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Analysis of series and shunt resistance in silicon solar cells using single and double exponential models

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Series and shunt resistances in solar cells are parasitic parameters, which affect the illuminated current–voltage (I–V) characteristics and efficiency of cells. Very high values of series resistance (R_s) and very low values of shunt resistance (R_{sh}) reduce short-circuit current density (J_{sc}) and open-circuit voltage (V_{oc}), respectively. In this study, the analysis of R_s and R_{sh} for silicon solar cells using single and double exponential models are described. R_s and R_{sh} for solar cells are determined from its illuminated I–V curves. The pre-exponential constants and ideality factors, I_o and n in single and I_{o1}, I_{o2} and n_1, n_2 in double exponential models are determined. Shunt resistance is nearly the same for both single and double exponential models. However, the series-resistance values are lower when calculated with double exponential model as compared with single exponential model.

1. Introduction

Series and shunt resistances in solar cells affect the illuminated current–voltage (I–V) characteristics and performance of cells. The curve factors of commercial solar cells are lower than ideal, primarily due to R_s (Wolf and Rauschenbach, 1963). The resistive losses become larger as substrate size increases. However, in both a laboratory and a production cell, the curve factor is not only limited by series resistance (R_s) but also by low shunt resistance (R_{sh}) (Bowden and Rohatgi, 2001). In an n^+–p or n^+–p–p^+ silicon solar cell, R_s is mainly the sum of contact resistance on the front and back surfaces and the ohmic resistances of the bulk and the n^+ (and p^+) diffused layers on the front (and back) sides. Shunt resistance (McIntosh and Honsberg, 2000; McMahon *et al.*, 1996) can arise from imperfections on the device surface and in the bulk as well as from leakage currents across the edge of the cell. It represents a parallel high-conductivity path across the p–n junction and decreases the efficiency of the cells by increasing the leakage current that lowers the maximum output power (P_m), the open-circuit voltage (V_{oc}), and the curve factor (CF) (McIntosh and Honsberg, 2000; McMahon *et al.*, 1996). Very high values of R_s (Wolf and Rauschenbach, 1963) and very low values of R_{sh} (Abbott *et al.*, 2007) reduce short-circuit current density (J_{sc}) and V_{oc}, respectively. R_{sh} is crucial to photovoltaic (PV) performance, especially at reduced irradiance levels (McIntosh and Honsberg, 2000). Therefore, both R_s and R_{sh} need to be recognized and understood in order to improve the cell performance. A number of methods are available in the literature for determination of series (Swanson, Agarwal *et al.*, 1981; Singh and Singh, 1983; Aberle *et al.* 1993; Sharma *et al.* 1990; El-Adawi and Al-Nuaim, 2002; Priyanka *et al.* 2007; K. Bouzidi *et al.* 2007) and shunt (Priyanka *et al.* 2007; Schroder 1998; Breitenstein *et al.*, 2004) resistances of solar cells. The value of R_s is determined (Swanson) using illuminated I–V characteristics at two close intensities. Agarwal *et al.* (1981) used the nonlinearity in the short-circuit current (I_{sc}) at high intensity for the determination of the R_s of the solar cell. Singh and Singh (1983) developed one-curve method to calculate R_s. In a method by Aberle *et al.* (1993), the dark-forward I–V curve is compared with the illuminated I–V curve, and the series resistance is determined from the voltage shift between illuminated and dark-forward I–V curve. Sharma *et al.* (1990) have given a maximum power point method which uses the I–V characteristics under one illumination level and determines R_s. All these methods (Swanson, Agarwal *et al.*, 1981; Singh and Singh, 1983; Aberle *et al.* 1993; Sharma *et al.* 1990) assume that R_{sh} is infinite, an assumption that may not be valid for the cell having low R_{sh} values. Recently, new methods have been developed for series-resistance determination considering the shunt resistance of the cell (El-Adawi and Al-Nuaim, 2002; Priyanka *et al.* 2007; Bouzidi *et al.* 2007). Nevertheless, all these methods (Swanson, Agarwal *et al.*, 1981; Singh and Singh, 1983; Aberle *et al.* 1993; Sharma *et al.* 1990; El-Adawi and Al-Nuaim, 2002; Priyanka *et al.* 2007; K. Bouzidi *et al.* 2007) are based on single exponential model. However, in many cases, I–V characteristics of the cells are better described by a double exponential model, as it permits to take into account the recombination mechanism in the space–charge region and in the quasi-neutral regions. In one of the previous works of the authors (Priyanka *et al.* 2007), a new method was developed for the 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. Unlike other methods (Swanson, Agarwal *et al.*, 1981; Singh and Singh, 1983; Aberle *et al*. 1993; Sharma *et al*. 1990), it does not assume R_{sh} to be infinitely large and enables the determination of R_s as a function of junction voltage (V_j) using practical values of R_{sh}. The method is described in detail by Priyanka *et al*. (2007). In this study, the method proposed by Priyanka *et al*. (2007) is used for the determining R_s and R_{sh} using single and double exponential models for silicon solar cells. The corresponding diode parameters I_o, n and I_{o1}, n_1, I_{o2}, n_2 for single and double exponential models, respectively, are determined using the V_{oc}–I_{sc} characteristics (Arora, 1982).

