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A NOVEL APPROACH FOR EVALUATING THE SERIES RESISTANCE OF SOLAR CELLS

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Summary

A new method is presented to evaluate the series resistance of a solar cell. The method not only takes into account the effects of light and temperature on the series resistance, but also takes the diode junction ideality factor as an output current dependent parameter such that the values of the resistance measured are more accurate compared with previous calculations in which the diode junction ideality factor is a constant parameter along the entire output I–V curve.

1. Introduction

Several methods have been suggested for measuring the series resistance R_s of a solar cell [1 - 5]. The basis for most of these methods is the single exponential lumped constant parameter model and the assumption of a constant diode junction ideality factor along the entire output I–V curve under illuminated conditions, a constant diode junction ideality factor under different illumination condition levels, or a constant diode junction ideality factor under dark and illumination. However, it should be pointed out that the diode junction ideality factor is light intensity and temperature dependent [6, 7]. The diode junction ideality factor dependence on the output current of a solar cell under illumination should be taken into account in finding R_s.

In this paper, based on the single exponential lumped constant parameter model and the theory of diode junction ideality factor as a light intensity, temperature and output current dependent parameter, a method for evaluating the series resistance of a solar cell is sucessfully introduced. The accuracy as well as the advantages of this approach are also demonstrated.

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2. Theory

The equivalent electrical circuit of a solar cell based on the single exponential lumped constant parameters model is shown in Fig. 1. The I–V characteristic of a theoretical solar cell based on this model is given by

$$I = I_{\mathrm{ph}} - I_{\mathrm{s}}\left(\exp\left\{\frac{V + IR_{\mathrm{s}}}{nV_{\mathrm{t}}}\right\} - 1\right) - \frac{V + IR_{\mathrm{s}}}{R_{\mathrm{sh}}} \tag{1}$$

where I_{ph} is the photogenerated current, I_{s} is the diode saturation current, n is the diode junction ideality factor, R_{s} and R_{sh} are the lumped effective series resistance and shunt resistance respectively, and $V_{\mathrm{t}} = kT/q$ is the thermal voltage.

The output I–V characteristic under given test conditions (for example, AM 1.5, 100 mW cm^{-2}, 25 °C) is shown in Fig. 2. From the theoretical point of view underlying the diode behaviour, a solar cell under a given light in-

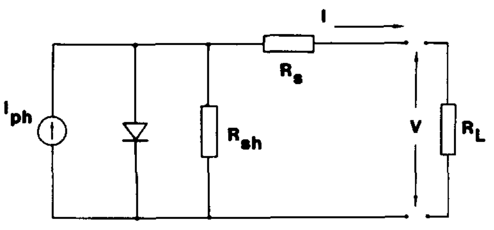

Fig. 1. The equivalent electrical circuit of a solar cell based on a single exponential lumped constant parameter model.

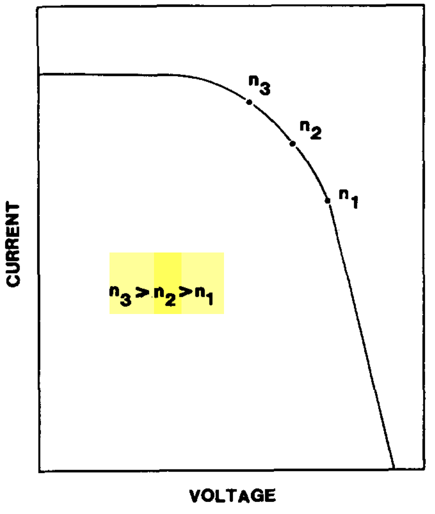

Fig. 2. The relationship between the diode junction ideality factor of a solar cell and the output current.

tensity level has a diode current dependent on the output current delivered to the load. This is easily understood from the equivalent circuit of a solar cell based on the single exponential lumped parameter model as shown in Fig. 1. Clearly, the current through the diode decreases as the output current I increases. At the open-circuit point the current is almost all passing through the diode. However, at the short-circuit point most of the current is passing through the load and there is little current passing through the diode. Theoretically, it is reasonable to assume n to be unity at the open-circuit point (high injection) and n equal to or greater than 2 at the short-circuit point (low injection).

