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Research

SHORT COMMUNICATION

Dark I–V Curve Measurement of Single Cells in a Photovoltaic Module

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A simple method of obtaining single cell dark I–V curves in a photovoltaic module was developed. The method does not require disassembling the module and was verified experimentally. From the dark I–V curves, the cell characteristic parameters were obtained. By following the time evolution of the characteristic parameters it is possible to determine the main degradation mechanisms and predict the mean life time of the module before failure. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: dark *I–V* curves; degradation; electrical model; photovoltaic module

INTRODUCTION

Photovoltaic energy conversion is currently one of most common ways of solar energy exploitation. The solar cell is the conversion device and a set of them connected in series, called a photovoltaic module, is the typical commercial application. Several photovoltaic module suppliers assure more than 25 years of useful life. Therefore, the prediction of mean life before failure (MLBF) is of the greatest importance in order to know the service life of each component of an electric generation facility and thus the true cost of the produced kW h.

The loss of generation efficiency, or degradation, of photovoltaic modules may be associated with different factors: (1) increase of series resistance because of contact failures;[1,2] (2) decrease of cell shunt resistances;[2,3] (3) Variation of diffusion and recombination currents.[4,5]

Degradation related to optical losses and delamination of the encapsulant polymer[1,6,7] are also important issues, but they are not discussed here. This paper presents a novel noninvasive method for dark *I–V* curve measurement of single cells arranged in a photovoltaic module. The cell characteristic parameters are obtained from the dark *I–V* curves and their effect on module degradation is discussed.

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METHOD FOR OBTAINING CELL DARK I–V CURVES

Direct I–V curve

An outstanding feature of the method for obtaining the dark *I–V* curves is that, even for individual cell measurement, it is not necessary to disassemble the module. From this individual cell dark *I–V* curves, the diode ideality factor and saturation currents may be obtained. These parameters, together with shunt resistance obtained by a two-terminal method,[8,9] allowing for the complete characterization of every cell in the module. Moreover, we think that by following their time evolution it would be possible to determine the main degradation mechanisms and predict the module mean life before failure. The method is applicable to modules with no parallel cell connections and also the bypass diodes must be removed.

In order to obtain the dark *I–V* curve of an individual cell in the module, the following steps should be followed:

1. Measure the illuminated module *I–V* curve for voltage values greater than V_{oc}. A variable power source connected in series with the module should be used. The source polarity must be opposite to the module voltage and varied to get a current intensity from 0 to about 500 mA. This part of the *I–V* curve is slightly deviated from a straight line.
2. Fit the *I–V* curve with a quadratic or cubic function and record the fitting constants. The quadratic fitting function is:

$$V = aI^2 + bI + c \tag{1}$$

   where a, b and c are constants, b being closely related to the series resistance of the illuminated module. Parameters a and b allow for the correction of the module *I–V* curve when a cell is covered, as it is discussed below.
3. Cover one of the cells in the module and measure again the *I–V* curve for voltage values greater than V_{oc}. A curve similar to that of Figure 1 is obtained.
4. Calculate the applied voltage to the cell from the following equation:

$$V_c = V - \left[\frac{(m-1)a}{m} I^2 + \frac{(m-1)b}{m} I + V_{oc}\right] \tag{2}$$

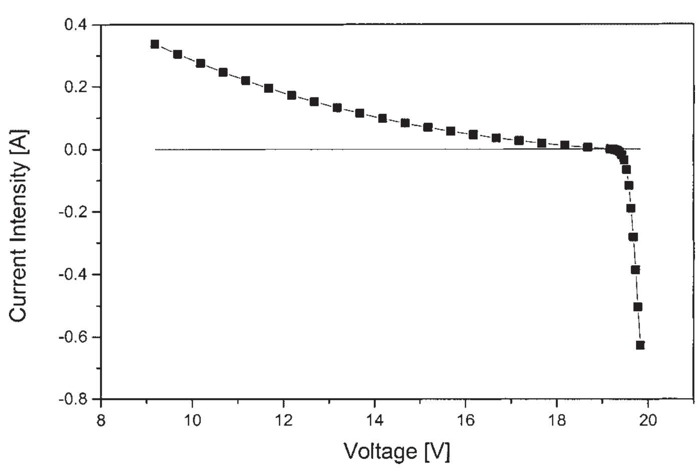

Figure 1. *I–V* curve obtained from a module with one covered cell

where V_c = cell corrected applied voltage, V = voltage measured between module terminals, V_{oc} = Voltage measured between module terminals at zero current intensity with the cell covered, m = number of cells in the module.

