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Local Series Resistance: Why the Model of Independent Diodes Fails and How to Understand Silicon Solar Cells in General by the LR-R_s Concept

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Abstract. The theoretical basics of the series resistance behavior of Si solar cells are reviewed and discussed, with an emphasis on the physical understanding of the linear response (LR) concept and the predominant role of experimental results. From this concept, a general fit model for the variation of the lumped series resistance along the *I–V* curve is derived. Important consequences of general validity for all series resistance determination methods are discussed, showing why the model of independent diodes is inappropriate for Si solar cells.

Keywords: Local and Lumped Series Resistance, Voltage-Dependent Series Resistance, Illumination Intensity Variation Method, Linear-Response Concept, Model of Independent Diodes

1. Introduction

Recently, results from series resistance (R_s) measurements based on the combination of several *I–V* curves, taken at different illumination intensities, were brought to our attention [1,2]: Based on a fit formula derived from the LR-R_s concept (LR: linear response [3,4]), an attribution of certain R_s-related problems to certain parts of the solar cells was possible. In essence, this attribution follows from the variation of the series resistance along the *I–V* curve (R_s decreases for increasing forward voltage; cf. Subsection 2.3). In [1,2], the R_s data were obtained according to the illumination intensity variation method (IIVM, aka the multi-light method [5]) for which the general LR-R_s formula for the lumped series resistance was derived. Moreover, it was found in [1,2] that the fit works equally well for different kinds of solar cells (*e.g.* HJT, TOPCon, PERC), *i.e.* even also for those for which the LR-R_s formula wasn't explicitly derived. To address this astonishing finding [1,2], in this contribution we summarize this derivation, developed originally for older types of solar cells, and we discuss the physical and mathematical background of the LR-R_s approach as well as the resulting benefits, challenges, necessities, and further possibilities to improve the reliability of R_s measurements as well as *I–V* data fits.

The lumped series resistance of a solar cell results from the external current internally passing many, spatially separated elements, effectively averaging over their individual effects. There are several methods to determine R_s locally; typically, luminescence-based methods are employed for this (cf., *e.g.*, [6]). To analyze those measurement results, most commonly the model of independent diodes is used [7,8]. However, in this model there is no variation of R_s with the operating point of the solar cell. This is already a hint that this model misses the physics relevant for the series resistance behavior of solar cells. Here, we will discuss further aspects which lead to the same conclusion that the model of independent diodes basically fails to describe the way silicon solar cells work w.r.t. the series resistance. We begin with summarizing relevant experimental findings for the series resistance properties of Si solar cells.

2. Basic series resistance properties known from experiments

2.1 The highly conductive emitter

We consider simple p–n junction solar cells with an emitter at the front. To illustrate how good the lateral conductivity of the emitter is, we present a CELLO voltage map in Fig. 1(left): The data measured by the reference electrode (positioned on the busbar in the lower left corner) are the surplus voltages caused by the laser beam scanning the whole solar cell. One can see that this electrode receives a signal from *all* emitter locations, with the strength of the signal depending on the lateral series resistance of the combined network of emitter and grid.

