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Two methods for extracting the parameters of a non-ideal diode

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We describe two methods of extracting physical parameters of a non ideal p-n diodes. These include the ideality factor, saturation current and series resistance. The proposed techniques that treat extraction parameters, using the current-voltage characteristic (I,V) forward biased. The first method is to learn three different points of the curve, with the coordinates of these points, one can generate a system of nonlinear equations expressing the electrical parameters. The resolution of these non-linear equations was performed by the numerical method of Newton-Raphson. The second is based on the least squares method. Both methods are tested using programs developed in Matlab code based on the experimental characteristic (I-V) of two different diodes in silicon.

Key words: Diode characteristic, electrical parameters, w-function Lambert, equations of non-linear system, method of least squares.

INTRODUCTION

Photovoltaic (PV) cells are the elementary components of a PV generator and their electrical properties are exhibited nonlinear in light of recent research results (Masoum et al., 2002). A commercial PV module is composed of a series of PV cells connected electrically. In view of the fact that the power generated by PV modules is heavily dependent on a number of atmospheric conditions (e.g. temperature and solar irradiance), the efficiency of energy conversion has drawn the most attention in PV system design (Hussein et al., 1995; Chun and Kwasinski, 2011; Kumar and Panchal, 2013). The solar cell behavior under illumination is interpreted by several models; whose the equivalent electrical circuit based on single diode is the most widely used (Kumar and Panchal, 2013; Fathabadi, 2013; Rajasekar et al., 2013). Although the one-diode model is considered accurate, it is often times elaborated in order to follow the behavior of solar cells more adequately. Ben-Oretal and Appelbaum (2013) extended the set of conventional parameters in the one-diode model, to

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include 8 parameters instead of 5. By adding to the model α; V_{br} and m – the cell's correction coefficient, break down voltage and exponent-power, respectively, the model was extended to cover the cell's negative-voltage operation mode, the extraction of the parameters of the single-diode solar cell model from experimental I-V characteristics of Si and Multi-junction solar cells by Appelbaum and Peled (2014). The current-voltage relationship of a diode is non-linear. The nonlinearity complicates the resolution of electrical circuits (rectifying the alternating current limiting circuit etc.). Despite this, the current-voltage (*I-V*) biased can serve as a basis for the extraction of physical parameters of ideality factor (η), series resistance (R_s) and saturation current (I_s) the knowledge precisely of these parameters allows us to understand and explain some electrical phenomena in these junctions (Mott, 1990; Sertap et al., 2010; Alivisatos, 1996). The parameters extraction requires the device and method for data analysis. A large number of published techniques (Ferhat-Hamida et al., 2002; Ortiz-Conde and García Sánchez, 2005; Zhou et al., 2009; Ranuárez et al., 2000; Lien et al., 1984; Sato and Yasumura, 1985; Cheung and Cheung, 1986; Lugo et al., 2010) describe solutions to this problem. Each of these methods has drawbacks, either in terms of use and accuracy, or at the convergence and speed (Ortiz-Conde et al., 1999). The Lambert W-function has been used in many branches of physics, especially in fractal structures (Asgarani and Mirza, 2008). The application of physics-based mixed-mode simulations to the analysis and optimization of the reverse recovery for Si-based fast recovery diodes (FREDs) using Platinum (Pt) lifetime killing is given by Cappelluti et al. (2006).

In this work, we presented two numerical methods to study the electrical behavior (I,V) of a diode. Examination of the electrical characteristic (IV) is used to extract the main parameters that characterize it, including the saturation current, series resistance and coefficient of ideality. The first method is based on the coordinates of three distinct points of the electrical characteristic (IV), to generate a system of nonlinear equations that express the electrical parameters according to the coordinates of these points and the resolution of this system non-linear equation has been performed by the digital method of Newton-Raphson. The second method developed is articulated on the least squares algorithm. The both methods are tested on the characteristic (I-V) of two diodes 1N4005 and Motorola (Ortiz-Conde et al., 2000) based on silicon, using programs developed in Matlab code. The results are discussed on the speed plan, precision and error.

