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Production-Ready Decomposition of Series Resistance Into Lateral and Fixed Components

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Abstract. The series resistance (Rs) of a solar cell is commonly treated as a constant, but this is a very poor approximation: in modern cells, Rs can vary by a factor of 4 depending on illumination, bias voltage, and temperature. The naïve model leads to incorrect characterization of cell parameters and misattribution of cell losses. Wagner's linear-response series resistance (LR-Rs) model attempts to treat Rs rigorously but experimental confirmation of the model is limited to EL and PL measurements. In this work we validate the LR-Rs model using IV measurements at multiple light intensities. We find a hyperbolic dependence of Rs on diode current as predicted by Wagner. The LR-Rs model fits the data extraordinarily well, but with a much higher geometric dependency than predicted by Wagner. We show that the model allows us to decompose series resistance into lateral and fixed components. This decomposition is now available in all WAVELABS commercial LED flashers. We illustrate the immediate benefits of this improved model in commissioning of a heterojunction production line.

Keywords: Rs, Lateral Resistance, Characterization, Series Resistance

1. Introduction

The series resistance (Rs) of a solar cell is commonly treated as a constant. This was already recognized to be a very poor assumption by Wolf et al[1] in 1961. in modern cells, Rs can vary by a factor of 4 depending on illumination, bias voltage, and temperature. The naïve model leads to incorrect characterization of cell parameters and misattribution of cell losses.

A transmission-line model of Rs was proposed in [1] but was not widely adopted. Transmission line models are unable to predict observed cell behaviour, because they do not include lateral injection effects [2]. A rigorous derivation including supercomputer modelling was presented in [3]. It modelled lateral injection effects by introducing pseudo-current sources to the transmission-line model. However, the pseudo-current sources are complicated and not directly measurable. None of these models have seen widespread adoption.

Lateral injection effects were included in an alternative way by Wagner et. al.[4], who derived a linear-response series resistance (LR-Rs) model in which the distributed Rs *Rsdist* depends only on the diode current I_D, and is given by

$$\frac{1}{Rsdist(I_D)} = \frac{1}{Rs,\infty} + g\, I_D \frac{q}{kT} \tag{1}$$

where $R_{s,\infty}$ encapsulates the emitter sheet resistance and finger resistance, and *g* is a weighting factor which should be 0.5 for a rectangular grid, 1 for a circular geometry. The total Rs is given by Rs = Rsnondist + Rsdist(I_D), where *Rsnondi<st* is constant, giving a simple

lumped-element model (Fig. 1). After including the effects of bulk resistivity [5], *g* may be substantially larger than 1.

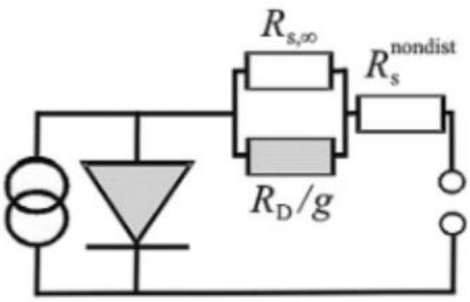

Figure 1. *Equivalent circuit for Wagner's LR-Rs model (after [4]). R_D is the differential resistance at the operating point*

2. Validation of Wagner's LR-Rs Model

2.1 The Two-Irradiance Level Method for Determining Rs

The "two irradiance level" method (Fig. 2), first described in [1], is the IEC standard (IEC 60891) for determining the Rs of a solar cell or module at an operating point of interest. The method requires IV curves acquired at two different light intensities. Two points with identical diode currents are identified, and the Rs is determined from them using equation 2.

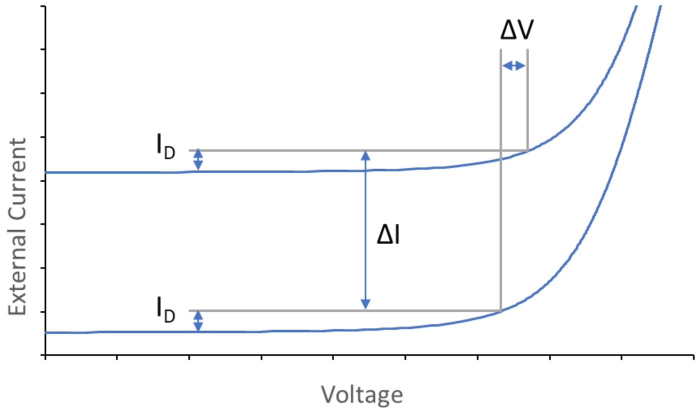

Figure 2. *Two-irradiance level method for determining Rs, according to IEC 60891.*

$$Rs = \frac{\Delta V}{\Delta I} \qquad (2)$$

Typically, a single point in the vicinity of the one-sun maximum power point is chosen. The same technique can be applied, however, to all points on the IV curve. When this is performed on a commercial heterojunction cell, Rs is seen to vary by a factor of 4 depending on voltage bias (Fig 3).

