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A new method of determination of series and shunt resistances of silicon solar cells

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Abstract

A new method of measurement of series resistance R_s and shunt resistance R_{sh} of a silicon solar cell is presented. The method is based on the single exponential model and utilizes the steady state illuminated I–V characteristics in third and fourth quadrants and the V_{oc}–I_{sc} characteristics of the cell. It enables determination of values of R_{sh} and R_s with the intensity of illumination. For determination of R_s it does not require R_{sh} to be assumed infinite and realistic values of R_{sh} can be used. The method is very convenient to use and in the present study it has been applied to silicon solar cells having finite values of R_{sh}. We have found that R_{sh} is independent of intensity but the R_s decreases with both the intensity of illumination and the junction voltage.

Keywords: Silicon solar cell; Series and shunt resistances; I–V characteristics

1. Introduction

Series and shunt resistances in solar cells are parasitic parameters, which affect the illuminated I–V characteristics and efficiency of an otherwise good cell. In an n^+–p or n^+–p–p^+ silicon solar cell the series resistance (R_s) is mainly the sum of contact resistance on the front and back surfaces and the resistances of the bulk and the n^+ diffused layer on the top. The shunt resistance (R_{sh}) represents a parallel high-conductivity path across the p–n junction or the cell edges and decreases the efficiency of the cells by increasing the leakage current that lowers the maximal output power (P_m), the open-circuit voltage (V_{oc}), and the curve factor (CF) [1,2]. In presence of series resistance, a low value of shunt resistance can affect the short-circuit current density as well. R_{sh} is crucial to PV performance, especially at reduced irradiance levels. When intensity level falls, as on cloudy days or when the sun is lower in the sky, low R_{sh} becomes an increasing concern [3]. Therefore, R_s and R_{sh} both need to be recognized and understood in order to analyze cell performance. Several methods are available in the literature for the measurement of series [1,2,4,5] and shunt resistances [6,7] of a solar cell. Wolf and Rauschenbach [1] method gives the value of R_s using illuminated I–V characteristics at two close intensities. In a method by Rohtagi et al. [4], the comparison of dark forward I–V curve with the illuminated I–V curve transferred from the fourth quadrant to the first quadrant gives the value of R_s that corresponds to open-circuit point. Agarwal et al. [5] used the nonlinearity in the short-circuit current at high intensity versus light intensity for determination of the R_s of the solar cell. This method [5] cannot be used at low intensities. Another limitation of this method [5] is that it presumes R_s to be independent of the intensity of illumination, which may not be valid. All these methods [1,2,4,5] are based on single exponential model of solar cell and assume that R_{sh} is infinite, an assumption that may not be valid for the cell having low R_{sh} values [8].

In this paper we present a new method for determination of R_{sh} and R_s of a solar cell using illuminated I–V characteristics of the cell extending from fourth to third quadrant. It shows that R_{sh} is practically independent of the intensity of illumination. Unlike other methods it does not assume R_{sh} to be infinitely large and enables the

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determination of R_s as a function of junction voltage (V_j) and the intensity using the practical values of R_{sh}.

2. Theoretical analysis

The illuminated I–V characteristics of a p–n junction solar cell in fourth and third quadrants can most simply be described using single exponential model as

$$I = -I_{ph} + I_o(e^{q(V_j)/nKT} - 1) + V_j/R_{sh}, \tag{1a}$$

$$V_j = V - IR_s, \tag{1b}$$

where I_{ph} represents the photogenerated current, I_o is the reverse saturation current, V_j is the voltage developed or dropped across the junction, n is the ideality factor, k is the Boltzman constant, T is the temperature of the cell and V is the terminal voltage. In Eqs. (1a) and (1b) we note that I assumes a negative value in both the third and fourth quadrants. To derive a mathematical expression for R_s and R_{sh} it is convenient to consider all parameters including the variables I, V and V_j as positive quantities. Then for the fourth quadrant we can write

$$I_f = I_{ph} - I_o(e^{q(V_j)/nKT} - 1) - V_j/R_{sh}, \tag{2a}$$

where

$$V_j = V_f + I_f R_s \tag{2b}$$

and for the third quadrant we can write

$$I_r = I_{ph} + I_o + (V_r - I_r R_s)/R_{sh}. \tag{3}$$

Here I, V are represented by I_f, V_f in fourth quadrant and I_r, V_r in the third quadrant.

Eqs. (2a) and (2b) show that at short-circuit condition ($V_f = 0$, $I = I_{sc}$) the current I_{sc} is given by

$$I_{sc} = \frac{R_{sh}}{(R_s + R_{sh})} I_{ph}. \tag{4}$$

This shows that $I_{sc} < I_{ph}$ when R_s is not zero.

