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Solar cells parameters evaluation from dark I-V characteristics

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Abstract

In this paper, a comparative analysis of three methods to determine the four solar cells parameters (the saturation current (Is), the series resistance (Rs), the ideality factor (n), and the shunt conductance (Gsh)) of the single diode lumped model from its dark curve is presented. These methods are based on Gromov, Werner, and Mikhelashviliet al. methods that were used to extract the Schottky diode parameters. These techniques have been adequately modified, extended to cover the case of solar cells and used to extract the parameters of interest from experimental I-V characteristic of a Poly-Si solar cell under dark condition.

Keywords: Extraction; silicon solar cell; series and shunt resistances; dark I–V characteristics.

1. Introduction

The I–V characteristics of solar cells measured under dark and illuminated conditions provide an important tool for the assessment of their performance. The dark characteristics are the easiest way to estimate the quality of the junction and the grid and contact resistances. The mathematical relation of the dark I–V characteristics considering the series resistance and the shunt conductance is given by the following equation:

$$\mathrm{I} = I_s\left[\exp\left(\frac{q}{nkT}\left(V - IR_s\right)\right) - 1\right] + \mathrm{G}_{\mathrm{sh}}\left(V - R_s I\right) \tag{1}$$

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Where q is the electronic charge, k is the Boltzmann constant and T is the absolute temperature. Is, n, Rs and Gsh being the diode saturation current, the diode quality factor, the series resistance and the shunt conductance, respectively.

Over the years, several methods have been suggested for extracting these parameters from the dark I-V characteristics [1, 2], and illuminated curves [3-13]. Norde [14] used a special function giving a minimum versus V and I, but this method is not valid for general cases with different conduction processes and the determination of a minimum is not very accurate. This method has been improved by Lien et al. [15]. Ortiz-Conde et al. [16] uses the integral of equation (1), whereas Kaminski et al [17] used a simulated I–V curve using the one exponential model, considering the series resistance to extract the solar cell parameters under dark conditions. Other methods have been proposed in order to extract the relevant device parameters of the Schottky-diodes and pn junctions. Gromov et al. [18] proposed a method based on the function V = f (I) of the PtSi/Si Schottky-diodes of different quality. Werner [19] used three formulas based on the current and the conductance of both Schottky diode and pn junctions. Another method based on the current–voltage (I –V) characteristics and the voltage-dependent differential slope in order to extract the relevant device parameters of the nonideal Schottky barrier, p-n and p-i-n diodes, has been presented by Mikhelashvili et al. [20]. Here these methods [18, 19, and 20] have been adequately modified, extended to cover the case of solar cells, and used to extract the parameters of interest.

2. Improved methods

The problem to be solved is the evaluation of a set of four parameters (Gsh, n, Rs and Is) in order to fit a given experimental current-voltage characteristics using an analytical model described by Eq.(1).

2.1. The modified Gromov method.

This technique includes the presentation of the standard I = f (V) function as V = f (I) that provide the calculation of the solar cell parameters.

Starting from equation (1) which can be written as:

$$\mathrm{I} = I_0\left[\exp\left(\frac{q}{nkT}\left(V - IR_s\right)\right) - 1\right] + \mathrm{G_a V} \tag{2}$$

Where:

$$\begin{cases} I_0 = \dfrac{\mathrm{I_s}}{1 + G_{sh}R_s} \\ \mathrm{G_a} = \dfrac{G_{sh}}{1 + G_{sh}R_s} \end{cases} \tag{3}$$

In the low and the negative voltage region of the I-V curve the linear part dominates. We obtain from equation (2).

$$\mathrm{I} = \mathrm{G_a V} \tag{4}$$

The procedure starts with the search for the values of G_a, which it can be extracted from the equation (4) by a simple linear fit.
The calculated value of G_a gives the product (G_aV) which can be added in turn to the measured current to yield the corrected current across the solar cell and is given by

$$I_c = I - G_a V \tag{5}$$

Under forward bias and for ($V+R_sI$)>>kT the current across the device is given by

$$I_c = I_0\left[\exp\left(\frac{q}{nkT}\left(V - IR_s\right)\right)\right] \tag{6}$$

