A New Method for Experimental Determination of the Series Resistance of a Solar Cell

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Abstract—A new method for determining the series resistance of a solar cell from illuminated I-V measurements is presented. The method, based on the computation of the area A, under the I-V curve, evaluates R_s using the equation

$$R_s = 2\left[\frac{V_{oc}}{I_{sc}} - \frac{A}{I_{sc}^2} - \frac{mkT}{q}\frac{1}{I_{sc}}\right].$$

This technique takes advantage of the special feature of integration as a procedure to smooth data errors. The R_s obtained represents the resistive effects globally.

I. Introduction

For concentrator solar cells the ohmic losses should be kept as small as possible in order to avoid a quick dropping of the efficiency with concentration. The concept of a lumped series resistance R_s relies on an approximate and to some extent imprecise model, but provides a practical method for estimating ohmic losses and for designing concentrator solar cells. For this reason, several methods have been proposed for measuring R_s with reasonable accuracy [1]-[4].

Some of the methods imply measurements of the illuminated I-V characteristics at different illumination levels [1], while others involve dark and illumination measurements [2], as well as dynamic measurements [3], [4].

In a certain way, all these methods compute slopes for determining the value of R_s and are sensitive to the point of the characteristic considered. That is so in practice, although theoretically the methods should give a result depending neither on the functional form of the diode characteristic nor on the point of the curve where the measurement is being done. The error can be introduced by a difference in temperature between the two points considered in the measurements [5], nonhomogeneities in the illumination [6], the uncertainty in knowing the effective quality factor assumed to be known or at least constant in some dynamic methods [3], and by the distributed nature of the series resistance itself [7].

It is the purpose of this paper to propose a new method to evaluate an effective series resistance of a solar cell from I-V illumination measurements. The method takes advantage of computing areas rather than slopes, a technique that smooths experimental data error rather than enhancing the noise. A similar procedure, for fitting error functions to data, has been recently published [8].

II. Theory

The four-parameter one-exponential model for a solar cell can be written as

$$I = I_L - I_0\left(\exp\frac{V + IR_s}{mkT/q} - 1\right) \tag{1a}$$

or

$$V = \frac{mkT}{q}\ln\left(\frac{I_L + I_0 - I}{I_0}\right) - R_sI \tag{1b}$$

I_L, I_0, m, and R_s being the photocurrent, diode saturation current, diode quality factor, and lumped effective series resistance, respectively.

The total area under the curve defined by (1b) is

$$A = \int_0^{I_{sc}} V(I)\,dI = \frac{mkT}{q}\left[(I_L + I_0)\ln\frac{I_L + I_0}{I_L + I_0 - I_{sc}} + I_{sc}\ln\frac{I_L + I_0 - I_{sc}}{I_0} - I_{sc}\right] - \frac{R_sI_{sc}^2}{2} \tag{2}$$

where I_{sc} is the short-circuit current of the cell. For most practical solar cells, $I_0 \ll I_L$ and the ohmic voltage drop R_sI_{sc} are less than a few times $m\,kT/q$, therefore, the following approximations are highly and extensively accepted:

$$I_{sc} \cong I_L + I_0 \tag{3a}$$

and

$$V_{oc} \cong \frac{m\,kT}{q}\ln\frac{I_{sc}}{I_0} \tag{3b}$$

V_{oc} being the open-circuit voltage. Taking (3) into account, (2) can be written in a different way as

$$R_s = 2\left[\frac{V_{oc}}{I_{sc}} - \frac{A}{I_{sc}^2} - m\frac{kT}{q}\frac{1}{I_{sc}}\right]. \tag{4}$$

The idea of the method is now obvious. If one evaluates numerically the area A from the experimental data, that should include the measurement of V_{oc} and I_{sc}; the series resistance can be calculated by (4). The uncertainty in the value of m produces no significant effect at high enough short-circuits, due to two facts. First, for many concentrator solar cells at the illumination level required for the resistance effects to show, the emitter diffusion current is dominant along almost the entire characteristic and, therefore, m is close to unity. Second, the contribution of the third term of (4) is increasingly less as the short-circuit current increases.

III. Experimental Results

One 0.4-$\Omega \cdot$ cm 2-in diam n^+-p-p^+ concentrator solar cell designed for medium concentration and fabricated in our

Manuscript received January 12, 1982; revised April 8, 1982.
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0018-9383/82/1000-1511$00.75

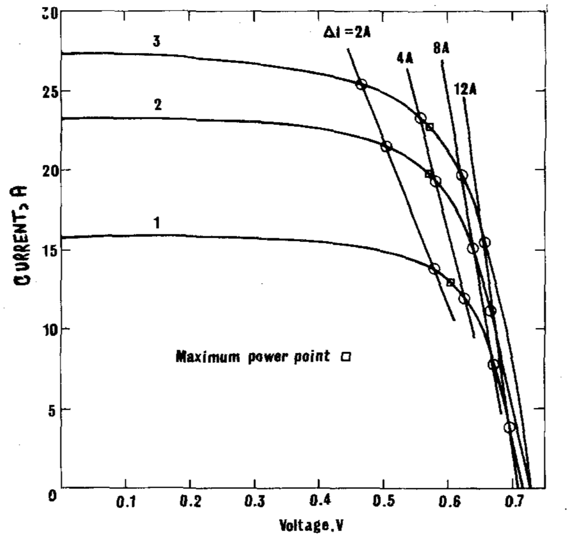

Fig. 1. Experimental I–V characteristic at three different levels of illumination. The straight lines used to evaluate the series resistance by the method of Wolf and Rauschenbach [1], are also shown.