2. Theory

The methods described in the previous section (Swanson, Agarwal *et al*., 1981; Singh and Singh, 1983; Aberle *et al*. 1993; Sharma *et al*. 1990) assume R_{sh} to be infinitely large and R_s to be invariant with junction voltage and have a limitation in that they determine R_s using a certain small region of the I–V characteristics. However, the method given by Priyanka *et al*. (2007) enables determination of R_s corresponding to different values of juction voltage and is applicable to the entire region of I–V characteristics except a small portion near the open-circuit point. In this study, the method by Priyanka *et al*. (2007) is used for calculating the values of R_s at two points P_1 and P_2 (P_1 is close to short-circuit current and P_2 is near the maximum power point in the illuminated I–V curve) from the I–V characteristics of the solar cells in the third and fourth quadrant using the relation (Priyanka *et al*. ,2007):

1. $$R_s = \frac{1}{I_f}\left(\left(\frac{nkT}{q}\right)\ln\left(\frac{I_r P - (V_r + V_f + I_f P)}{I_o (P - R_s)}\right) - V_f\right)$$

where $P = R_s + R_{sh}$, V_f, I_f represent voltage and current, respectively, in the fourth quadrant and V_r, I_r represent voltage and current, respectively, in the third quadrant of the I–V characteristics of the cell. P is the slope of the V_r–I_r curve (third quadrant). Priyanka *et al*. (2007) applied Equation 1 for calculating R_s and R_{sh} using the single exponential model. However, in this study, the method is extended to double exponential model. The values of pre-exponential constants and ideality factors, I_o and n in single and I_{o1}, I_{o2} and n_1, n_2 in double exponential model are determined using I_{sc}–V_{oc} characteristics of the cell (Arora, 1982).

Aforementioned methods (Swanson, Agarwal *et al*., 1981; Singh and Singh, 1983; Aberle *et al*. 1993; Sharma *et al*. 1990; El-Adawi and Al-Nuaim, 2002; Priyanka *et al*. 2007; K. Bouzidi *et al*. 2007) for R_s determination are based on single exponential model. However, double exponential model becomes important when taking into account the recombination mechanism in the space–charge region and in the quasi-neutral regions. I–V characteristics of a double exponential can be described using the following equations:

2a. $$I = -I_{ph} + \left[I_{o1}(e^{qV_j/n_1KT} - 1) + I_{o2}(e^{qV_j/n_2KT} - 1)\right] + V_j/R_{sh}$$