Eq. (3) can be written as

$$I_r = \frac{R_{sh} I_{ph}}{(R_s + R_{sh})} + \frac{V_r}{(R_s + R_{sh})}, \tag{5}$$

where $I_o \ll I_{ph}$.

The slope of curve (5) from the V_r axis gives $(R_s + R_{sh})^{-1}$.

Let us take

$$(R_s + R_{sh}) = P. \tag{6}$$

It may be pointed out that the first term on the RHS of Eq. (5) represents the short-circuit current, I_{sc} of the cell. A combination of Eqs. (2)–(6) eliminates the theoretical parameter I_{ph} and yields a relation for R_s as

$$R_s = \frac{nkT}{qI_f} \ln\left\{\frac{I_r P - (V_r + V_f + I_f P)}{I_o(P - R_s)}\right\} - \frac{V_f}{I_f}. \tag{7}$$

Eq. (7) can be used to determine R_s by iteration. However, if we consider $R_s \ll P$, which is generally valid for a practical solar cells, then we can obtain a simplified relation for R_s as

$$R_s = \frac{nkT}{qI_f} \ln\left\{\frac{I_r P - (V_r + V_f + I_f P)}{I_o P}\right\} - \frac{V_f}{I_f}. \tag{8}$$

For determining R_s from (7) or (8) the value of I_o and n have to be known besides P, V_f, V_r, I_f and I_r. The values of I_o and n can be determined from V_{oc}–I_{sc} characteristics of the cell where R_{sh} may be assumed equal to P since usually $R_s \ll R_{sh}$.

To correctly use Eq. (7) for calculation of R_s we first determine an approximate value of R_s using Eq. (8). Then, this value of R_s is used in Eq. (7) to determine correct value of R_s by iteration. I_f and I_r should be chosen such that

$$I_r P - (I_f P + V_r + V_f) > 0. \tag{9}$$

3. Experimental

Solar cells used in this study were based on n^+–p structure and were fabricated from ⟨100⟩ oriented, 1 Ω cm resistivity, p-type, Cz silicon wafers ($10 \times 10\,cm^2$ pseudo-square, 350 μm thick) using $POCl_3$ liquid diffusion source of phosphorous for creating an n^+–p junction on the front side. The wafers were textured in a hot NaOH solution before junction fabrication. The contacts were made by screen printing of Ag paste on the front and Ag/Al paste on the back sides of the cells followed by sintering at ~700 °C in dry air. Subsequently, an antireflection coating of PECVD Si_3N_4 was applied on the front side. First, the I–V characteristics of the cells were measured under dark reverse bias conditions, after that the illuminated I–V characteristics were measured under no bias and reverse bias conditions at different intensities of illumination. For all measurements reported in this work the illumination consisted of a simulated AM1.5 spectrum, only the intensity was varied when required. The values of I_o and n were determined using the V_{oc}–I_{sc} [9] characteristics, which does not require R_s to be known. However, it requires the value of R_{sh} which in the first case can approximately be taken as equal to P. It will become clear in the next section that approximation $R_{sh} = P$ does not introduce any significant errors because R_{sh} does not vary with the intensity of illumination and R_s is generally negligible in comparison with R_{sh}.

4. Results and discussion

The present method was applied to determine R_s and R_{sh} values of a number of silicon solar cells fabricated as described in the preceding section. However, in this section we give detailed description of the measurements and results for only one cell, viz. S_1. Fig. 1 shows $\ln(I_d)$ versus V_j curve of cell S_1 obtained from the V_{oc}–I_{sc} characteristics [9]. I_d is the ideal diode current that was determined using the relation

$$I_d = \left(I_{sc} - \frac{V_{oc}}{R_{sh}}\right) = I_o e^{q(V_{oc})/nKT}, \tag{10}$$

where $V_{oc} = V_j$.

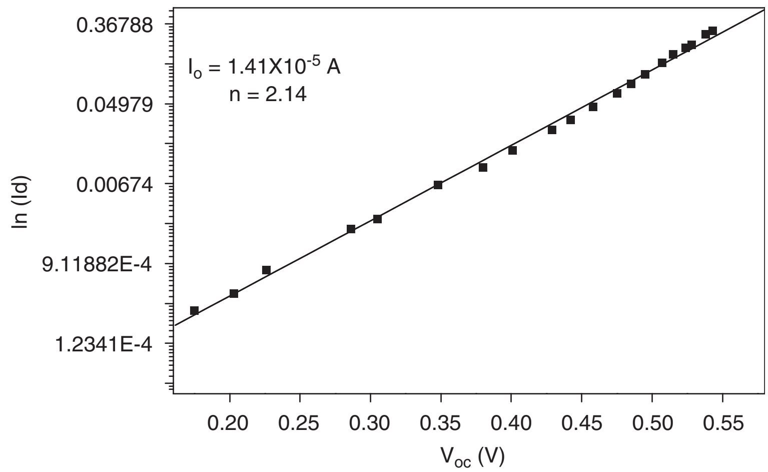

Fig. 1. $\ln(I_d)$ versus V_j curve for cell S_1 obtained from I_{sc}–V_{oc} characteristics at room temperature (25 °C).