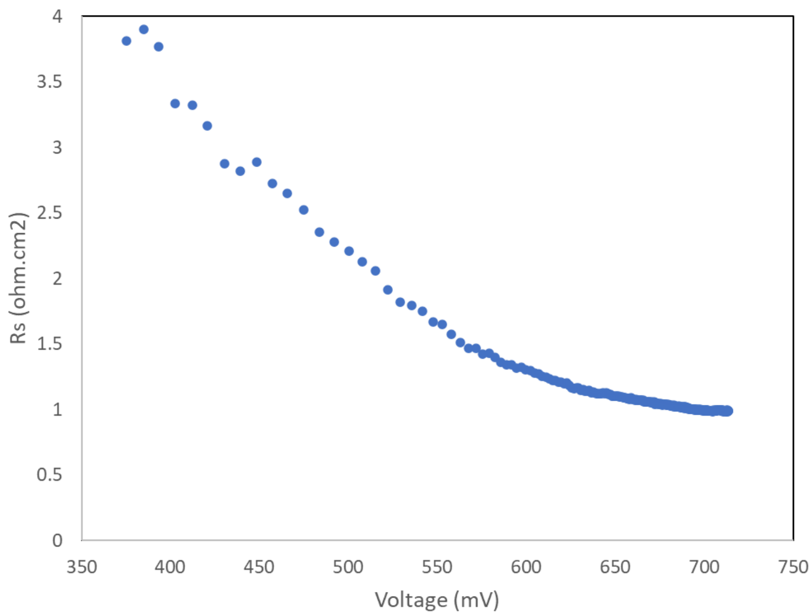

Figure 3. *Rs calculated using IEC 60891 for IV curves acquired from an HJT cell at 1.0 and 0.5 suns*

2.2 Comparison with Wagner's Model

When the data from Fig. 3 is replotted as a function of diode current (Fig 4), Rs is seen to be a hyperbolic function of diode current, as predicted by Wagner. Repeating the measurement on the same cell with multiple light intensities shows that the Rs is independent of illumination level. The data is extremely well modelled by Wagner's model, if *g* is used as an unconstrained fit parameter.

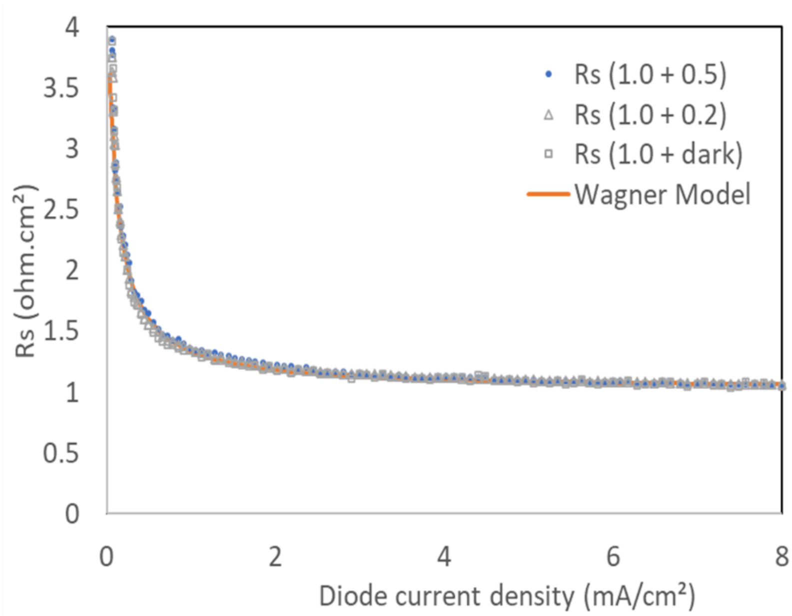

Figure 4. *Series resistance as a function of diode current measured using the two-light level method, for several combinations of light intensity, together with a fit to Wagner's LR-Rs model [4].*

This experiment was repeated for a variety of TOPCon, heterojunction, and PERC cells. All showed the same hyperbolic behaviour of Rs as a function of diode current.

Lateral current flow is not the only potential cause of voltage-dependent series resistance. For example, bulk resistance modulation may be present, or the contact resistance could be voltage dependent. Such effects can be expected to cause departure from strictly hyperbolic behaviour. However, the excellent match with Wagner's model shows that distributed current flow is the dominant cause of non-constant series-resistance in typical commercial cells.