The term between brackets in Equation (2) corresponds to the voltage drop in the cells that are illuminated in the module, which must be subtracted from the total voltage in order to obtain the voltage drop in the covered cell. The first two terms account for the module series resistance and the observed deviation from linearity, as discussed above in points 1 and 2, and the third is the module open-circuit voltage without the contribution of the covered cell. The factor $(m-1)/m$ is introduced in Equation (2) because the active cells in the module are $m-1$ instead of m when one of them is covered. As a first approximation all the cells are considered as contributing with identical weight because the deviation from linearity in Equation (1) is small. From the calculated voltage and the measured intensity current, the dark *I–V* curves for positive voltages can be obtained.

Reverse cell dark I–V curve

This curve is obtained when the external voltage polarity is opposite to the cell diodes. In order to get the curve for a cell integrated in a module it is only necessary to completely cover the cell and measure the normal *I–V* curve of the module. The measure curve corresponds to the cell inverse curve[10] because when one of the cells is covered the voltage generated by the others inversely polarizes the non-illuminated cell. If an external voltage larger than V_{oc} of the module with one covered cell is applied, the direct section of the cell *I–V* curve is obtained (Figure 1).

EXPERIMENTAL RESULTS

Direct dark I–V curves

The measurements were performed on a solar module with 33 monocrystalline 10×10 cm silicon cells connected in series. The module nominal power is 48 W_p, I_{sc} is 3·4 A and V_{oc} 19·8 V.

The *I–V* curves, in shadow and under normal insolation, were obtained with an electronic acquisition system, which needs only 5 s to get more than 50 points. The module was kept in shadow at approximately 25°C before being exposed to the sun. The same procedure was followed in the lab, where a stationary simulator was used. The module was exposed to the light for only a few seconds, so the thermal effects on the measurements are not necessary to be considered. Flash simulators can also be used to maintain the cells close to room temperature.

In order to get an experimental validation of the proposed method, an additional (34th) 10×10 cm single-crystal silicon cell, exactly the same as those in the module, was connected in series with it and the *I–V* curves were obtained. The equivalent electrical circuit is represented in Figure 2.

In Figure 3 dark *I–V* curves for cell 34th measured with the electrical circuit of Figure 2 and calculated following Equation (2) are shown. As can be seen in Figure 3, the measured and calculated *I–V* curves are practically coincident, showing the validity of the proposed method.

A two-diode electrical model for each cell in the module was also adopted for obtaining the cell electrical parameters.[11,12] The electrical model is represented in Figure 4. The electrical current is then given by:

$$I = I_{ph} - I_{S1}\left[\exp\left(\frac{e(V+IR_s)}{n_d kT}\right) - 1\right] - I_{S2}\left[\exp\left(\frac{e(V+IR_s)}{n_r kT}\right) - 1\right] - \frac{V+IR_s}{R_{sh}} \tag{3}$$

where: I = electrical current circulating through R_s; V = cell external voltage; I_{ph} = cell photocurrent; I_{S1} = diffusion diode inverse saturation current; n_d = diffusion diode ideality factor; I_{S2} = recombination diode inverse saturation current; n_r = recombination diode ideality factor; e = electron charge $1{\cdot}60217733 \times 10^{-19}$ A; k = Boltzmann constant $k = 1{\cdot}380658 \times 10^{-23}\,\mathrm{J\,K^{-1}}$; T = absolute temperature; R_{sh} = shunt resistance; R_s = series resistance.

