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# A Novel Analytical Approach to the Solar Cell Junction Physical Parameters Identification

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Studies are being actively conducted to improve the efficiency and performances of photovoltaic and thermo-photovoltaic systems and cells. To ameliorate designs and performances of these systems, where semiconducting junctions are generally used, it is very necessary to understand the electrical properties of these devices and conduction processes occurring across the interface of the structure. It is well known that operation and performances of photovoltaic components are strongly related to what is called dark current. Knowing the origin of this current allows improving the structure's configuration of a device, for example by adjusting the semiconducting layers thicknesses and their doping concentrations. However, solar cell models have a non-linear form with numerous parameters. To obtain accurate parameter values, assumptions that differ from real operating conditions must be made to avoid computational complexity. In this work, we proposed a new analytical approach to analyze the experimental current density-voltage of the solar cell models, and to the numerically extraction of the intrinsic solar cells parameters (i.e., the ideality coefficient and the series resistance). Our approach gives very good results. Moreover it is very simple to use and presents the advantage of being independent of the voltage step in contrary to the derivative and to the integral. We have then applied our technique to a whole solar cell current density-voltage curve and the results are very good.

**Keywords:** Photovoltaic, Single diode model, Parameter estimation, Analysis of *J-V* curves, Illumination.

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## 1. INTRODUCTION

The device's ideality coefficient has been introduced for a p-n junction solar cell after consideration of the conduction phenomenon that occurs in device. For example, value of the ideality coefficient equal 1 or 2 when the forward current is limited by diffusion mechanism or generation-recombination mechanism, respectively [1, 2]. Values of the ideality coefficient between 1 and 2 indicate that the transport mechanism is due to minority carrier's diffusion and generation-recombination processes. Values of ideality coefficient greater than 2 have been observed owing to various phenomenon including shunt resistance effects.

Another important parameter is frequently significant in *p-n* junction based devices, it is parasitic resistance also name series resistance, is originated from metal-semiconductor contact resistances to the device and from the resistances of the semiconductor regions. When this resistance is sufficiently important, it's effect can be clearly observed on forward semi-logarithmic plot of the current density-voltage characteristic and causes a deviation from linearity of this plot.

A precise determination of solar cell electrical parameters (i.e., the ideality coefficient $m$ and the series resistance $Rs$) from real current density-voltage ($J$-$V$) characteristics is of great importance for the operation control and evaluation of the performance of the device. Several recent techniques in the literature have been developed for determining the electrical parameters of a solar cell [3-10]. Certain of the proposed techniques use both dark and illuminated *J-V* characteristics [11], while others involve derivation [12] and integration procedures [13] to the measured data. Some numerical or curve fitting techniques have also been applied to extract all the diode parameters from a single *J-V* curve obtained under different illumination conditions [14]. All these methods present some problems or imperfections. Methods using derivation or integration operations on the *J-V* data suffer from numerical errors. These methods are also very sensitive to measurement's noise and fail in the presence of excess currents due to surface or bulk defects. Another important parameter which can influence the results for the reverse saturation current density and the ideality coefficient is the applied step voltage, particularly in the case of the techniques using derivation or integration procedures.

In this work, we have developed a simple and accurate analytical approach for the extraction of solar cell single-diode model parameters. The parameter extraction method proposed in this paper uses characteristics of the diode *J-V* curve to extract the series resistance and the ideality coefficient from the measured *J-V* curve of the solar cell. Our method, based on an external resistance, connected in series to the device under analysis. This method gives many values of series resistance at different points on the *J-V* curve. In this case the value of $Rs$ varies with the voltage applied across the p-n junction of the solar cells. Our analytical method is not sensitive to the applied step voltage and do not use any derivation or integration scheme.

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## 2. THEORY AND APPLICATION

The *J-V* characteristic of the solar cell can be presented by either a two diode model or by a single diode model. Under illumination and non stressed operating conditions, the single diode model is however the most popular model for solar cells. At a given illumination, the current density-voltage relation for a solar cell is given by [15-18]:

$$J = J_{ph} - J_S \left[ e^{\left(\frac{\beta}{m}(V+R_S J)\right)} - 1 \right] - G_p \left( V + R_S J \right), \quad (1)$$

where *V* is the voltage developed or dropped across the junction, *J* is the current density, $J_{ph}$ is the photo-generated current density, *Js* is the reverse saturation current density, *m* is the ideality coefficient, $G_p$ is the parallel conductance, *Rs* is the series resistance. Thermal voltage $\beta = q/kT$, where q is the electron charge, *k* is the Boltzmann and *T* is the absolute temperature in Kelvin and can be calculated by 273.15 plus the cell temperature in Celsius. The reverse saturation current density *Js* depends on the transport mechanism across the solar cell. The *Js* is given by the expression:

$$J_S = AA^{**} T^2 e^{\left(-\frac{q\Phi}{kT}\right)} . \quad (2)$$

Here *A* is the effective area, $A^{**}$ is the Richardson constant, and *Φ* is the Schottky barrier height of the diode.