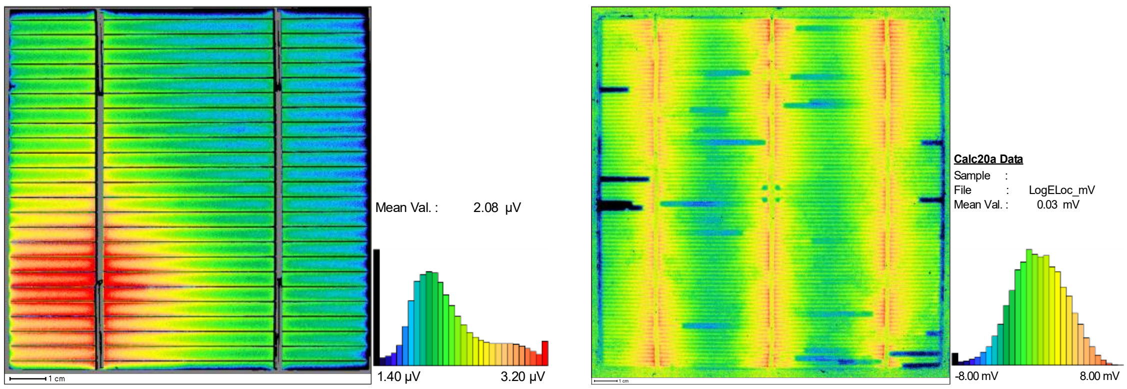


Figure 1. *Left: Light-beam-induced voltage map of a monocrystalline cell at open-circuit condition, taken by the CELLO method (cf. [9]). Right: Map of the voltage variation on a multicrystalline cell, caused by a change in external current. It was obtained from luminescence images in EL mode and PL-oc mode (cf. [10]); the arithmetic average was subtracted in order to display only the variation.*

In Fig. 1(right) we present a map of the voltage variation ΔV on a multicrystalline cell, obtained from luminescence measurements as follows: EL and PL-oc images are taken with $I_{ext}(EL) = I_{photo,1sun}(PL)$. From the respective intensities Φ one obtains the map pixel-by-pixel: $\Delta V = V_{therm} \cdot \ln(\Phi_{EL} / \Phi_{PL\text{-}oc}) - V_{offset}$ (with the offset being the arithmetic average of the logarithmic part); thereby, only the lateral variations remain. The result shows a highly systematic pattern: The voltage increase is strongest at the busbars and becomes gradually smaller towards the center between the grid fingers. Note that despite the external current equals the cell's full 1-sun photocurrent, the voltage variation is still small, well below the thermal voltage. This means that due to the high lateral conductivity, the emitter is nearly at equipotential.

2.2 Non-generation losses

Due to the "nearly equipotential" property of the emitter, current losses due to inhomogeneous junction voltages are negligible; non-generation losses only occur if the voltage differences exceed the thermal voltage $V_{therm} = kT/e$ [11]. However, we are not interested in badly performing solar cells and demand the cells under investigation to be free from non-generation losses.

2.3 Decreasing R_s for increasing forward voltage

Although this phenomenon was firstly described already quite long ago [12], it seems to never have made it properly into common knowledge, let alone into the relevant textbooks; hence, "PV researchers keep rediscovering that R_s is actually not constant" (D. Clugston, remark on the conference poster [2]). Instead, the systematic variation of R_s along the I–V curve (cf., *e.g.*, [5,13,14]) was perceived only indirectly: A comparison of various methods to determine the lumped series resistance led to the notion of discerning between $R_{s,dark}$ and $R_{s,light}$, with the former being smaller than the latter (cf., *e.g.*, [15]). However, this is just an artefact coming from the different measurement conditions: $R_{s,dark}$ is usually measured at higher voltages than $R_{s,light}$, hence the smaller value of the former. Yet if one performs the measurement of $R_{s,light}$ in the same range of the *I–V* curve as that used for $R_{s,dark}$, the same R_s value results; hence, there is no real difference between the two. This we have shown already previously [10,16].

3. The basics of the linear response (LR) series resistance concept

3.1 The general approach

Our theory requires some preconditions for the solar cells it can be expected to work well for (see below for the relevant details). However, many measurements show that it can also be applied to various other types of cells; in fact, it is an ongoing process to explore the applicability range of our theory. Therefore we want stress right from the beginning that, in general, a result obtained from the LR-R_s concept is a series resistance only if the *measured* data show it to be the proportionality constant between voltage and current or, more precisely, between a change in voltage and a change in the current causing the voltage change. We refer explicitly to the changes because in the LR-R_s concept, the series resistance is determined according to the IIVM: The solar cell's operating point is given by the dark current $I_D = I_{ext} + I_{photo}$ (cf. Fig. 2; here, $I_D > 0$ and $I_{photo} > 0$, so the sign of I_{ext} follows from the resulting flow direction), and in the IIVM I_D is kept constant; the variation of the external current is obtained by adjusting the illumination intensity accordingly. This method is applied both in the measurement and in the theory, and it is used both for the local and the lumped series resistance. As an example, consider the open-circuit condition of a solar cell at some illumination intensity. Measuring the terminal voltage of this cell for increasing external current, while increasing the illumination intensity as to keep I_D constant, will result in a linearly decreasing voltage; the slope of this curve is the lumped series resistance belonging to this dark current, *i.e.* it is $R_s(I_D)$. Note that this linearity holds even for rather large external currents, up to the 1-sun photocurrent [16].