TABLE I
SERIES RESISTANCE FROM THE METHOD OF (1), CORRECTED IN TEMPERATURE AS IN (5) AND FROM THE METHOD PROPOSED HERE

Current increment I_{sc} (A)	Series resistance R_s in milliohms		
	Method Ref. (1)	Method Ref (1) corrected in temperature	Method of this work
2	9.7	9.0	
4	6.2	5.5	
8	3.9	3.2	
12	3.4	2.7	
Around maximum power point	∿6.2	∿5.5	
Curve 1:			5.4
Curve 2:			5.5
Curve 3:			4.8

laboratory, was measured under three levels of illumination. The three I–V curves are shown in Fig. 1. During the measurements the cell was water cooled and the temperature was kept constant at 24°C.

In Table I, the values of the series resistance obtained by using the method of Wolf and Rauschenbach [1] are summarized for different values of the current increments considered. A first correction of these results was made by evaluating the thermal resistance [9] of the experimental set-up as well as the difference between the junction temperatures between the higher and lower levels of illumination. A difference of about 5°C was found hence considering a voltage variation with temperature in the order of −2 mV/°C, the new R_s values were corrected following the method of [5]:

$$\Delta R = (\partial V/\partial T)\, \Delta T_j/\Delta I_{sc} = 0.7 \text{ m}\Omega.$$

The corrected values are also shown in Table I.

As can be seen, the R_s values increase as the current increment decreases. One reason for that could be the nonuniformity of the illumination produced by the Fresnel lens used to concentrate the light. This nonuniformity was evident in the higher level case. Another reason could be the distributed nature of R_s [7]. Both effects can be seen as an apparent (and variable) added series resistance. The R_s value around the maximum power point is in the order of 5.5 mΩ (corrected value).

The area under the three curves of Fig. 1 was evaluated by taking 12–15 values from the graphic and by using the trapezoidal rule. Assuming a value of $m = 1$, the following values of R_s were calculated using (4): curve 1: $R_s = 5.4$ mΩ; curve 2: $R_s = 5.5$ mΩ; and curve 3: $R_s = 4.8$ mΩ. These values are in good agreement with those obtained by the method of Wolf and Rauschenbach [1] around the maximum power point.

IV. Conclusions

The work discussed in this paper presents a simple method for determining an effective series resistance of a solar cell from illuminated I-V measurements. The method is based on the computation of the area under the I-V curve, therefore, taking advantage of the special feature of integration as a procedure to smooth rather than to enhance data errors. The method deals only with one I-V curve, avoiding the error introduced in other methods by the differences of temperature between two different illumination I-V curves or one illumination and one dark I-V measurement. The R_s obtained by this method represents the resistive effects globally, which should be taken into account when comparing them with other methods that can allow evaluation of R_s for each point of the solar cell characteristics.

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A p-i-n Heterojunction Model for the Thin-Film $CuInSe_2$/CdS Solar Cell

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Abstract—**By treating the high-resistivity CdS and $CuInSe_2$ layers in high efficiency cells as insulating, a simple p-i-n model results that predicts the behavior seen in these cells. The relatively low open-circuit voltage and the diode factor are both directly related to the width of the insulating CdS layer. Substantial improvements in both V_{OC} and fill factor can be expected if the width of this CdS layer can be reduced.**

The demonstrated high efficiency [1] (~10 percent) of the thin-film $CuInSe_2$/Cd(Zn)S solar cell makes it a leading candidate for low-cost terrestrial power generation. The structure of the cell produces very high AMI short-circuit current (~39 mA/cm^2) but only moderate open-circuit voltage (0.4 V) and fill factor (~0.6). A model that accounts for these properties is presented here. The model predicts a strong dependence of the open-circuit voltage and diode factor on the widths of the high-resistivity regions that exist on both sides of the junction, and indicates how the efficiency of these cells may be substantially increased by the appropriate tailoring of these regions.

In Fig. 1, the structure of the high efficiency cell is illustrated. In Fig. 2, a tentative electronic band structure that results from treating the high resistivity regions as insulating, is shown. Based upon a model in which interface recombination of holes at the interface is the dominant diode current, the current-voltage relation can be written as [2], [3] (neglecting series

Manuscript received February 1, 1982; revised April 13, 1982.

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0018-9383/82/1000-1513$00.75 © 1982 IEEE