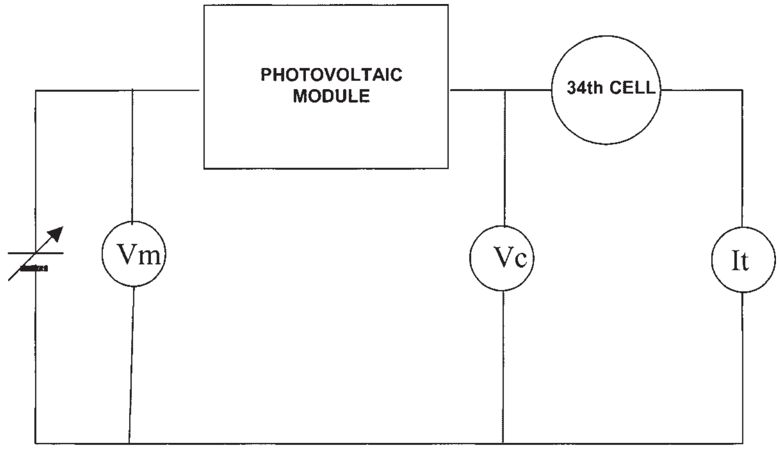

Figure 2. Electrical circuit for *I–V* curve measurement

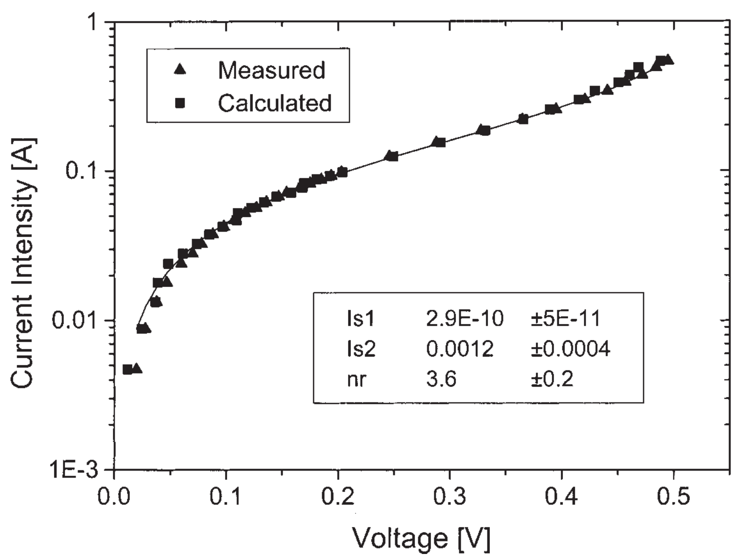

Figure 3. *I–V* curves for cell 34 in series with a PV module, as measured and calculated by using the proposed method. The fitting curve for the calculated values is also included

In Equation (3) the first term corresponds to a current source, the cell-generated photocurrent I_{ph}. The second and third terms come from the diode diffusion and recombination in the spatial charge region, the surfaces and interfaces. The additional parasitic losses due to series and shunt resistances are also included. The solid line in Figure 3 is the fitting curve for the calculated values obtained from Equation (3) with $I_{ph} = 0$. The IR_s terms were neglected because the current intensity is small (lower than 0·5A) and R_s is typically around 0·03 Ω.

In Figure 5 the *I–V* curves for two different cells in a module obtained by using the proposed method are shown. The fitting curves obtained from Equation (3) with $I_{ph} = 0$ are also included. R_{sh} values were obtained following a method described elsewhere.[9] R_{sh} values were taken as 106 and 64 Ω for cells 4 and 7, respectively.

From the fitting curves the corresponding I_{S1}, I_{S2} and n_r values were obtained. They are presented in Table I. It can be seen from the results in Table I that the cell 7 parameters show some degradation compared with those of cell 4. Also R_{sh} is lower for cell 7 and there appears to be a correlation between R_{sh} and the other cell parameters.