From the above analysis, a more accurate expression for calculating the series resistance should be possible if we do not take the diode junction ideality factor as a constant parameter along the entire output I–V curve of a solar cell. If $V = V_{oc}$, $n = 1$ (high injection), from eqn. (1)

$$I_{ph} = I_s\left(\exp\frac{V_{oc}}{V_t} - 1\right) + \frac{V_{oc}}{R_{sh}} \tag{2}$$

If $I = I_{sc}$, $n = 2$ (low injection), from eqns. (1) and (2)

$$I_s\left(\exp\frac{V_{oc}}{V_t} - \exp\frac{I_{sc}R_s}{2V_t}\right) - I_{sc}\left(1 + \frac{R_s}{R_{sh}}\right) + \frac{V_{oc}}{R_{sh}} = 0 \tag{3}$$

At the maximum power point, from eqns. (1) and (2)

$$I_s\left(\exp\frac{V_{oc}}{V_t} - \exp\frac{V_m + I_mR_s}{nV_t}\right) - I_m\left(1 + \frac{R_s}{R_{sh}}\right) + \frac{V_{oc} - V_m}{R_{sh}} = 0 \tag{4}$$

If $r = 1 + R_s/R_{sh}$, and $\exp\{I_{sc}R_s/(2V_t)\} \ll \exp(V_{oc}/V_t)$, then from eqn. (3) I_s can be simplified to

$$I_s = \left(I_{sc}r - \frac{V_{oc}}{R_{sh}}\right)\left(\exp\frac{V_{oc}}{V_t}\right)^{-1} \tag{5}$$

From eqns. (4) and (5), n (at the maximum power point) can be expressed as

$$n = (V_m + I_mR_s)\left[V_{oc} + V_t \ln\left\{\frac{(I_{sc} - I_m)r - V_m/R_{sh}}{I_{sc}r - V_{oc}/R_{sh}}\right\}\right]^{-1} \tag{6}$$

For most solar cells, $R_{sh} > 10^4\ \Omega$, or theoretically, R_{sh} is infinite, so eqn. (6) can be expressed as

$$n = (V_m + I_mR_s)/\left\{V_{oc} + V_t \ln\left(\frac{I_{sc} - I_m}{I_{sc}}\right)\right\} \tag{7}$$

To obtain the series resistance R_s, the solar cell power can be expressed as $P = IV$.

At the maximum power point,

$$\left(\frac{\mathrm{d}P}{\mathrm{d}I}\right)_{\substack{I=I_{\mathrm{m}}\\ V=V_{\mathrm{m}}}} \approx 0 \tag{8}$$

that is

$$\left(\frac{\mathrm{d}V}{\mathrm{d}I}\right)_{\substack{I=I_{\mathrm{m}}\\ V=V_{\mathrm{m}}}} \approx -\frac{V_{\mathrm{m}}}{I_{\mathrm{m}}} \tag{9}$$

From eqn. (1)

$$\frac{\mathrm{d}V}{\mathrm{d}I} = -\left[R_{\mathrm{s}} + \left\{\frac{1}{nV_{\mathrm{t}}}\left(I_{\mathrm{ph}} + I_{\mathrm{s}} - I - \frac{V+IR_{\mathrm{s}}}{R_{\mathrm{sh}}} + \frac{1}{R_{\mathrm{sh}}}\right)\right\}^{-1}\right] \tag{10}$$

By combining eqns. (9) and (10)

$$\frac{V_{\mathrm{m}}}{I_{\mathrm{m}}} = R_{\mathrm{s}} + \left\{\frac{1}{nV_{\mathrm{t}}}\left(I_{\mathrm{ph}} + I_{\mathrm{s}} - I_{\mathrm{m}} - \frac{V_{\mathrm{m}}+I_{\mathrm{m}}R_{\mathrm{s}}}{R_{\mathrm{sh}}} + \frac{1}{R_{\mathrm{sh}}}\right)\right\}^{-1} \tag{11}$$

where n is the diode junction ideality factor at the maximum power point. If R_{sh} is infinite, and for most high efficiency solar cells, $I_{\mathrm{ph}} \approx I_{\mathrm{sc}}$, $I_{\mathrm{s}} < 10^{-10}$ A, thus R_{s} can be found by solving eqns. (7) and (11)

$$R_{\mathrm{s}} = \frac{V_{\mathrm{m}}}{I_{\mathrm{m}}}\,\frac{(1/V_{\mathrm{t}})(I_{\mathrm{sc}}-I_{\mathrm{m}})[V_{\mathrm{oc}} + V_{\mathrm{t}}\ln\{1-(I_{\mathrm{m}}/I_{\mathrm{sc}})\}] - I_{\mathrm{m}}}{(1/V_{\mathrm{t}})(I_{\mathrm{sc}}-I_{\mathrm{m}})[V_{\mathrm{oc}} + V_{\mathrm{t}}\ln\{1-(I_{\mathrm{m}}/I_{\mathrm{sc}})\}] + I_{\mathrm{m}}} \tag{12}$$