During the last years, we have continuously refined the LR-R_s concept, and this process isn't finished yet. Here, we summarize the present status, highlighting some key experimental findings (as the example given above) relevant as the underlying basis, we discuss in detail some of the steps that are crucial for the understanding, and we point out some further issues to be investigated. The basic preconditions of the LR-R_s concept are as follows: We consider a solar cell with a p–n junction and a grid on the front side. There shall be no severe series resistance faults on the solar cell (as, *e.g.*, several neighbouring grid fingers broken), and the inhomogeneities of the material properties (lifetime, surface recombination velocity, …) and the localized vertical currents (shunts, "second diode") shall have no cross-correlation to the series resistance distribution. (For example, a clustering of strong defects is not covered by the modelling.) The explicit results for the series resistance are determined from Eq. (1), starting with the local R_s, from which the lumped R_s follows by a well-justified averaging procedure.

3.2 Background of the local series resistance theory

In our full-analytical theory, we only consider grid, emitter, and p–n junction, but not the base; its effect will be incorporated later in a lumped manner. Our modeling is based on the following equations: The voltage distribution in the emitter results from Ohm's law for the lateral currents and the continuity equation (giving the changes in the lateral current due to the vertical junction current density $J_z = J_D - J_{photo}$). This results in a general equation for the local emitter voltage:

$$\Delta_2 V(x,y) = \rho\, J_z(x,y), \tag{1}$$

with the two-dimensional Laplace operator Δ_2 and the emitter sheet resistivity ρ. Hence, the local current density J_z determines the Laplacian of the local voltage, not the voltage itself. To solve this general differential equation, it has to be integrated over the whole cell area, taking into account the boundary conditions determining the operating point. Due to the integration, all vertical currents contribute to the local voltage; this is in full agreement with the measurement, as can be seen in the CELLO map of Fig. 1 (*all* cell locations contribute to the signal).

Applying the IIVM to Eq. (1) permits to split current and voltage into a sum of a constant and a varying part. Since these parts are independent from another, two independent equations for the two parts follow from Eq. (1). The equation for the constant parts contains the exponential characteristic of the p–n junction. However, just defining the operating point, it need not to be solved: In the IIVM, the local R_s is determined by the varying parts only. The equation for the latter can be solved by applying two linearization steps, which both are motivated by the same physical fact: Due to the emitter being low-ohmic (cf. Subsection 2.1), the lateral voltage variations caused by a variation of the external current can be kept small, typically lower than V_{therm} – at least when the variation of the external current is kept small. This can easily be realized, for example, in the case of the open-circuit condition as starting situation for the IIVM as described above. Then, (i) the local dark current variation need not be described by the exponential p–n characteristic but can be approximated in linear order, and (ii) the lateral voltage variation is linear in the sheet resistivity. From (i) one has that Eq. (1) becomes