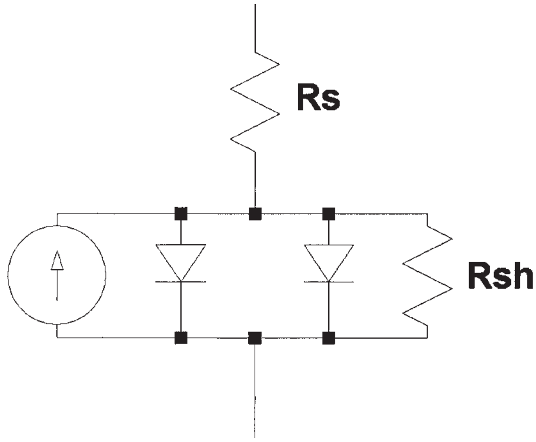

Figure 4. Solar cell electrical model

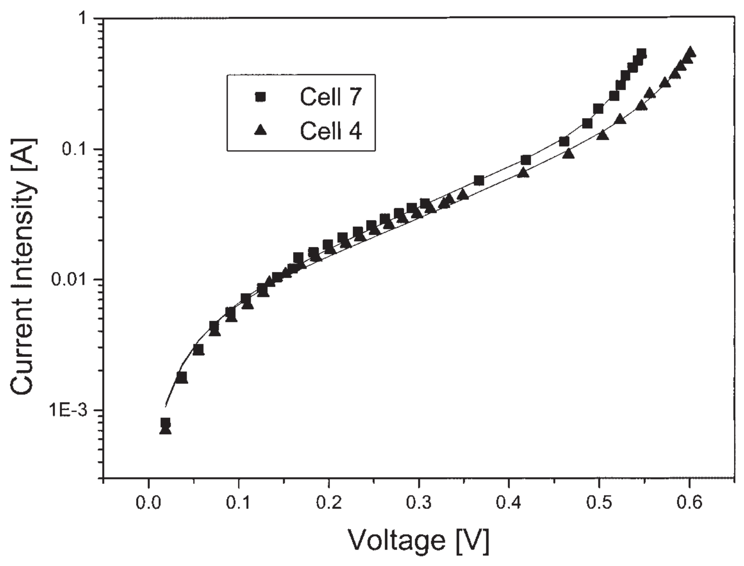

Figure 5. *I–V* curves for two different cells in a module obtained by the proposed method. The fitting curves obtained from Equation (1) are also included

Table I. Fitting parameters from the *I–V* curves of Figure 5

	Cell 4	Cell 7
I_{S1} (A)	$1{\cdot}6 \times 10^{-11}$ +/− 9×10^{-13}	$1{\cdot}9 \times 10^{-10}$ +/− 6×10^{-12}
I_{S2} (A)	8×10^{-4} +/− 2×10^{-4}	$3{\cdot}3 \times 10^{-3}$ +/− 7×10^{-4}
n_r	4·1 +/− 0·2	5·3 +/− 0·3
R_{sh} (Ω)	106	64

Reverse dark I–V curves

I–V curves for voltage values lower than V_{oc} were obtained for the module with the fully covered 34th cell connected in series. The measurements were taken for the module in the shadow and under normal insolation. The dark *I–V* curve for the single cell (34th) was also obtained. Figure 6 shows the three inverse curves. They are

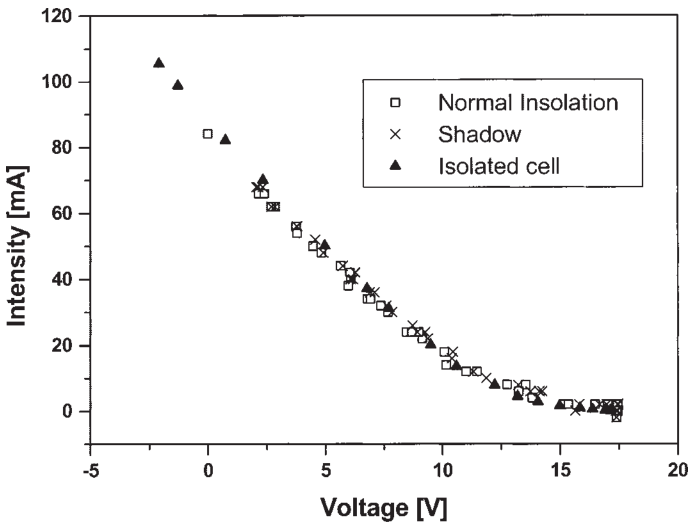

Figure 6. Curves *I–V* for cell 34 covered, in one case alone and in the other two connected in series with the module

scaled in such a way that the intensity is zero at the same voltage, in this case V_{oc} for the module exposed to normal insolation. As it can be seen the three curves are coincident, clearly showing that the inverse *I–V* curve obtained from a module with a covered cell corresponds to the inverse *I–V* curve of that cell.

The inverse diode curve may be represented by the following equation:[10]

$$I = I_{ph} - I_{S1}\left[\exp\left(\frac{e(V+IR_s)}{n_d kT}\right) - 1\right] - I_{S2}\left[\exp\left(\frac{e(V+IR_s)}{n_r kT}\right) - 1\right] - \frac{V+IR_s}{R_{sh}} - \alpha(V+IR_s)\left(1 - \frac{V+IR_s}{V_b}\right)^{-n} \quad (4)$$

The last term in Equation (4) comes from the avalanche breakdown for high negative voltage values. The new parameters in Equation (3) are: V_b = breakdown voltage, between 15 and 50 V; α-correction factor; n-avalanche breakdown exponent.

CONCLUSIONS

A simple method for obtaining dark *I–V* curves of single cells arranged in a photovoltaic module, without disassembling it, has been developed. The method was experimentally verified by connecting an additional cell in series with the module. Both *I–V* curves, calculated by using the proposed method and obtained by measuring the voltage and current intensity on the cell, are nearly coincident.

By fitting the dark *I–V* curves, the ideality factor and diode saturation currents can be obtained. These parameters, together with the shunt resistance, can be used for cell characterization and the possible degradation of the whole module can also be followed.

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