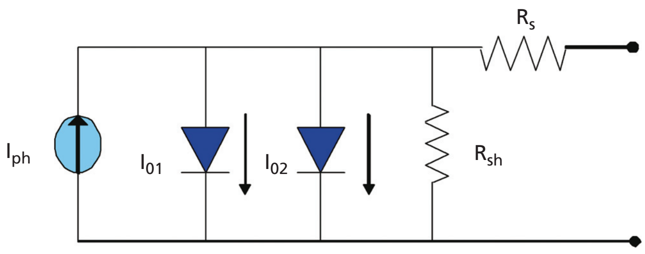

Figure 1. Schematic diagram of a solar cell described by the two-diode model

2b. $$V_j = V - IR_s$$

where I_{ph} represents the photogenerated current, V_j is the voltage developed or dropped across the junction, k is the Boltzmann constant, T is the temperature of the cell, V is the terminal voltage, I_{o1}, n_1 are the pre-exponential constant and ideality factor due to the recombination in quasi-neutral (or bulk) regions and I_{o2}, n_2 are due to the recombination in the space–charge (or the depletion) region of the cell. The schematic diagram of a solar cell for the two-diode model is prescribed in Figure 1.

3. Results and discussion

In this section, the performance parameters, open-circuit voltage, short-circuit current density CF, efficiency (η) and the determined diode parameters I_o, n, I_{o1}, n_1, I_{o2}, n_2, R_s, R_{sh} for three cells, namely Cell 1 (area ~23cm^2), Cell 2 (area ~23.6 cm^2) and Cell 3 (area ~25cm^2) are discussed using both single and double exponential models. The cells, Cell 1, Cell 2 and Cell 3 are based on n^+–p structure and are fabricated from <100> oriented, 1 Ωcm, resistivity, p-type, Cz silicon wafers. The details of the solar cell processing and the methodology of R_s determination are discussed in detail elsewhere (Priyanka *et al*., 2007). In this work, the series and shunt resistances are determined at One Sun illumination intensity using single and double exponential models. The values of I_o, n and I_{o1}, n_1, I_{o2}, n_2 were determined using the V_{oc}–I_{sc} (Arora, 1982) characteristics.

Figure 2 shows $\ln(I_d)$ versus V_j curves for three cells (Cell 1, Cell 2 and Cell 3) obtained from the V_{oc}–I_{sc} characteristics. I_d is the ideal diode current, determined for single and double exponential models using the following equations, respectively;

3a. $$I_d = \left(I_{sc} - \frac{V_{oc}}{R_{sh}}\right) = I_o e^{q(V_{oc})/nKT}$$

3b. $$I_d = \left(I_{sc} - \frac{V_{oc}}{R_{sh}}\right) = \left[I_{o1}\exp\left(qV_{oc}/n_1 kT\right) + I_{o2}\exp\left(qV_{oc}/n_2 kT\right)\right]$$

where, $V_{oc} = V_j$.

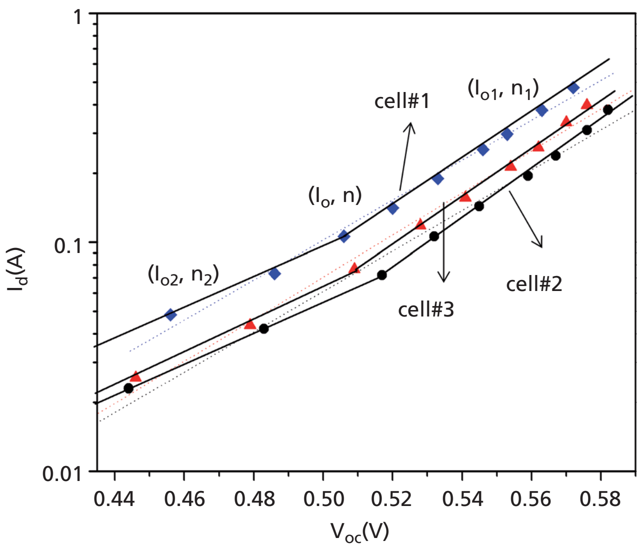

Figure 2. $\ln(I_d)$ versus V_j curve for cells (Cell 1, Cell 2 and Cell 3) obtained from I_{sc}–V_{oc} characteristics at room temperature (25°C)