$$\Delta_2 V^*(x,y) = \rho\, K\, V^*(x,y), \tag{2}$$

where K contains the slope of the exponential J_D–V characteristic and V^* (the asterisk indicating it to be the varying part of V) contains also the homogeneous photocurrent variation (for the details see [17]). As an approximation, a single, average slope value is used for the whole cell: $K = \langle J_{D,0}\rangle / V_{therm} = I_{D,0} / (A_{cell} V_{therm}) = 1 / (A_{cell} R_D)$; the index 0 refers to the constant part defining the operating point, the angle brackets indicate the lateral averaging, and $R_D = V_{therm} / I_{D,0}$ is the effective diode resistance at the given operating point (with the ideality factor taken to be $n = 1$; it will turn out that this assumption can easily be relaxed). This may seem to be a strong simplification, possibly contradicting the actual local solar cell properties (especially in the case of a multicrystalline cell) or being unjustified if due to large external currents the various parts of the solar cell effectively are at different operating points. However, also here one can argue that the local properties have a minor influence on the overall voltage distribution. And the lateral variation of the effective operating points is smaller than might be expected from Eq. (1) alone, since this equation describes only the emitter; lateral balancing effects in the base are not considered in our theory at all. For these it was found that they effectively reduce the lateral voltage build-up in the emitter [18], which is in favor of the approximation of a homogeneous K; whether it works or not, however, can only be determined experimentally.

The general solution of Eq. (2) is the hyperbolic cosine function, and from (ii) one has that it is sufficient to keep only the constant and quadratic terms of its Taylor series. After determining all remaining parameters, one obtains an expression which is linear in the sheet resistivity and in the finger line resistivity [17]. Most importantly, the so-obtained local voltage variation $V^*(x,y)$ is exactly the quantity needed for the determination of the local R_s according to the IIVM. The final result for $R_s(x,y)$ shows an explicit dependence on the lumped dark current I_D, with R_s decreasing for increasing I_D [19]. Therefore, from the LR-R_s concept, not a voltage-dependent series resistance is found, but $R_s(I_D)$ – as already discussed above.

However, so far, all this is just a lot of technicalities; this approach needs to be checked by processing experimental data accordingly. Basically, (i) and (ii) mean that no matter what local vertical current is present at the operating point, and no matter what local voltage belongs to it, one should expect a *change* in local voltage that is proportional to the *change* in external current. If one finds a linear relation, the proportionality constant is $R_s(x,y)$. The best candidate to test this “no matter what” obviously is a multicrystalline cell. For such a cell, this decoupling of the variational response from the working-point-related part can indeed be found [19], with the response being linear in the external current variation. How nicely this decoupling works can be seen in the luminescence-derived voltage map in Fig. 1(right) from which such a local R_s follows; it was obtained according to the IIVM. This shows that the local vertical current is irrelevant for the local series resistance. – The dependence of R_s on I_D, which is also found in these measurements, will be discussed below.

3.3 Generalization of the lumped LR-R_s expression

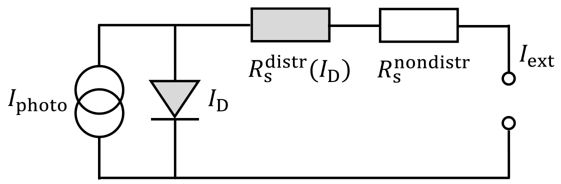
As mentioned already above, the lumped series resistance of a solar cell results from the external current internally passing many, spatially separated elements. This causes various losses, which can be quantified either by a voltage drop or by Joule heating power. Measuring the lumped R_s according to the IIVM, one obtains an effective resistance value from the change in terminal voltage being proportional to the change in external current. However, this doesn't mean that the lumped R_s results from an internal average of all the local voltage drops: Only those quantities can be arithmetically averaged for which their sum is a meaningful physical quantity. For example, since energies can be added up to give the total energy of a system, one can define an average energy per particle in a system. The same holds for summing volumes, masses, charges and so on; in thermodynamics, those quantities are called "extensive". Adding up voltages to obtain a total voltage, however, is only possible if these voltages are switched in series – while on a solar cell, the local voltages exist in parallel (cf. Fig. 1). This makes the voltage an intensive quantity, which therefore cannot be averaged. Hence, also the local R_s (following directly from the local voltage) cannot be arithmetically averaged *per se*.