The model considered here is useful because of the presence of five parameter having different origins. The analysis of their values can give us very important information about the influence of some external conditions on the mechanisms giving rise to the terminal current in the cells. Technological problems in the manufacturing process of a general purpose solar cell or irradiation effects on space solar cells are well known examples.

For large negative bias voltages $- qV << kT$ with shunt resistance $R_{sh} = (1/G_p) > Rs$, which is usually true, the shunt conductance $G_p$ is evaluated from the reverse bias characteristics by a simple linear fit. The calculated value of $G_p$ gives the shunt current $J_p = G_p V$ which can be subtracted in turn from the measured current to yield the current across the solar cell. Under forward bias for $V + R_S J >> kT$ the current across the diode is given by

$$J = J_{ph} - J_S e^{\left(\frac{\beta}{m}(V+R_S J)\right)} . \quad (3)$$

As can be seen in equation (3), series resistance effect appears as departure from linearity at high voltage values. As mentioned bellow, our technique, for the determination of the series resistance and the ideality coefficient is to impose a variable parasitic resistance in series with the solar cell studied. The value of the chosen ($R_X$) is not important. It can be lower or greater than the unknown value of *Rs* because it does not affect the final result. Using these definitions, equation (3) is written as:

$$J = J_{ph} - J_S e^{\left[\frac{\beta}{m}(V+(R_S+R_X)J)\right]}, \quad (4)$$

or

$$V = \frac{m}{\beta}\log(J_{ph} - J) - \frac{m}{\beta}\log(J_S) - (R_S + R_X)J . \quad (5)$$

In our suggested method we need only two values of the additional resistances $R_1$ and $R_2$, but for more confirmation of the value of the series resistance *Rs* obtained one can take several values of $R_X$, the equation (5) given by:

$$V_i = \frac{m}{\beta}\log(J_{ph} - J_{1i}) - \frac{m}{\beta}\log(J_S) - (R_S + R_1)J_{1i} . \quad (6)$$

and

$$V_i = \frac{m}{\beta}\log(J_{ph} - J_{2i}) - \frac{m}{\beta}\log(J_S) - (R_S + R_2)J_{2i} . \quad (7)$$

By addition Eq. (6) and Eq. (7) and for another value of *Vj*, we obtain:

$$2\,(V_i - V_j) + R_1\,(J_{1i} - J_{1j}) + R_2\,(J_{2i} - J_{2j}) = \frac{m}{\beta}\log\left[\frac{(J_{ph} - J_{1i})(J_{ph} - J_{2i})}{(J_{ph} - J_{1j})(J_{ph} - J_{2j})}\right] + R_S\,(J_{1j} + J_{2j} - J_{1i} - J_{2i}) . \quad (8)$$

Eq. (8) can be written in a simpler form:

$$X = \frac{m}{\beta} Y + R_S Z . \quad (9)$$

where

$$X = 2(V_i - V_j) + R_1(J_{1i} - J_{1j}) + R_2(J_{2i} - J_{2j})$$

$$Y = \log\left[\frac{(J_{ph} - J_{1i})(J_{ph} - J_{2i})}{(J_{ph} - J_{1j})(J_{ph} - J_{2j})}\right]$$

$$Z = J_{1j} + J_{2j} - J_{1i} - J_{2i}$$

Firstly we divided the Eq. (9) by *Y* and secondly by *Z*, we defined two new quantities *X*/*Y* and *X*/*Z* as follow:

$$\frac{X}{Y} = \frac{m}{\beta} + R_S \frac{Z}{Y} . \quad (10)$$

and

$$\frac{X}{Z} = \frac{m}{\beta}\frac{Y}{Z} + R_S . \quad (11)$$

Our technique is based on the graph of the function *X*/*Y* against *Z*/*Y* and the graph of the function *X*/*Z* against *Y*/*Z*, the both functions should produce a straight lines. Using equation (10), we can obtain the series resistance *Rs* and the ideality coefficient *m*, from the slope and the intercept with the *y* axis, respectively, of the plot *X*/*Y* versus *Z*/*Y*. Again the ideality coefficient *m*, and the series resistance *Rs*, are determined from the slope and the intercept with the y axis, respectively, of the plot *X*/*Z* versus *Y*/*Z* of equation (11). The evaluation of the reverse characteristic yields a value of the parallel conductance $G_p$ by neglecting the series resistance *Rs*. The reverse saturation current density *Js* is usually computed from the simplified relationship for a diode under reverse bias.