To evaluate the series resistance, the ideality factor and the diode saturation current, we use (I) instead of (V) as the independent variable in Eq. (6), we obtain

$$\mathrm{V} = -\frac{n}{\beta}\ln I_0 + \frac{n}{\beta}\ln I_c + R_s I \tag{7}$$

This expression can be presented in the common form:

$$f(I) = A + BI + C\ln I_c \tag{8}$$

The values of factors A, B, C can be obtained by means of the experimental current–voltage data array using a least-squares method. This results in the system of equations

$$\begin{cases} A\sum_{i=1}^{N} I_i^2 + B\sum_{i=1}^{N} I_i \ln I_{\mathrm{ci}} + C\sum_{i=1}^{N} I_i = \sum_{i-1}^{N} I_i V_i \\ A\sum_{i=1}^{N} I_i + B\sum_{i=1}^{N} \ln\ I_{ci} + CN = \sum_{i-1}^{N} V_i \\ A\sum_{i=1}^{N} I_i \ln I_{ci} + B\sum_{i=1}^{N} \ln^2\ I_{ci} + C\sum_{i=1}^{N} \ln I_{ci} = \sum_{i-1}^{N} V_i \ln\ I_{ci} \end{cases} \tag{9}$$

The given system can be easily solved by means of Kramer’s rule. (I_i-V_i) are the measured values of the current-voltage at the i_{th} point among N data points.
The series resistance, the ideality factor, and the current I_0 values are determined from the following equations:

$$\begin{cases} R_s = B \\ n = \beta C \\ I_0 = \exp\left(-A/B\right) \end{cases} \tag{10}$$

Substituting the obtained values of R_s and I_0, the shunt conductance and the diode saturation current values are determined from:

$$\begin{cases} G_{sh} = \dfrac{G_a}{1 - G_a R_s} \\ I_s = \dfrac{I_s}{1 - G_a R_s} \end{cases} \tag{11}$$

2.2. The simple conductance method

Werner [19] used three plots based on the conductance G=dI/dV of both Shottky diodes and pn junctions to extract the parameters of interest. The second method is modified of this method that utilizes of the derivate of equation (1).

The shunt conductance Gsh is evaluated from the reverse bias characteristic by a simple linear fit. The calculated value of Gsh gives the shunt current Ip=GshV.

Before extracting the ideality factor and series resistance, our measured current-voltage are corrected considering the value of the shunt conductance as obtained from linear fit. We obtain for (V-RsI)>>kT) the current across the diode as:

$$I_{cor} = I_s \left[\exp\left(\frac{\beta}{n} (V - IR_s) \right) \right] \tag{12}$$

The corrected conductance Gcor=dIc/dV of the diode is obtained:

$$G_{cor} = \frac{\beta}{n} I_{cor} \left[1 - R_s G_{cor} \right] \tag{13}$$

Another possibility for this equation is:

$$\frac{1}{G_{cor}} = \frac{n}{\beta I_{cor}} + R_s \tag{14}$$

Moreover;

$$\frac{1}{G_{cor}} = \frac{dV}{dI_{cor}} = \frac{1}{I_{cor}} \frac{dV}{d \ln I_{cor}} \tag{15}$$

The equation (14) takes a more convenient form as:

$$\frac{dV}{d\ln I_c} = \frac{n}{\beta} + R_s I_c \qquad (16)$$

Eq. (16) shows that a plot of $dV/d\ln I_c$ versus I_c yields a straight line with y-axis intercept β/n and slop R_s. Figure 1 represents this data for the cases of a poly -Si solar cell.