However, currents that run in parallel can be added up to give the total current. On a solar cell, for the total external current it holds that it equals the integral of the vertical junction current density J_z, taken over the whole area. In the LR-R_s theory, the varying part of this current is given by $J_z^* = K\,V^*$, so the change of the external current is $\Delta I_{ext} = \int J_z^*(x,y)\,\mathrm{d}x\mathrm{d}y = \int K\,V^*(x,y)\,\mathrm{d}x\mathrm{d}y = KA_{cell} \langle V^* \rangle = \langle V^* \rangle / R_D$. This means that due to the linear relation between current and voltage present in the LR-R_s theory, the current conservation leads to a meaningful voltage averaging procedure, from which a lumped R_s follows (for the details see [17]). This lumped value is identical to the one obtained from the IIVM, but applied only to emitter and grid; experimentally, this can be realized as shown in Fig. 1(right) where an offset was subtracted. This part of the series resistance is called "distributed resistance" R_s^{distr} in the sense already described by Wysocki [20] as "cannot be considered independently of the junction." For this part of the series resistance we obtain the explicit dependence on the dark current, so we have $R_s^{distr}(I_D)$. For the total series resistance we have $R_s(I_D) = R_s^{distr}(I_D) + R_s^{nondistr}$; that $R_s^{nondistr}$ is indeed a constant (*i.e.* it doesn't depend on I_D) was originally found in [16]. The analytic result for $R_s^{distr}(I_D)$ can be brought into the following simple form:

$$\frac{1}{R_\mathrm{s}^\mathrm{distr}(I_\mathrm{D})} = \frac{1}{R_{\mathrm{s},\infty}} + g\,\frac{1}{R_\mathrm{D}} \approx \frac{1}{R_{\mathrm{s},\infty}} + g\,\frac{I_\mathrm{D}}{V_\mathrm{therm}}. \tag{3}$$

Here, $R_{s,\infty}$ is the value of R_s^{distr} in the limit of infinite diode resistance (or, equivalently, in the limit of $I_D \to 0$) and equals the well-known text book expression for the lumped effect of sheet and finger resistivity [19], whereas g is a parameter that, according to our present theory and to numerical simulations, is related to the grid geometry and to the resistivities of emitter and base [4]. Equation (3) shows that the larger I_D, the smaller $R_s^{distr}(I_D)$ becomes; this is our explicit result for the effect discussed in Subsection 2.3 above. According to the present understanding of the theory, the physical reason for this effect is that for increasing junction voltage there is the possibility for lateral emitter currents to flow back into the base, so the average distance relevant for the lateral currents that become the external current is reduced, effectively leading to smaller ohmic losses [21,22]. In addition, there can also be a certain contribution of the base that leads to smaller losses in the emitter [18].

We want to stress that although Eq. (3) looks like a weighted parallel arrangement of $R_{s,\infty}$ and R_D, this does not mean that on the solar cell there is effectively the diode in parallel to the emitter. Instead, this "parallel" is only related to current conservation as already discussed above: Currents can either continue to flow through the emitter sheet or can vanish from the emitter via the p–n junction. In previous publications we have drawn a modified equivalent circuit featuring such a parallel arrangement, but since this led to unnecessary confusion, we now propose the simpler circuit shown in Fig. 2(left).



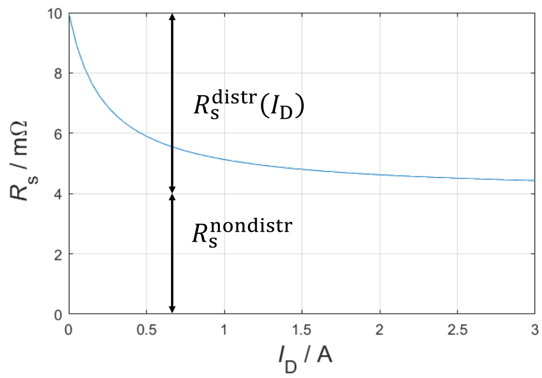


Figure 2. *<u>Left:</u> Modified equivalent circuit, containing the explicit dependence of the series resistance on the operating point of the solar cell as given by Eq. (3). <u>Right:</u> Example plot for $R_s(I_D)$ according to the LR-R_s concept. The measured data shown in [1,2] follow exactly this general fit model (see text).*