By using

$$i = \frac{1}{V_{\mathrm{t}}}(I_{\mathrm{sc}} - I_{\mathrm{m}})\left\{V_{\mathrm{oc}} + V_{\mathrm{t}}\ln\left(1 - \frac{I_{\mathrm{m}}}{I_{\mathrm{sc}}}\right)\right\} \tag{13}$$

the series resistance of a solar cell can be expressed as

$$R_{\mathrm{s}} = \frac{V_{\mathrm{m}}}{I_{\mathrm{m}}}\,\frac{i - I_{\mathrm{m}}}{i + I_{\mathrm{m}}} \tag{14}$$

Expressions (13) and (14) are the final forms to calculate the series resistance R_{s}. Clearly, if R_{s} can be calculated from expression (14), then based on eqns. (7) or (11), the diode junction ideality factor at the maximum power point can be calculated.

3. Experimental details

The tested samples are MINP and n^+/p silicon solar cells. The MINP cell has an area of 1.11 cm^2, and the n^+/p cell measures 1 cm × 2 cm. The sub-

TABLE 1

Calculated series resistance and diode junction ideality factor of MINP and n^+/p silicon solar cells under illuminated conditions (AM 1.5, 100 mW cm^{-2}, 25 °C)

Structure	V_{oc} (mV)	I_{sc} (mA)	V_m (mV)	I_m (mA)	R_s [a] (Ω)	n	*Area* (cm^2)
MINP	612	38.4	510	35.3	4.38	1.22	1.11
N^+/P	550	63.4	426	56.2	3.20	1.23	2.00

[a] Calculated by eqn. (14).

strate resistivity of the cells is 1 - 2 Ω cm. Aluminum is used as the front and back contact metal and single-layer silicon nitride is used as an antireflective coating. The fabrication details are shown elsewhere [8]. The characteristics of the cells were tested under illuminated conditions (AM 1.5, 100 mW cm^{-2}, 25 °C). Table 1 shows the characteristics of the cells and the calculated series resistance and diode junction ideality factor according to the theory outlined in the previous section.

4. Discussion

Because the cell series resistance and diode junction ideality factor can be easily determined from the data V_{oc}, I_{sc}, V_m and I_m, without requiring more information about the cell characteristics, R_s and n can also be determined for the cells fabricated by other researchers if they give the parameters V_{oc}, I_{sc}, V_m and I_m. Compared with other methods [9], as shown for the first two samples in Table 2, this proposed method gives more reasonable results. The assumption of a constant diode junction ideality factor along the entire $I-V$ curve is not accurate and can lead to erroneous results in calculating series resistance.

The values of the series resistance of the cells calculated according to this method are somewhat larger than those reported [11]. The method described here does not give negative values of series resistance of solar cells compared with the method suggested by Picciano [9]. In practice, if a relative value of the series resistance of a solar cell is known then the characteristics of a solar cell can be evaluated.

An additional advantage of the method proposed here is that the diode junction ideality factor at the maximum power point can be determined as long as the series resistance is obtained. The error introduced owing to the approximation of

$$\exp\frac{V_{oc}}{V_t} \gg \exp\frac{I_{sc}R_s}{2V_t} \tag{15}$$

TABLE 2

The influence of different methods on the calculated values of the cell series resistance

Cell number	V_{oc} (mV)	I_{sc} (mA)	V_m (mV)	I_m (mA)	R_s [a] (Ω)	R_s [b] (Ω)	*Reference*
1	662	550	532	500	0.391	−0.099	10
2	652	145	559	135	0.935	−0.132	11
3	606	45	400	42	2.696	3.620	12
4	612	53	430	49	2.322	2.361	12