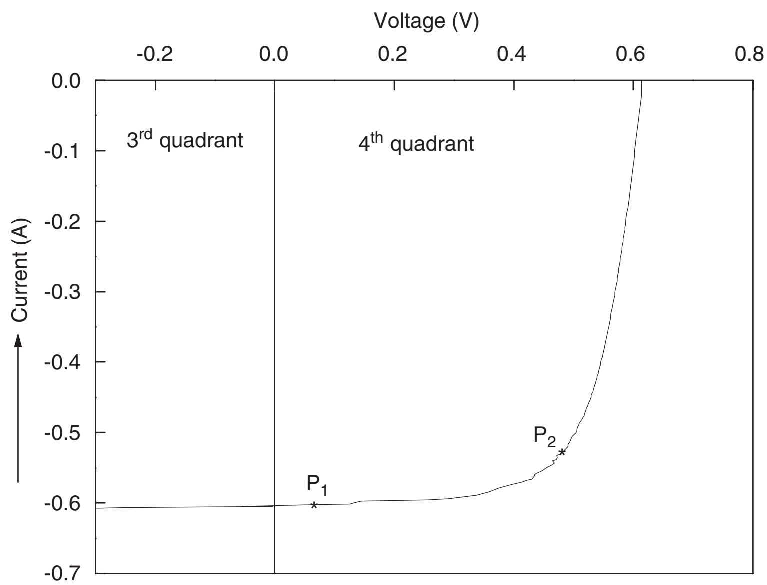

Fig. 2. I–V curves without bias (fourth quadrant) and with reverse bias (third quadrant) at room temperature (25 °C) under a simulated AM1.5 solar irradiance of 100 mW/cm^2 intensity.

Since R_{sh} was not known its value, was approximately taken as equal to P. The slope of the $\ln(I_d)$ versus V_j is equal to (q/nkT) which gives the value of n. The intercept of the curve on Y-axis gives the value of I_o. The values of I_o and n for cell S_1 were found to be $I_o = 1.41 \times 10^{-5}$ A and $n = 2.14$, respectively, when $R_{sh} = P$ was assumed.

Illuminated I–V curve for cell S_1 in third and fourth quadrants under a simulated AM 1.5 solar radiation of 100 mW/cm^2 intensity is shown in Fig. 2. Series resistance R_s was calculated near the two points, P_1 and P_2, on the illuminated I–V characteristics of fourth quadrant. P_1 is near the short-circuit point and thus corresponds to a low V_j value, whereas, P_2 is near the maximum power point and therefore corresponds to a higher V_j value. Tables 1 and 2 provide values of R_s and R_{sh} for five different intensities of illumination and the various other parameters used for the determination of R_s and R_{sh}.

The variation of R_{sh} and $(R_s + R_{sh})$ with intensity is shown in Fig. 3 and that of R_s in Fig. 4. These figures show that R_{sh} and $(R_s + R_{sh})$ are almost invariant with intensity and the values of R_s are negligibly small in comparison with R_{sh}. This shows that for determining the values of I_o and n from the V_{oc}–I_{sc} [9] characteristics of the cell the approximation that R_{sh} is nearly equal to P and does not depend on the intensity of illumination is fairly valid. However, Fig. 4 shows that the values of R_s corresponding to both near the short-circuit point P_1 and near the maximum power point P_2 decrease with intensity. Also the values of R_s are found to be smaller at P_2 than at P_1. This is because at P_2 the junction voltage was higher than at P_1. These observations are in agreement with those of Chakrabarty and Singh [10] who showed that R_s decreases with the junction voltage.