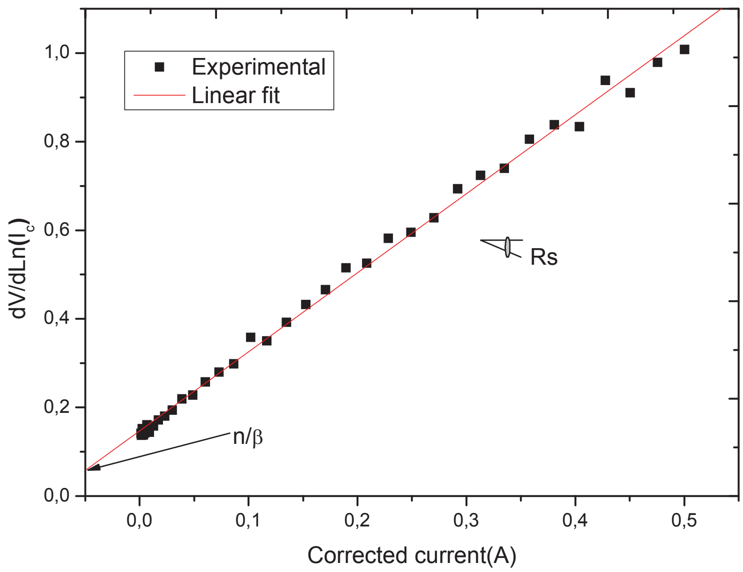

Figure 1: Experimental and fitted plot of $dV/d\ln I_c$ versus I_c for poly-Si solar cell

2.3 *The derivative* $\boldsymbol{\alpha_c}$ *method.*

The suggested technique uses the dark current–voltage (I –V) characteristics and the voltage dependent differential slope curve $\boldsymbol{\alpha_c}$ of the solar cells.

Equation (1) can be written as:

$$\mathrm{I} = G_{shr}\mathrm{V} + I_{sr}\left[\exp\left(\frac{q}{nkT}\left(V - IR_s\right)\right) - 1\right] \qquad (17)$$

Where: $$\begin{cases} I_{sr} = I_s / B \\ G_{shr} = G_{sh} / B \end{cases} \quad \text{with} \quad B=1+G_{sh}R_s \qquad (18)$$

The value of G_{shr} is extracted from the low bias voltage by a simple linear fit. Then the measured I-V characteristics are corrected using the value of G_{shr} and the current voltage relation for $(V+R_sI)>>kT$ becomes:

$$\mathrm{I_{cr}} = I_{sr}\left[\exp\left(\frac{q}{nkT}(V - IR_s)\right)\right] \tag{19}$$

To extract the series resistance, the ideality factor and the diode saturation current, expression (19) can be presented in the common form:

$$V = \frac{n}{\beta}\ln I_{cr} - \frac{n}{\beta}\ln I_{sr} + R_s I \tag{20}$$

The proposed technique makes use of the parameter (α_c) define by:

$$\alpha_c = \frac{d\ln I_c}{d\ln V} \tag{21}$$

Simple manipulation of eq. (20) using eq. (21), leads to the takes the form:

$$\alpha_c = \frac{qV}{nkT + qR_s I_c} \tag{22}$$

Figure 2 shows the plot of α_c versus V of the experimental data (poly –Si). At low bias, the α_c–V curve increases reaching a maximum α_{cm} before decreasing. For the maximum value α_{cm} of α_c corresponding to the current corrected $I_{cm,}$ and the tension V_m. these values (α_{cm}, I_{cm} and V_m) are easily found by differentiating Eq. (22) and setting ($d\alpha_{cm}/dV=0$). They are uniquely related to the physical parameters of the solar cell:

$$\begin{cases} R_s = \dfrac{V_m}{I_{cm}\alpha_{cm}^2} \\ n = \dfrac{qV_m(\alpha_{cm} - 1)}{kT\delta_m^2} \\ I_{sr} = \exp[-(\alpha_{cm} + 1)] \end{cases} \tag{23}$$