To illustrate the principle of method proposed in this work, a schematic representation of dark current density-voltage curves, for the two additional resistors $R_1$ and $R_2$, is presented in Fig. 1. When $R_S$ is sufficiently important, it's effect $R_S$ can be clearly observed on forward semi-logarithmic plot of the *J-V* characteristic and causes a deviation from linearity of this plot [19].

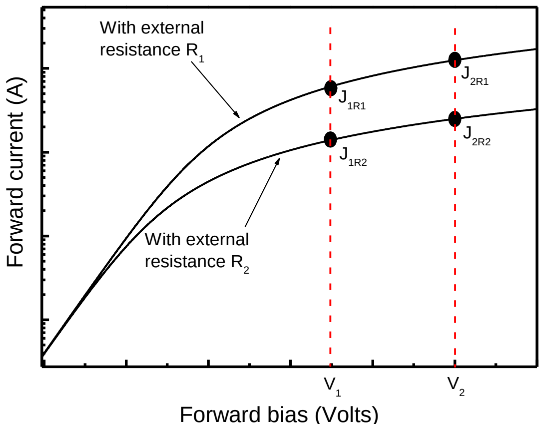

**Fig. 1** – Representation of a semi-logarithmic graph of dark *J-V* characteristic, with additional resistance $R_1$ and $R_2$

In the figure above, $J_{1R1}$ and $J_{1R2}$ are, respectively, the currents density measured at a chosen voltage $V_1$ for both additional resistance $R_1$ and $R_2$. $J_{2R1}$ and $J_{2R2}$ are those measured at $V_2$. The set of two data points ($J_{1R1}$, $J_{1R2}$) and ($J_{2R1}$, $J_{2R2}$) can be used to calculate two values for each quantity *X*/*Z* and *Y*/*Z*, as represented on Fig. 2 and Fig. 3.

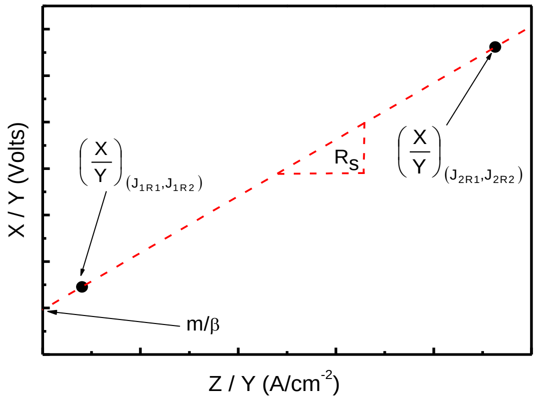

**Fig. 2** – Schematic representation of graph *X*/*Y* (Eq. 10)

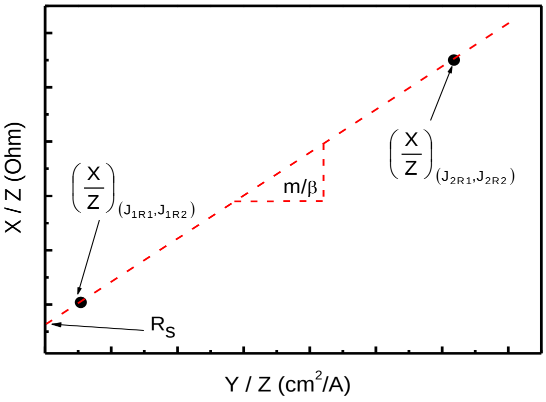

**Fig. 3** – Schematic representation of graph *X*/*Z* (Eq. 11)

## 3. RESULTS AND DISCUSSION

The validity of the proposed procedure was examined by analyzing theoretically calculated forward current density-voltage characteristics of *p-n* junction based cell using the single exponential expression of the type of equation (4) with five values of the external resistances $R_X = 0.05$, 0.10, 0.15, 0.20 and 0.25 Ω. For all the simulations the values used for reverse saturation current density, ideality coefficient, photo-generated current density and series resistance are $13.6 \times 10^{-9}$ A/cm$^{-2}$, 2.32, $7.94 \times 10^{-3}$ A/cm$^{-2}$ and 0.05 Ω, respectively. The results of the simulation are represented in Fig. 4. As mentioned in the section 2, our novel analytical approach only two value of the external resistor is needed. For the simulations and in order to test the effect of the difference between the series resistance of the solar cell and the one used as external resistor, we used different values of $R_X$.