Explicit analytical solutions

The equation relating the current I to the voltage V in an ideal diode is given by:

$$I = I_S\left(\exp\left(\frac{qV}{KT}\right)-1\right) \quad (1)$$

This equation is derived from the physics of semiconductors. This simplified physical model brings up a single parameter: the saturation current I_S is a leakage current flowing through the junction regardless of the type of polarization. It is due to the phenomenon of diffusion of minority carriers into the neutral areas (holes towards the p-type region and the electrons toward the n-type region) and the phenomenon of generation of free carriers in the space charge zone, $q = 1.6\times10^{-19}$C is the electron charge, $k = 1.38\times10^{-38}$ J/K is the Boltzmann constant and T is the temperature in degrees Kelvin. A slightly more sophisticated model gives (Physics of Semiconductor Devices, 2006):

$$I = I_S\left(\exp\left(\frac{V - R_S I}{\eta V_T}\right)-1\right) \quad (2)$$

Where R_S is the series resistance, which is a parameter of major interest, the higher the value, the greater the distance from the ideal diode model. It is due to the resistance of the neutral regions of semiconductor material and making contacts ohmic semiconductor metal that can be reduced by overdoing the surface region of the semiconductor where we want to establish the ohmic contact. H is the ideality factor or quality which depends on the bias voltage. It provides information about the origin of the current flowing in the junction. It takes the value 1 if it is a diffusion mechanism. For the recombination mechanism it takes the value 2. When the two streams are similar, the factor η is a value between 1 and 2. If it takes other values, this means that other mechanisms are involved in the current transport.

Figure 1 shows the equivalent circuit for this model. It is well known that the transcendental Equation (2) cannot be solved explicitly in general *I* or *V* using common elementary functions. Therefore, it is customary to use approximate solutions explicit modeling purposes. Many of these approximate solutions have been proposed (Ortiz-Conde and Garcia Sánchez, 1992; Le Bihan, 2001) that use only the basic functions. After all, the exact explicit analytical solutions of I and V today already exist (Banwell and Jayakumar, 2000) that make use of the special function called W function Lambert of (Khalis et al., 2011), a special feature that is not expressible in terms of elementary analytic functions. W function Lambert is defined as the solution of the equation w (x) exp (w(x)) = x this function is used to solve some unsolved analytically diode. The exact analytical solution of the general equation (2) is expressed in terms of W function Lambert.

$$I = -I_S + \frac{\eta V_T}{R_S} Lambertw\left(\frac{I_S R_S}{\eta V_T}\exp\left(\frac{V + R_S I_S}{\eta V_T}\right)\right) \quad (3)$$

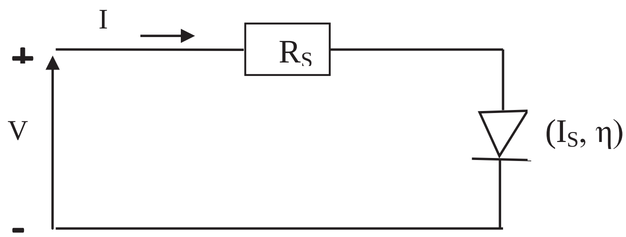

Figure 1. Equivalent circuit of a diode in a single exponential including parasitic series resistance. V_T = KT / q is the thermal voltage, *V* and *I* are the voltage and current output respectively.

METHODS

The first technique is to learn three different points of the curve, the first point to the beginning of the curve, the second just code and the third at the end. Is based on the coordinates of these points, one can generate a non-linear system of equations expressing the unknown electrical parameters (I_S, R_S and η).