Substituting the values of R_s and I_{sr} obtained in (23), the shunt conductance, the photocurrent, and the diode saturation current values are determined from:

$$\begin{cases} G_{sh} = \dfrac{G_{shr}}{1 - G_{shr} R_s} \\ I_s = \dfrac{I_{sr}}{1 - G_{shr} R_s} \end{cases} \tag{24}$$

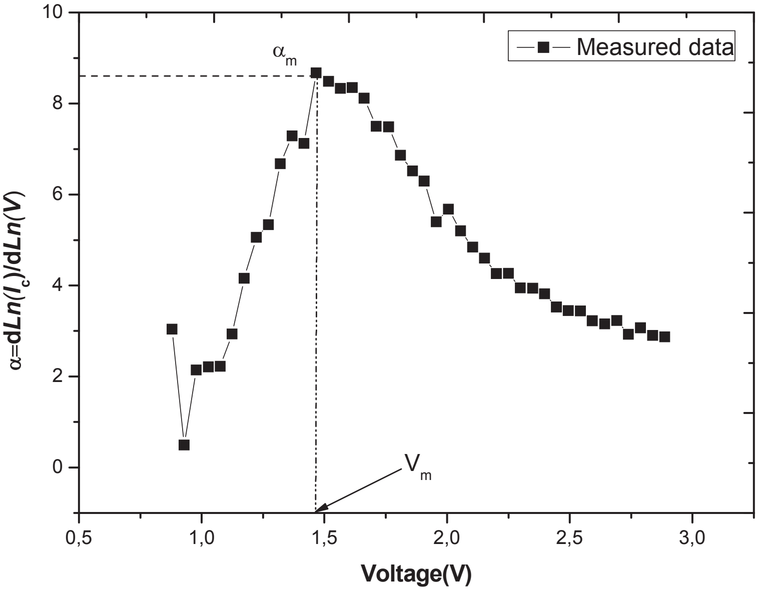

Figure 2: Experimental α_c -V characteristic of a poly silicon solar cell.

3. Comparison of the methods

We have compared the preceding methods that have been tested on the experimental I-V curve of the poly silicon solar cells (Poly-Si) at 25°C. We represent an histogram of the values of R_s,I_s,n and G_{sh} in Figure 3, found using different methods in order to simulate I-V data. One can see that the different techniques give almost similar extracted parameters.

In order to check the consistency of the curve fit obtained from eq (1) with the measured values, the root mean squared error was calculated from the following equation:

$$\sigma = \left[(1/N) \sum_{1}^{N} \left(I_{meas,i} / I_{cal,i} - 1 \right)^2 \right]^{1/2} \tag{25}$$

Where N is the total number of measured points, $I_{meas,i}$ is the measured current value and $I_{cal,i}$ is the calculated current value.