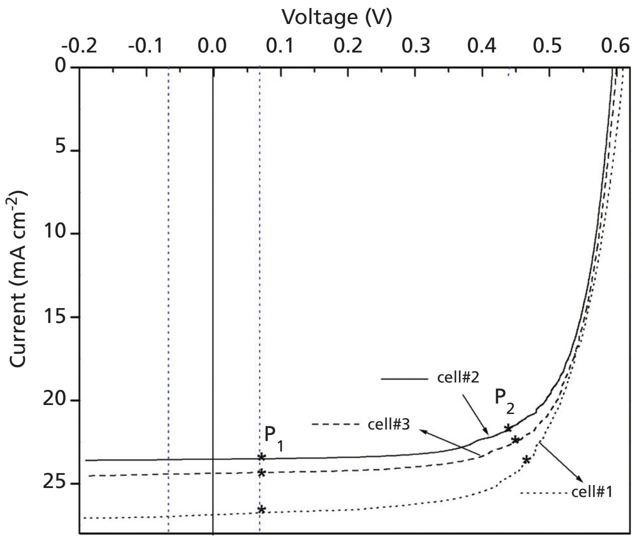

Figure 3. I–V curves without bias (fourth quadrant) and with reverse bias (third quadrant) at room temperature (25°C) under a simulated AM 1.5 solar irradiance of 100 $mWcm^{-2}$ intensity for the cells (Cell 1, Cell 2 and Cell 3)

Cell	I_o (A), n		I_{o1} (A), n_1		I_{o2} (A), n_2		P (R_{sh}+ R_s)Ω
Cell 1	2.4 x 10^{-6}	1.94	1.7 x 10^{-7}	1.55	3.9 x 10^{-5}	2.52	276.5
Cell 2	4.3 x 10^{-6}	1.96	8.3 x 10^{-7}	1.70	2.3 x 10^{-5}	2.52	452.8
Cell 3	1.7 x 10^{-6}	1.86	5.7 x 10^{-8}	1.44	1.2 x 10^{-5}	2.27	333.4

Table 1. Values of various parameters used for determination of R_s and R_{sh} near short-circuit point P_1 for three cells (Cell 1, Cell 2 and Cell 3) (V_r = 0.067V)

Cell (Area)	V_{oc} (V)	J_{sc} ($mAcm^{-2}$)	CF	η (%)
Cell 1 (23 cm^2)	0.609	26.78	0.68	11.1
Cell 2 (23.6 cm^2)	0.593	23.61	0.71	9.9
Cell 3 (25 cm^2)	0.599	24.45	0.72	10.4

Table 2. Values of performance parameters, V_{oc}, J_{sc}, CF and η for three cells (Cell 1, Cell 2 and Cell 3) measured under a simulated AM 1.5 solar irradiance of 100 $mWcm^{-2}$at room temperature (25°C)

The slope of 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. For the two exponential models, the two slopes (q/n_1kT), (q/n_2kT) and two intercepts I_{o1}, I_{o2} were determined. In Figure 2, the dotted line represents the single exponential fitting and solid lines represent the double exponential fitting. This method is independent of R_s and therefore, more reliable than dark-forward I–V characteristics method as discussed earlier (Arora, 1982). The values of I_o, I_{o1}, I_{o2} and n, n_1, n_2 are determined from single and double exponential fitting of data as shown in Figure 2. The values of diode parameters for the cells, Cell 1, Cell 2 and Cell 3 are listed in Table 1. It can be seen from Figure 2 and Table 1 that Cell 2 has higher values of I_o, n, and I_{o1}, n_1 as compared with Cell 1 and Cell 3.

The illuminated I–V characteristics (Figure 3) extends from fourth to third quadrant for the cells; Cell 1, Cell 2 and Cell 3 are measured at room temperature (25°C) under a simulated AM (air mass) 1.5 solar irradiance of 100 $mWcm^{-2}$ intensity. The values of P (R_{sh}+R_s) determined from slope of the V_r–I_r curve (third quadrant) for the cells are listed in Table 1. The performance parameters, V_{oc}, J_{sc}, CF and efficiency for the solar cells, namely Cell 1, Cell 2 and Cell 3 are listed in Table 2. It is evident from Figure 3 and Table 2 that Cell 1 has higher V_{oc} and J_{sc} values and hence higher efficiency as compared with Cell 2 and Cell 3. The solar cells Cell 1 and Cell 2 are of approximately equal area (~23 cm^2) and larger difference is in their J_{sc} values. Despite higher R_{sh} for Cell 2, higher I_o and n values might have resulted in lower V_{oc} value as compared with Cell 1 and Cell 3. The higher V_{oc}, J_{sc}, lower I_o and n values attributed to the higher efficiency of Cell 1.