[a] R_s is calculated according to expression (14) in the text.
[b] R_s is calculated according to the expression proposed by Picciano [9], where a constant diode junction ideality factor along entire I–V curve is assumed. The expression for R_s in ref. [9] is

$$R_s = \frac{V_m}{I_m} - \frac{2V_m - V_{oc}}{I_m + (I_{sc} - I_m)\ln\{1 - (I_m/I_{sc})\}}.$$

and neglecting the influence of $\exp(I_{sc}R_s/2V_t)$ on the calculation of I_s can be evaluated as follows. For small R_s an expansion of the exponential may be made

$$\exp\left(\frac{I_{sc}R_s}{2V_t}\right) = 1 + \frac{I_{sc}R_s}{2V_t} + \frac{1}{2}\left(\frac{I_{sc}R_s}{2V_t}\right)^2 + \ldots \tag{16}$$

If we only take two terms in eqn. (16) and assume $R_{sh} \to \infty$, I_s can be expressed as

$$I_s = I_{sc}\left(\exp\frac{V_{oc}}{V_t} - 1 - \frac{I_{sc}R_s}{2V_t}\right)^{-1} \tag{17}$$

By combining eqns. (4), (11) and (17) the following expression can be obtained

$$nV_t\left(\exp\frac{V_{oc}}{V_t} - 1 - \frac{I_{sc}R_s}{2V_t}\right) = \left(\frac{V_m}{I_m} - R_s\right)I_{sc}\exp\frac{V_m + I_mR_s}{nV_t} \tag{18}$$

$$nV_t = (V_m + I_mR_s)\bigg/\ln\left\{\left(1 - \frac{I_m}{I_{sc}}\right)\exp\frac{V_{oc}}{V_t} + \frac{I_m}{I_{sc}} + \frac{I_mR_s}{2V_t}\right\} \tag{19}$$

A more accurate solution for R_s may be obtained by including one more term in eqn. (16), I_s can be expressed as

$$I_s = I_{sc}\left\{\exp\frac{V_{oc}}{V_t} - 1 - \frac{I_{sc}R_s}{2V_t} - \frac{1}{2}\left(\frac{I_{sc}R_s}{2V_t}\right)^2\right\}^{-1} \tag{20}$$

By combining eqns. (4), (11) and (20), the following expression can be obtained

$$nV_t\left\{\exp\frac{V_{oc}}{V_t}-1-\frac{I_{sc}R_s}{2V_t}-\frac{1}{2}\left(\frac{I_{sc}R_s}{2V_t}\right)^2\right\}=\left(\frac{V_m}{I_m}-R_s\right)I_{sc}\exp\frac{V_m+I_mR_s}{nV_t} \tag{21}$$

$$nV_t=(V_m+I_mR_s)/\ln\left\{\left(1-\frac{I_m}{I_{sc}}\right)\exp\frac{V_{oc}}{V_t}+\frac{I_m}{I_{sc}}+\frac{I_mR_s}{2V_t}+\frac{I_m}{2I_{sc}}\left(\frac{I_{sc}R_s}{2V_t}\right)^2\right\} \tag{22}$$

With the help of a Newton interative method, R_s and n can be calculated from eqns. (18) and (19) or (21) and (22). The results calculated from eqns. (18) and (19) or (21) and (22) are the same as the results calculated according to eqn. (14). Since we only use simple calculation procedures based on eqn. (14), R_s can be accurately determined. It should be pointed out that $R_{sh}\to\infty$ is assumed in the calculation. Experimentally, as long as $R_{sh}>10^4$ Ω, the influence of R_{sh} on the calculated values of R_s can be neglected.

A final evaluation of this technique involved the last two samples of Table 2. In addition to R_s calculations, R_s was also experimentally determined. Dark I–V measurements gave $R_s = 1.533\ \Omega$ and $1.314\ \Omega$, respectively, for samples 3 and 4. R_s was also determined from

$$R_s=\frac{V_d-V_{oc}}{I_{sc}} \tag{23}$$

where V_d is the voltage when $I = I_{sc}$ in the dark condition [13]. These values were 1.886 Ω and 1.642 Ω, respectively, for samples 3 and 4. The formula proposed herein again gave R_s values closer to the experimental method than those obtained using previously proposed techniques.

5. Conclusion

A novel approach for evaluating the series resistance of a solar cell is presented. The main feature of this method is that the diode junction ideality factor is taken as an output current dependent parameter. The advantage of this method to evaluate series resistance is that no complicated testing steps or calculations are involved. Finally, it should be pointed out that with this method of evaluating series resistance of a solar cell, the diode junction ideality factor at the maximum power point can be determined as long as the series resistance is known.

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