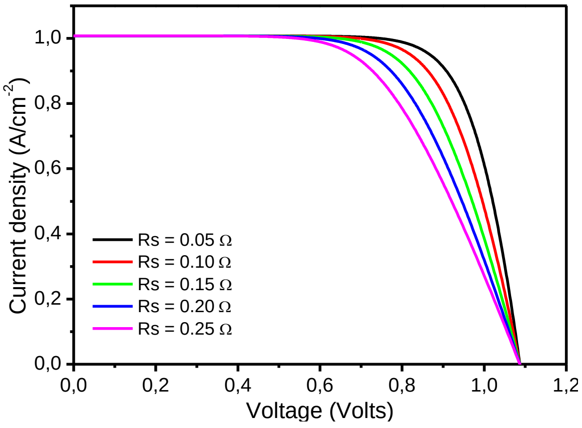

**Fig. 4** – *J-V* characteristics of a solar cell simulated by the exponential expression (4) with $J_S = 13.6 \times 10^{-9}$A/cm$^{-2}$, $m = 2.32$, $J_{ph} = 7.94 \times 10^{-3}$A/cm$^{-2}$, $Rs = 0.05$ Ω and different values of $R_X$

For all external resistors and in the forward voltage range from 0.7 volts to 1.0 volts, the corresponding curves of quantity (*X*/*Y*) as extracted by Eq. (10) is presented in Fig. 5. A mean value of series resistance equal to 0.049 ± 0.016 Ω can be extracted from its slope, and the ordinates axis intercept gives an extracted mean value of ideality coefficient equal to 2.31 ± 0.02. Alternatively, a curves of quantity (X/Z) as calculated by Eq. (11), is shown in Fig. 6. It has a slope that corresponds to a mean value of ideality coefficient equal to 2.31 ± 0.01, and an ordinates axis intercept corresponding to an extracted mean value of series resistance equal to 0.048 ± 0.016 Ω.

Table 1 regroups the values of the ideality coefficient (*m*) and series resistance (*Rs*), evaluated from the theoretical data of the Fig. 5 and Fig. 6, for different values used of additional resistor. It is clear that all the parameters evaluated with the proposed technique are very close to those used for the simulation. This situation is valid for any value of the chosen variable resistance. The choice of the value of this resistance does not matter.

To calculate the technique sensitivity to measurement error and noise, we used a simple descriptive analysis of the results corresponding to the different values of the external resistances (Table 1).

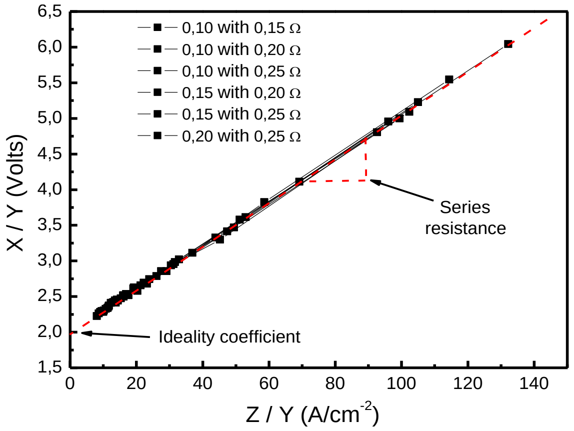

**Fig. 5** – Graph of equation (10) using simulated data of Fig. 4 for different values of external resistance: $R_X = 0.10$, 0.15, 0.20 and 0.25 Ω

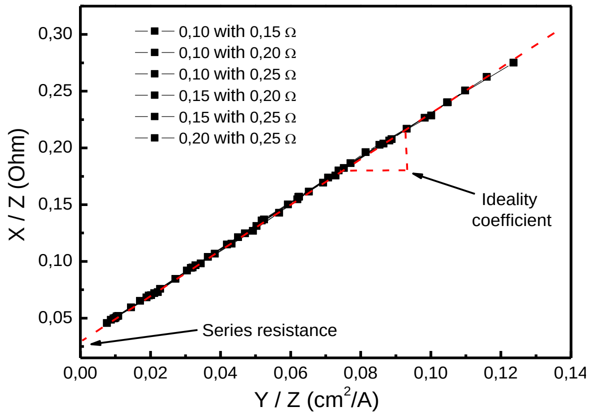

**Fig. 6** – Graph of equation (11) using simulated data of Fig. 4 for different values of external resistance: $R_X = 0.10$, 0.15, 0.20 and 0.25 Ω

Table 2 presents the resulting maximum percentile errors observed in parameters extracted under these conditions using both equations (10) and (11).