The calculated values of R_s and R_{sh} at points P_1 and P_2 using single (I_o, n) and double exponential parameters (I_{o1}, I_{o2} and n_1, n_2) are

Cell		V_f (V)	I_f (A)	I_r (A)	R_s (Ω) Using I_o,n	R_s (Ω) Using I_{o2}, n_2	R_{sh} (Ω) Using I_o,n	R_{sh} (Ω) Using I_{o2}, n_2
Cell 1	P_1	0.068	0.615	0.62	0.372	0.233	276.06	276.13
	P_2	0.478	0.529	0.62	0.038	0.034	276.47	276.47
Cell 2	P_1	0.065	0.550	0.557	0.484	0.448	452.41	452.52
	P_2	0.479	0.490	0.557	0.094	0.084	452.75	452.74
Cell 3	P_1	0.067	0.608	0.610	0.359	0.271	332.98	333.04
	P_2	0.477	0.545	0.610	0.071	0.051	333.37	333.36

Table 3. Values of R_s and R_{sh} at P_1 and P_2 for three cells (Cell 1, Cell 2 and Cell 3) (V_r = 0.067V)

determined using Equation 1 and are listed in Table 3. The values I_{o1}, n_1 were used for higher junction voltages (V_j > 0.5V) and I_{o2}, n_2 were used for lower junction voltages (V_j < 0.5V). Since both points P_1 and P_2 lie at V_j < 0.5V, I_{o2}, n_2 were used to determine R_s. Using I_{o2} and n_2, lower R_s values were obtained as compared with R_s evaluated using I_o and n. As can be seen from Table 3, Cell 1 has lower R_s values as compared with Cell 2 and Cell 3 at both points P_1 and P_2. At P_1, R_s is higher as compared with P_2 because P_1 is close to 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. The values of R_s determined using the double exponential parameters I_{o2}, n_2 are lower as compared with those determined from single exponential model parameters I_o and n. The lower R_s values may be attributed to the dependence of R_s on I_o and n in Equation 1. It can be seen from Table 1 that I_{o2}, n_2 values are higher than I_o, n and hence reduce the values of R_s. Similar observation is seen for Cell 1, Cell 2 and Cell 3. Therefore, Equation 1 can be easily used for the determination of R_s considering practical values of R_{sh} for both single and double exponential models. On the other hand, the determined R_{sh} values are approximately the same for single and double exponential models. The lower V_{oc} and I_m (current at maximum power point), values in Figure 3 of Cell 2 may be attributed to higher I_o value (Table 1) and larger R_s values at points P_1 and P_2 (Table 3) as compared with Cell 1 and Cell 3.

The variation of R_s with the junction voltage determined from I–V characteristics of cells, Cell 1, Cell 2 and Cell 3 at room temperature (25°C) under a simulated AM 1.5 solar irradiance of 100 mWcm^{-2} intensity is shown in Figure 4. These R_s values are determined using double exponential parameters, I_{o2} and n_2. R_s decreases linearly with V_j; dependence of R_s on V_j is almost the same as reported in earlier studies (Chakrabarty and Singh, 1996; Priyanka *et al.*2007). Cell 1 has lower values of R_s as a function of