3. Application

Given IV curves at two light intensities, repeated application of the "two irradiance level" method yields Rs as a function of the diode current. Pathological cells show some departure from the pure hyperbolic behaviour predicted by the LR-Rs model, but nonetheless Rs asymptotically approaches a constant minimum value as diode current increases. If we denote this value as *Rs_nondist*, the Rs at the one-sun maximum power point as *Rs_mpp*, and define *Rs_dist* = *Rs_mpp* – *Rs_nondist*, we have split the series resistance into two independent components. This has an immediate benefit for cell manufacturing.

The method was applied to a batch of cells produced during the commissioning phase of a heterojunction production line (Fig 5). These cells suffered from poor series resistance, with high variability. From the Rs_mpp values, it is unclear which process was responsible for the problem. However, when the series resistance is split into Rs_dist and Rs_nondist, it becomes obvious that the non-distributed resistance is low and not causing much of the variance. This indicates that the bulk resistivity is under control, and the metallisation steps are performing adequately. However, the distributed component of Rs is extremely high, and with very high variance. This indicates that the problem lies with the transparent conducting oxide layer.

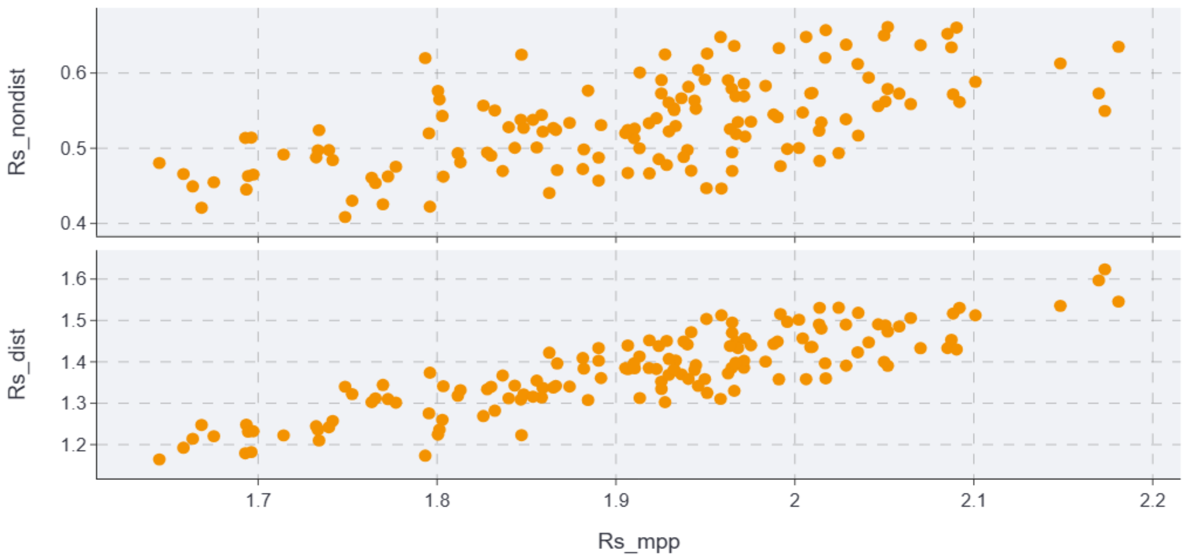

Figure 5. *Series resistance at the maximum power point (Rs_mpp) split into distributed (Rs_dist) and non-distributed (Rs_nondist) components, for a batch of heterojunction cells.*

4. Conclusions

We have provided experimental confirmation of the linear-response series resistance model of Wagner. The series resistance of a photovoltaic cell is the sum of two independent components: the resistance encountered by lateral current flow through the emitter, and the homogenous resistance due to busbars, metal resistance, and bulk resistance. The lateral resistance is an approximately hyperbolic function of the diode current. The success of this mathematically simple model allows the two components of Rs to be separated by an improved analysis of existing IV curves. It is available for all cell and module IV testers manufactured by WAVELABS. The model also provides a fit quality parameter, which can be used to identify pathological cases, in which other voltage-dependent series resistance effects are present. The analysis has been shown to be immediately useful during the ramp-up phase of a new production line.

Data availability statement

The production line data is from a third party and access is restricted. IV curve data is available from the authors.

Author contributions

Don Clugston – conceptualization, software, writing. Bernhard Klöter – software, review, editing, analysis of production data.

Competing interests

The authors declare that they have no competing interests.

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