**Table 1** – Values of $m$ and $Rs$ evaluated from Fig. 5 and Fig. 6, for various additional resistor ($R_X$)

| additional resistor (Ω) | Quantity (X/Y) | | Quantity (X/Z) | |
|---|---|---|---|---|
| | ***m*** | ***Rs*(Ω)** | ***m*** | ***Rs*(Ω)** |
| $\begin{cases} R_1 = 0.10 \\ R_2 = 0.15 \end{cases}$ | 2.310 | 0.049 | 2.325 | 0.050 |
| $\begin{cases} R_1 = 0.10 \\ R_2 = 0.20 \end{cases}$ | 2.319 | 0.051 | 2.318 | 0.049 |
| $\begin{cases} R_1 = 0.10 \\ R_2 = 0.25 \end{cases}$ | 2.321 | 0.048 | 2.322 | 0.051 |
| $\begin{cases} R_1 = 0.15 \\ R_2 = 0.20 \end{cases}$ | 2.310 | 0.047 | 2.320 | 0.050 |
| $\begin{cases} R_1 = 0.15 \\ R_2 = 0.25 \end{cases}$ | 2.311 | 0.049 | 2.321 | 0.052 |
| $\begin{cases} R_1 = 0.20 \\ R_2 = 0.25 \end{cases}$ | 2.320 | 0.050 | 2.310 | 0.048 |

As can be seen from the table 2, that the largest error in the value of series resistance $Rs$ is 1.6 %, and that the largest error in the value of ideality coefficient $m$ is 2 %. Also can be seen in table 2 the sensitivity of either quantity $X/Y$ or $X/Z$ are practically the same for series resistance extracted.

**Table 2** – Mean values of the $Rs$ and $m$, obtained from data of Table 1

| | ***m*** | **Δ*m*/*m*** | ***Rs*** | **Δ*Rs*/*Rs*** |
|---|---|---|---|---|
| **Quantity (X/Y)** | 2.31 | ± 0.02 | 0.049 | ± 0.016 |
| **Quantity (X/Z)** | 2.31 | ± 0.01 | 0.048 | ± 0.016 |

## 4. CONCLUSION

To conclude, a simple analytical approach for the analysis of a forward current density-voltage characteristic measured on a semiconductor-based device is presented. As mentioned above, our method which needs only two points from the *J*-*V* characteristics was tested using several points of the *J*-*V* graph and different values of the external resistor *R*. This method, allows an accurate extraction of electrical parameters like the ideality coefficient, the series resistance and the saturation current of a solar cell device. The application of the approach to non-ideal simulated forward *J*-*V* characteristics demonstrates that it is theoretically exact.

To study the errors produced from this analytical approach, simple descriptive analysis of the results corresponding to the different values of the external resistances were used. The relative error is around 2 % for both parameters. The results indicate that this process is an accurate and easily applicable parameter extraction procedure for illuminated solar cells.

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## Новий аналітичний підхід до ідентифікації фізичних параметрів контакту сонячних елементів

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Активно проводяться дослідження для підвищення ефективності та продуктивності фотоелектричних і термофотоелектричних систем і елементів. Для покращення конструкції та характеристик таких систем, де зазвичай використовуються напівпровідникові переходи, необхідно розуміти електричні властивості цих пристроїв і процеси провідності на межу поділу структури. Відомо, що робота та характеристики фотоелектричних компонентів тісно пов’язані з так званим темновим струмом. Знання походження цього струму дозволяє покращити структурну конфігурацію пристрою, наприклад, шляхом регулювання товщини напівпровідникових шарів і концентрації їх легування. Однак моделі сонячних батарей мають нелінійну форму з численними параметрами. Для отримання точних значень параметрів, необхідно зробити припущення, які відрізняються від реальних робочих умов, щоб уникнути складності обчислень. У даній роботі ми запропонували новий аналітичний підхід до аналізу експериментальної щільності струму-напруги моделей сонячних елементів і чисельного вилучення внутрішніх параметрів сонячних елементів (тобто коефіцієнта ідеальності та послідовного опору) . Наш підхід дає хороші результати, він простий у використанні та має перевагу незалежності від кроку напруги на відміну від похідної та інтеграла. Також нами була застосована дана методика до цілої кривої густина струму-напруга сонячного елемента, і отримані хороші результати.

**Ключові слова:** Фотовольтаїка, Однодіодна модель, Оцінка параметрів, Аналіз кривих *J*-*V*, Освітлення.