2013).
[9]T. C. M. Müller, B. E. Pieters, U. Rau, and T. Kirchartz, "Analysis of the series resistance in pin-type thin-film silicon solar cells," J. Appl. Phys. **113**(13), 134503 (2013).
[10]M. Wolf and H. Rauschenbach, "Series resistance effects on solar cell measurements," Adv. Energy Conv. **3**, 455 (1963).
[11]R. Handy, "Theoretical analysis of the series resistance of a solar cell," Solid-State Electron. **10**(8), 765–775 (1967).
[12]L. D. Nielsen, "Distributed series resistance effects in solar cells," IEEE Trans. Electron Devices **29**, 821 (1982).
[13]G. L. Araujo, A. Cuevas, and J. M. Ruiz, "The effect of distributed series resistance on the dark and illuminated current-voltage characteristics of solar cells," IEEE Trans. Electron Devices **33**, 391 (1986).
[14]A. Aberle, S. Wenham, and M. Green, "A new method for accurate measurements of the lumped series resistance of solar cell," in *23rd IEEE Photovoltaic Specialist Conference* (IEEE, 1993), pp. 133–138.
[15]P. P. Altermatt, G. Heiser, A. G. Aberle, A. Wang, J. Zhao, S. J. Robinson, S. Bowden, and M. A. Green, "Spatially resolved analysis and minimization of resistive losses in high-efficiency si solar cells," Prog. Photovoltaics: Res. Appl. **4**(6), 399–414 (1996).
[16]S. Bowden and A. Rohatgi, "Rapid and accurate determination of series resistance and fill factor losses in industrial silicon solar cells," in Proceedings of the 17th EU PVSEC, Munich, Germany, 2001.
[17]K. C. Fong, K. R. McIntosh, and A. W. Blakers, "Accurate series resistance measurement of solar cells," Prog. Photovoltaics: Res. Appl. **21**, 490 (2013).
[18]J.-M. Wagner, M. Hoppe, A. Schtt, J. Carstensen, and H. Föll, "Injection level dependent series resistance: Comparison of {CELLO} and photoluminescence-based measurements," Energy Procedia **38**(0), 199 (2013).
[19]O. Breitenstein and S. Riland, "A two-diode model regarding the distributed series resistance," Sol. Energy Mater. Sol. Cells **110**(0), 77–86 (2013).
[20]D. Pysch, A. Mette, and S. Glunz, "A review and comparison of different methods to determine the series resistance of solar cells," Sol. Energy Mater. Sol. Cells **91**(18), 1698–1706 (2007).
[21]I. Eisgruber, J. Granata, J. Sites, J. Hou, and J. Kessler, "Blue-photon modification of nonstandard diode barrier in cuinse2 solar cells," Sol. Energy Mater. Sol. Cells **53**(3–4), 367–377 (1998).
[22]B. Mazhari, "An improved solar cell circuit model for organic solar cells," Sol. Energy Mater. Sol. Cells **90**, 1021–1033 (2006).
[23]B. Romero, G. del Pozo, and B. Arredondo, "Exact analytical solution of a two diode circuit model for organic solar cells showing s-shape using lambert w-functions," Sol. Energy **86**(10), 3026–3029 (2012).
[24]M.-K. Lee, J.-C. Wang, S.-F. Horng, and H.-F. Meng, "Extraction of solar cell series resistance without presumed current–voltage functional form," Sol. Energy Mater. Sol. Cells **94**(3), 578–582 (2010).
[25]A. Ortiz-Conde, F. J. G. Sanchez, and J. Muci, "Exact analytical solutions of the forward non-ideal diode equation with series and shunt parasitic resistances," Solid-State Electron. **44**(10), 1861–1864 (2000).
[26]G. Araujo and E. Sanchez, "A new method for experimental determination of the series resistance of a solar cell," IEEE Trans. Electron Devices **29**(10), 1511–1513 (1982).
[27]O. Breitenstein, J. Bauer, P. P. Altermatt, and K. Ramspeck, "Influence of defects on solar cell characteristics," Solid State Phenom. **156**, 1 (2010).