Table 1
The values of various parameters used for determination of R_s and R_{sh} near the short circuit point P_1 for five different intensities of illumination for cell S_1

Intensity (mW/cm^2)	V_f (V)	I_f (A)	I_r (A)	P (Ω)	R_s (Ω)	R_{sh} (Ω)
10	0.061	0.051	0.052	148.4	1.38	147.0
16	0.062	0.081	0.082	148.5	0.827	147.7
23	0.064	0.119	0.121	148.2	0.490	147.7
31	0.067	0.16	0.161	148.6	0.355	148.2
100	0.065	0.602	0.604	148.7	0.293	148.4

$I_o = 1.41 \times 10^{-5}$ A, $n = 2.14$, $V_r = 0.067$ V.

Table 2
The values of various parameters used for determination of R_s and R_{sh} near the maximum power point P_2 for five different intensities of illumination for cell S_1

Intensity (mW/cm^2)	V_f (V)	I_f (A)	I_r (A)	P (Ω)	R_s (Ω)	R_{sh} (Ω)
10	0.315	0.04	0.052	148.4	1.11	147.3
16	0.322	0.069	0.082	148.5	0.622	147.9
23	0.365	0.100	0.121	148.2	0.305	147.9
31	0.354	0.144	0.161	148.6	0.196	148.4
100	0.421	0.568	0.604	148.7	0.013	148.7

$I_o = 1.41 \times 10^{-5}$ A, $n = 2.14$, $V_r = 0.067$ V.
$P = R_s + R_{sh}$.

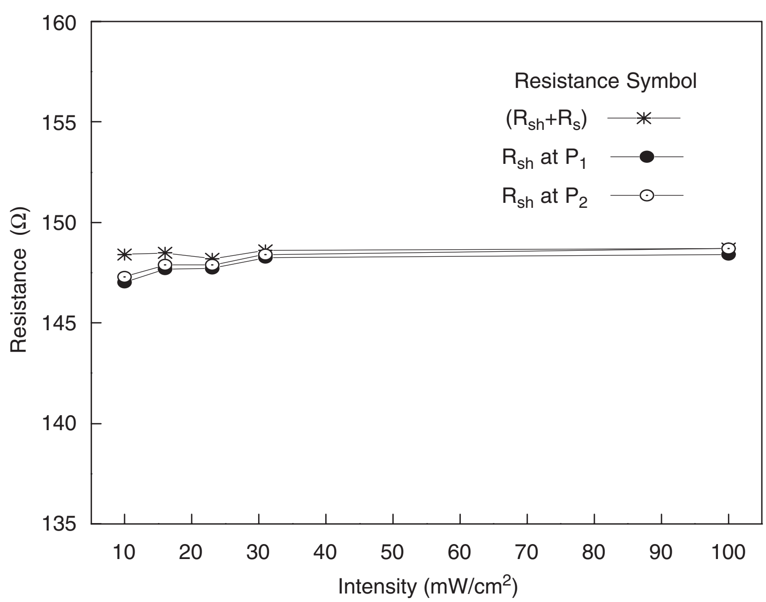

Fig. 3. Variation of ($R_s + R_{sh}$) and R_{sh} at points P_1 and P_2 with intensity, P_1 is near the short-circuit point and P_2 is the near the maximum power point.

In our method we can determine R_s with V_j very easily using various I_f, V_f values corresponding to different points between the short-circuit and open-circuit point on a single illuminated I–V characteristics. To demonstrate the effect of V_j on R_s we have determined the values of R_s using Eq. (7) for the I–V curve plotted for 100 mW/cm^2 intensity in Fig. 2. These values of R_s have been plotted against V_j in Fig. 5. The dependence of R_s on V_j shown in Fig. 5 is similar to that observed by Chakrabarty and Singh [10]. However, they had obtained the values of R_s at different V_j values by using the method of Ref. [4], which required measurements of illuminated I–V characteristics at various intensities, and then transferring each of these curves separately to the first quadrant to compare with the dark I–V characteristics of the cell. This was more time consuming and also assumed R_{sh} to be infinitely large.

It may be pointed that it is reasonable to assume $R_{sh} = P$ for determination of I_o and n values from the V_{oc}–I_{sc} characteristics in the first case since R_{sh} is not known then. However, having determined I_o and n the nearly correct values of R_{sh} and R_s can be obtained using Eqs. (6) and (7).