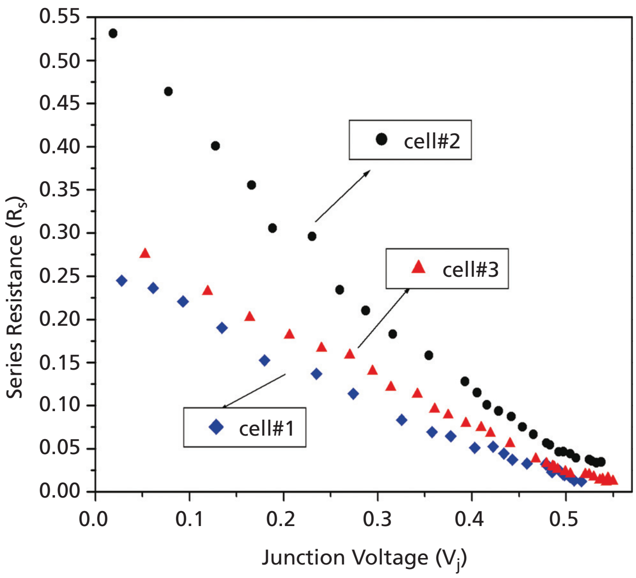

Figure 4. Variation of R_s with junction voltage determined from I–V characteristics of cells (Cell 1, Cell 2 and Cell 3) at room temperature (25°C) under a simulated AM 1.5 solar irradiance of 100 mWcm^{-2} intensity

V_j as compared with Cell 2 and Cell 3 and therefore has higher I_m as shown in Figure 3.

Figure 5 shows one experimental and three theoretical I–V curves of Cell 1 at room temperature (25°C). Three theoretical I–V curves #1, #2 and #3 are generated using the determined parameters; I_{o1}, I_{o2}, n_1, n_2 and R_{sh} for Cell 1 and compared with the experimental (Expt.) curve. Curve 1 has been obtained by considering the dependence of R_s on V_j (Figure 4) for Cell 1, whereas curves #2 and #3 correspond to two fixed values of R_s.

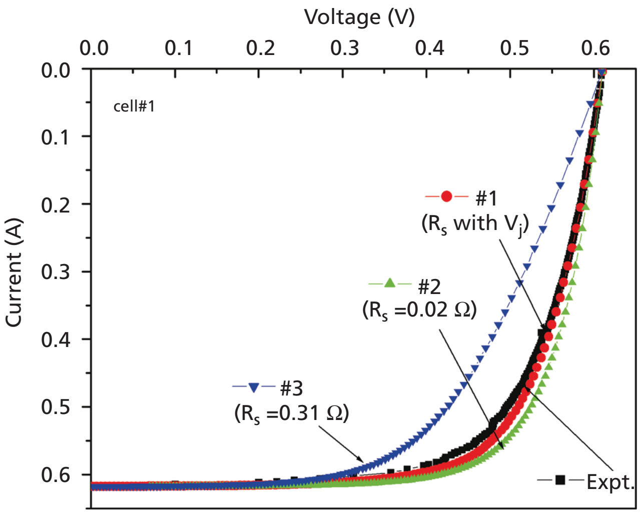

Figure 5. Experimental and theoretical illuminated I–V characteristics of solar cell (Cell 1) at room temperature (25°C)

Curves #2 and #3 are for $R_s < R_s$ at point P_2 ($R_s = 0.02\Omega$) and $R_s > R_s$ at point P_1 ($R_s = 0.31\Omega$), respectively. Curve #2 shows better I–V characteristics than the experimental curve (Expt.) whereas Curve 3 shows poor inferior I–V characteristics than the experimental curve. On the other hand, Curve 1 matches fairly well with the experimental curve. This shows that it is very important to consider the dependence of R_s on voltage in order to describe the I–V characteristics of a cell even using the two exponential model, especially near the maximum power point. The diode parameters R_s, R_{sh}, I_o and n (for single and double exponential models) are critical for the evaluation of the performance of solar cells.

4. Conclusions

Series and shunt resistances of silicon solar cells are determined using earlier published method (Priyanka *et al.*, 2007) at One Sun intensity. Pre-exponential constants and ideality factors, I_o and n in single and I_{o1}, I_{o2} and n_1, n_2 in double exponential models are determined using I_{sc}–V_{oc} characteristics of the cell. Values of series and shunt resistances are calculated using single (I_o, n) and double (I_{o1}, I_{o2} and n_1, n_2) exponential models. Shunt resistance is nearly the same for both single and double exponential models. However, the series-resistance values are lower when calculated using double exponential model as compared with single exponential model. R_s decreases linearly with the junction voltage. The earlier published method (Priyanka *et al.*, 2007) is easy to use for the determination of R_s for single and double exponential models. The diode parameters R_s, R_{sh}, I_o and n (single and double exponential models) are critical for evaluation of the performance of solar cells.

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