Recently it was found that if *g* is used as a general fit parameter, one can obtain an incredibly good agreement with the series resistances directly extracted from measured *I*–*V* data (*i.e.*, without applying any *I*–*V* fit), taken at different illumination intensities and analyzed according to the IIVM. As reported in [1,2], this even works for solar cells not having a standard p–n junction (*i.e.*, HJT); in all cases, the IIVM-derived lumped $R_s(I_D)$ data follow the trend shown in Fig. 2(right) by an example curve (generated only for illustrative purposes). This broad applicability can be understood by the fact that the approximation used here is very basic: By whatever function the *I*–*V* characteristic of a device might be described, in the LR-R_s concept only the linearization of this function is needed; therefore, our theory is not limited to solar cells having a standard p–n junction. Moreover, using *g* as a fit parameter in Eq. (3) has the advantage that the actual value of the ideality factor doesn't matter because it automatically becomes part of *g*; also this "side effect" contributes to a broad applicability of the LR-R_s concept. On the other hand, at present this goes hand in hand with the loss of the deeper physical meaning of *g*; only many more measurements and also numerical simulations that take the processes in the base fully into account can lead to a better understanding of *g*.

The obvious benefit of using the LR-R_s fit model for the lumped R_s is that one just needs a few *I*–*V* curves, measured at different illumination intensities, to be able to attribute large R_s values to certain parts of the solar cell, namely by the separation between R_s^{distr} (related to emitter and grid) and R_s^{nondistr} (related to all the rest). However, this mainly requires to extract the offset, given by R_s^{nondistr}, from the measured data. There are several possibilities to achieve this: (a) One can try to come as close as possible to the limiting case of $I_D \to \infty$, *i.e.* to use a very strong illumination. (b) One can try to apply the IIVM "in the first quadrant" (considering the photocurrent as negative) by combining (i) a measurement in the dark with a lot of current fed into the solar cell with (ii) a measurement with some illumination switched on and correspondingly less current fed in. (c) If one can measure luminescence images, one can proceed as we had shown in [16] by separately determining the full lumped $R_s(I_D)$ and the corresponding $R_s^{\mathrm{distr}}(I_D)$ by subtracting an offset from the R_s images so that they show the value zero at the busbar, then their average is $R_s^{\mathrm{distr}}(I_D)$, and one can determine $R_s(I_D) - R_s^{\mathrm{distr}}(I_D)$. This procedure is repeated for several I_D, and if one finds (besides some noise) a constant value for this difference, it is R_s^{nondistr}. [The word "try" used in (a) and (b) is due to not having done that so far, so we have no experience to share about these possibilities; feel free to be the first to try it.]

3.4 Discussion

We have seen that it's possible for various types of solar cells to have a different R_s value at each point along the I–V curve. If this is the case (which can be easily checked through determining R_s by the IIVM – and since one seldomly knows about it beforehand, one should *always* check this!), for obtaining reliable results it is *necessary* to use the IIVM or any other R_s determination method that combines only those data that belong to the same I_D value. Also, this means that standard I–V curve fits using a fixed R_s value aren't reliable; instead, one should first determine the lumped R_s by the IIVM (directly from the measured data), then use the LR-R_s fit model to have an analytical expression for $R_s(I_D)$, and finally the latter can be used in a fit for a single I–V curve.