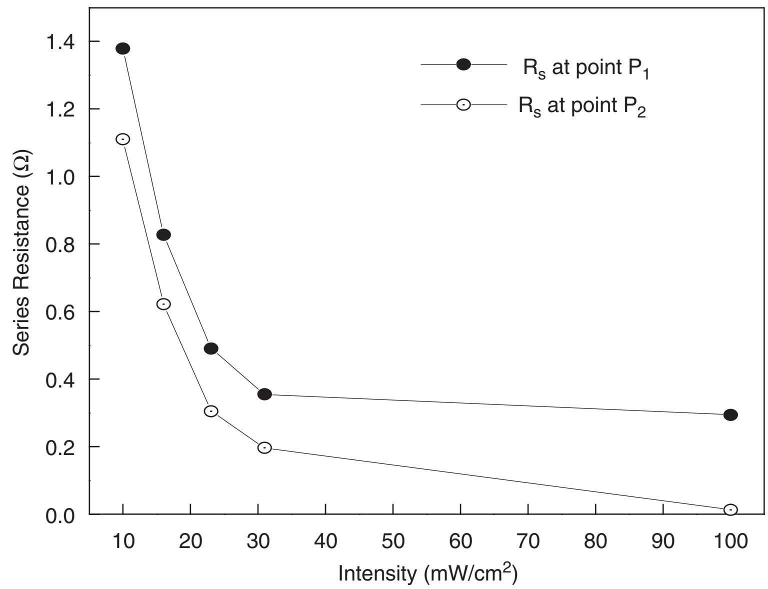

Fig. 4. Variation of series resistance (R_s) at points P_1 and P_2 with intensity, P_1 is near the short-circuit point and P_2 is the near the maximum power point.

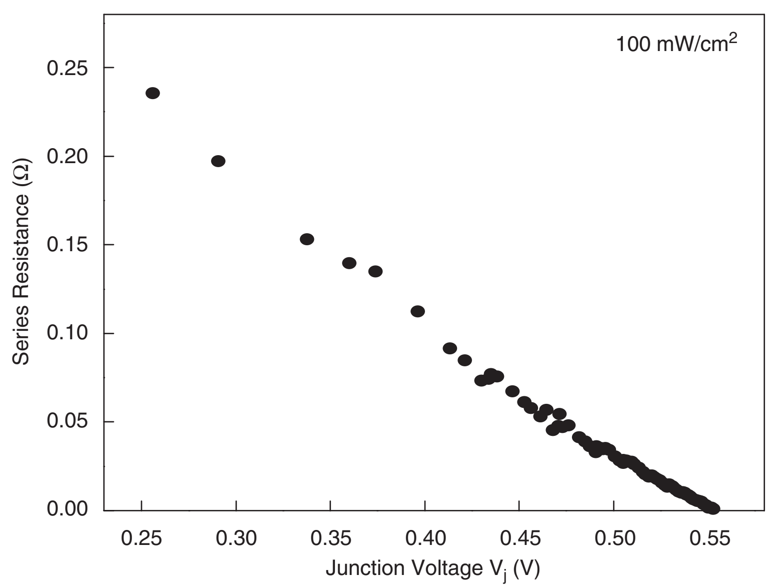

Fig. 5. Variation of R_s with the junction voltage determined from I–V characteristics of cell S_1 at room temperature (25 °C) under a simulated AM 1.5 solar irradiance of 100 mW/cm^2 intensity.

Table 3
The values of I_o, n and R_s determined with $R_{sh} = P$ approximation (when R_{sh} was unknown) and with known value of R_{sh}

Value of R_{sh} used in Eq. (10)	I_o (A)	n	R_s (Ω) at P_1	R_s (Ω) at P_2
$R_{sh} = P$	1.41×10^{-5}	2.14	0.293	0.013
$R_{sh} = P - R_s$	1.46×10^{-5}	2.17	0.295	0.019

The values of R_s correspond to 100 mW/cm^2 intensity of illumination.

For determination of R_{sh} from Eq. (6) for use in Eq. (10) the value of R_s corresponding to point P_1 should be used. This value of R_{sh} will yield more realistic values of I_o, n and R_s (at P_1 and P_2 points) than the earlier values. Table 3 compares the values of I_o, n and R_s determined for cell S_1 with $R_{sh} = P$ approximation when R_{sh} was not known with those determined after R_{sh} became known as described above. The difference in the values of I_o and n is less than 3.5% in the two cases and their effect on the value of R_s at P_1 is negligible and at P_2 is small.

5. Conclusion

A theoretical expression given in Eq. (7) has been derived to determine series and shunt resistance values of a silicon solar cell using the illuminated *I–V* characteristics of the cell in third and fourth quadrants for a given intensity. The method requires the values of the reverse saturation current I_o and the diode ideality factor n, which can be easily obtained using the V_{oc}–I_{sc} characteristics of the cell. The method shows that R_{sh} of a silicon solar cell is nearly independent of intensity of illumination but the series resistance decreases with both the intensity of illumination and the junction voltage. The method is very convenient to use and enables determination of the series resistance with the intensity of illumination and the junction voltage using the measured finite value of the shunt resistance of the cell.

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