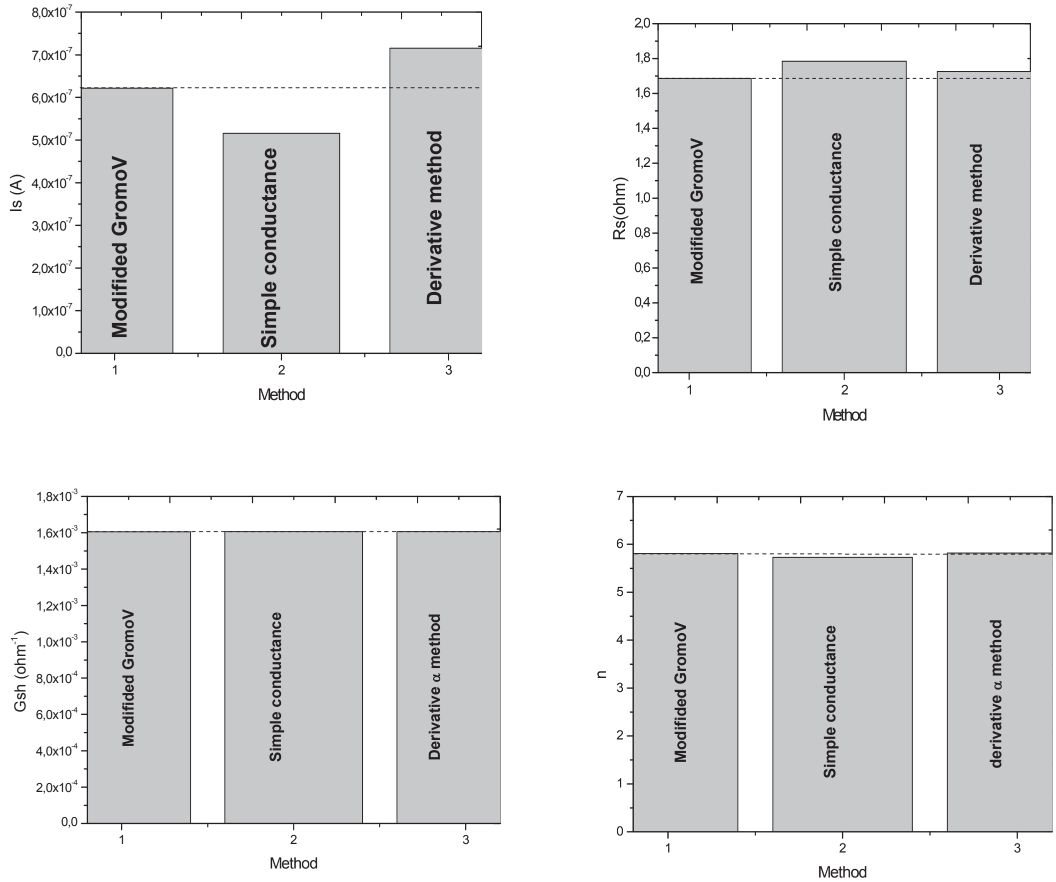

Figure 3: Extracted values of Is, R_s,n and G_{sh} using different methods.

Figure 4 show a comparison between the measured data and the fitted curves derived from (1) using the previous methods .The agreement between the obtained results is remarkable, and the root mean square error σ does not exceed 2% for all the methods. The best fits are obtained by the first method with σ less than 1% (0.7097) and (σ =0.995) for the third method, and less than 2% for the second method (σ =l.9462).

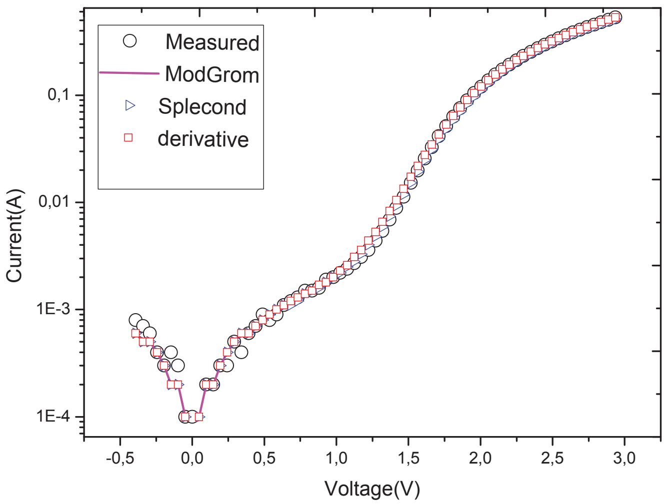

Figure 4: I-V characteristics curves for the poly silicon solar cell obtained from both the measurement and the theoretical results using the extracted parameters.

4. Conclusion

This work tests and analyses three different techniques for the determination of solar cell parameters (the series resistance R_s, the ideality factor n, the saturation current I_s, and the shunt conductance G_{sh}) from the dark experimental data. These are the modified Gromov method, the simple conductance method and the derivative $\boldsymbol{\alpha_c}$ method. The agreement between the results obtained using the different methods and the measurements is remarkable. The proposed techniques are easy, very convenient to use, straightforward, do not requires prior knowledge of any of the parameters of interest.

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