To simplify the writing of nonlinear equations (4) we take: $A(1) = I_S$, $A(2) = R_S$ and $A(3) = \eta V_T$ as (V_1, I_1), (V_2, I_2) and (V_3, I_3) designate the coordinates of the three distinct points of the characteristic (I-V). While applying the Equation (2) successively to the three preceding points, one gets a system of three non linear equations therefore in three unknown A(1), A(2) and A(3):

$$\begin{cases} A(1)*(\exp((V_1\text{-}A(2)*I_1)/A(3))\text{-}1) = I_1 \\ A(1)*(\exp((V_2\text{-}A(2)*I_2)/A(3))\text{-}1) = I_2 \\ A(1)*(\exp((V_3\text{-}A(2)*I_3)/A(3))\text{-}1) = I_3 \end{cases} \quad (4)$$

To solve the system of Equations (4), we will focus on the Newton-Raphson method for solving the system of nonlinear equations. We will try to find the value A = *(A(1) A(2) A(3))*, which more or less cancel the function f = (f_1 f_2 f_3). The function f is given by Equation (5):

$$\begin{cases} f_1 = A(1)*(\exp((V_1\text{-}A(2)*I_1)/A(3))\text{-}1)\ \text{-}I_1 \\ f_2 = A(1)*(\exp((V_2\text{-}A(2)*I_2)/A(3))\text{-}1)\ \text{-}I_2 \\ f_3 = A(1)*(\exp((V_3\text{-}A(2)*I_3)/A(3))\text{-}1)\ \text{-}I_3 \end{cases} \quad (5)$$

The Newton-Raphson iterations can approach the value A by using the following algorithm:

$$A_k = A_{k-1} - \begin{bmatrix} \frac{\partial f_1}{\partial A(1)} & \frac{\partial f_1}{\partial A(2)} & \frac{\partial f_1}{\partial A(3)} \\ \frac{\partial f_2}{\partial A(1)} & \frac{\partial f_2}{\partial A(2)} & \frac{\partial f_2}{\partial A(3)} \\ \frac{\partial f_3}{\partial A(1)} & \frac{\partial f_3}{\partial A(2)} & \frac{\partial f_3}{\partial A(3)} \end{bmatrix}_{A_{k-1}} * f(A_{k-1}) \quad (6)$$

In all iterative methods, it is necessary to avoid divergence of the solution, to choose the initial value A_0. To leave not too much from one point initial x0 far from the solution.

The second method is a technique based on the least squares method (Least Mean Square LMS), this method is based on that used by S-PLUS Manual (1998) to determine the physical parameters of a solar cell. The method of least squares is one of the most widely used to model the experimental measurements by predetermined analytical function (3) methods. This method is to minimize the mean absolute or relative difference between the set of *N* measurements I_i and V_i is the result set I (V_i-p) based on the model of Equation (3). In other words, it is to minimize the following function:

$$\varepsilon = \sum_{i=1}^{N} \left(I_i - I\left(V_i, p\right)\right)^2 \quad (7)$$

Where $p = p$ (I_S, R_S, η) is the set of parameters that will minimize the error ε.

RESULTS AND DISCUSSION

To validate the two proposed methods, a test was performed on the 1N4005 diode based on silicon (Lugo et al., 2010) and Motorola (Ortiz-Conde et al., 1999). The results of the characteristic measures (I-V) are shown in Figure 2.

The values of the electronic parameters found by solving nonlinear equations by the Newton-Raphson are summarized in Table 1. Substituting the average value I_S, R_S, η in Equation (3) of the diode characteristic and using the experimental data (I_i-V_i), one obtains the Figure 2.

From Equation (5) and from the experimental data (I_i-V_i), the principle of least squares is to minimize the function (ε) by the variation of parameters p until the deviation is minimum (where zero, if the agreement is perfect). To check if the data correctly overlay to Equation (5), the unknown electric parameters (I_S, R_S and η is plotted the two corresponding curves as shown in Figure 3. Then the Matlab output function provides). The values found by the least square method are given in Table 2.