4. On the failure of the model of independent diodes

4.1 General arguments and important details

Already years before the model of independent diodes was used for Si solar cells, the same approach was considered for thin-film solar cells and its validity was thoroughly tested: Firstly, it was found that models with independent diodes can be valid only on lateral length scales larger than several bulk diffusion lengths [23] – but Si solar cells don't fulfill this requirement. Secondly, it was found that models with independent diodes can be valid only if the electrical screening in the laterally conductive layer is very strong [24,25] – but Si solar cells don't fulfill this requirement (cf. Fig. 1). In addition, the model of independent diodes cannot explain the experimentally observed decrease of R_s for increasing forward voltage (cf. Subsections 2.3 and 3.3), occurring as a direct consequence of the coupling between lateral emitter currents and the p–n junction. Despite a relevant remark in a book chapter [6], the model of independent diodes has never been shown to originate from general equations governing the current and voltage distribution on a Si solar cell – and it never will be, since for the physical reasons given above, this is impossible. To understand this rather vividly, have a look again at Fig. 1(left): It shows that the local voltage is determined by all vertical currents, occurring anywhere on the solar cell, and not only the local one – yet in the model of independent diodes, only the local current determines the local voltage. Altogether, a "model of independent diodes" makes no sense for Si solar cells since they are laterally strongly coupled.

Another vivid insight comes from the following thought experiment: Consider a solar cell under illumination, but with the area of a single pixel (*i.e.*, one of the independent diodes) being shaded. On a real solar cell, this would result in a small voltage drop in the shaded area compared to its surrounding, because current can easily flow into the shaded area from the neighboring pixels, and since the series resistance between the pixel and its direct neighbors is very small, also the voltage difference would be very small. On the other hand, considering this situation in the case of the model of independent diodes (with the local resistances being determined from a preceding unshaded measurement), it would predict a significant, isolated voltage drop, because then the current inflow can only take place via the terminal, and the full series resistance for this pixel determines the voltage drop; obviously, this is unphysical.

4.2 Discussion

It might be surprising that the model of independent diodes is so far off from reality of Si solar cells, especially since this model has been used many times to successfully analyze series resistance problems. However, even if one comes to a reasonable conclusion, this doesn't mean that the underlying model is correct. This is due to the binary logic behind the implication operation: If one just knows that "from A follows B" and that "B is valid", one doesn't know anything about A, because the implication is valid in both cases – A being right or being wrong. The only valid conclusion that leads from B back to A is the negation "not-B implies not-A". So, the model of independent diodes isn't "saved" by its successful application.

Now, one could discuss why the model of independent diodes was yet so successful (despite being non-applicable to Si solar cells), or one could start to speculate about why this model wasn't fundamentally doubted earlier (despite the various artefacts it results in, *e.g.*, "shunt paradox" [26], "resistive blurring" [27], "unwanted contrast" [28]) – for sure its alluring simplicity is relevant for both aspects. However, here we want to stress that there is no chance to "repair" this model in any way. This is due to the severity of the two major shortcomings of this model: It is based on (and leads to) a completely wrong understanding of the series resistance, and it can never include the systematic variation of R_s along the I–V curve without becoming unphysical – the local resistors would have to depend on the current flowing through them, making them nonlinear = non-ohmic. All this shows that for Si solar cells, the model of independent diodes isn't an approximation of any kind; instead, it's an oversimplification.

5. Conclusion and outlook

It is time that the non-constancy of R_s entered both common knowledge as well as the relevant textbooks, and that the model of independent diodes got abandoned. For the former it is sufficient to discuss the behavior of the lumped R_s, determined experimentally according to the IIVM. For the latter, it's probably necessary to suspect the whole literature about local series resistance determinations as being potentially flawed and therefore to be used with caution: From the old data, one should (i) reconstruct the actual voltage distribution on the solar cell and (ii) determine the relevant external current; then, one can re-determine the local R_s by dividing the local voltage by the total external current (*i.e.*, as in the IIVM). The LR-R_s concept needs to be tested further by measurements and simulations. Relevant questions are: Which cell parts contribute to R_s^{distr} and $R_s^{nondistr}$ for different types of solar cells, and why so? Is there something we can learn when we deliberately drive the cell out of the linear response regime?

Data availability statement

The data shown were either measured or obtained from the formulae given in the text. We encourage all readers to perform similar measurements of their own.

Author contributions

J.-M. Wagner: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Project Administration, Software, Visualization, Writing – Original Draft Preparation; J. Carstensen: Formal Analysis, Software, Validation, Writing – Review & Editing, Resources.

Competing interests

The authors declare that they have no competing interests.

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