The application of our methods to two diodes different from two different companies. The results gotten by the two technical are in good agreement with those given in

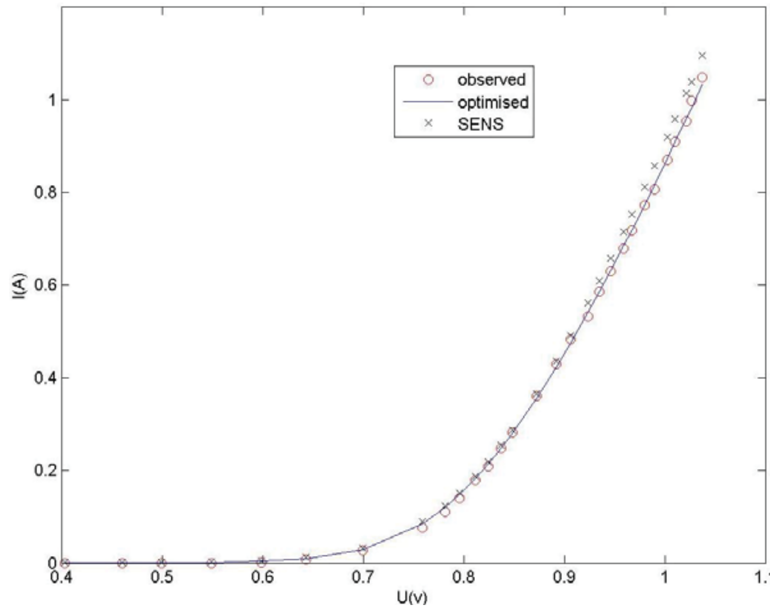

Figure 2. Comparison between the characteristic (I,V) and the method of solving the equations of nonlinear system (SENS) (Zarebski, 2007).

Table 1. Results found by the solving non-linear equations, least squares methods and Literature values for 1N4005 diode.

Parameter	Method of solving the system of nonlinear equations	Least squares method	Literature (Zarebski, 2007)
R_S (Ω)	0.14966	0.16931	0.15
I_S (nA)	31.4	11.198	4.63
Η	1.95	1.815	1.7756

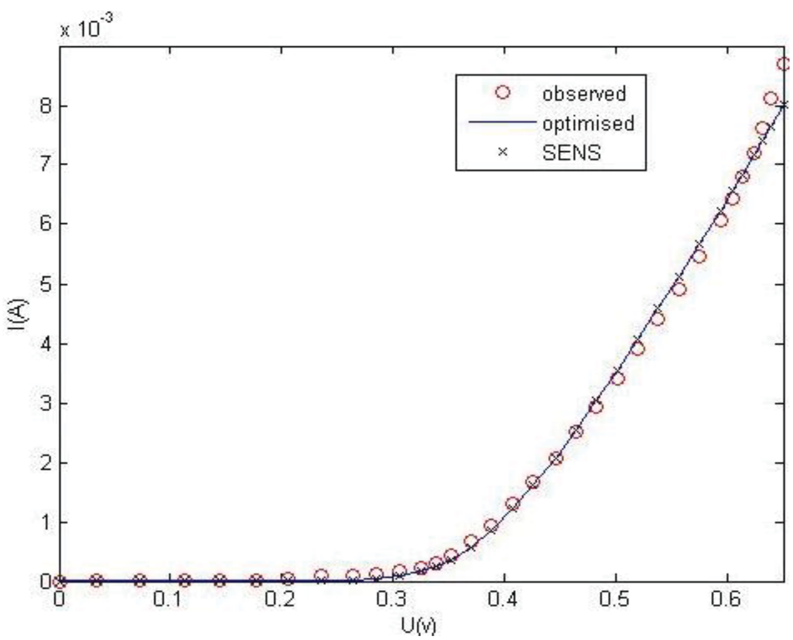

Figure 3. Comparison between the characteristic (I,V) and the method of solving the equations of nonlinear system (SENS) (Ortiz-Conde et al., 1999).

Table 2. Results found by the solving non-linear equations, least squares methods and Literature values for Motorola diode.

Parameter	Method of solving the system of nonlinear equations	Least squares method	Literature (Ortiz-Conde et al., 1999)
R_S (Ω)	27.857	28.922	33.4
I_S (nA)	0.5582	0.43968	0.58
η	0.97	0.97	1.05

the literature. It shows the hardiness of the two methods used in this work. The Newton-Raphson method converges faster in relation to least squares method.

Conclusion

In this article, we present two new methods of extracting three physical parameters of a non-ideal p-n junction from its current-voltage characteristic I = f (V). Both methods require the introduction of initial values. The first technical is method of solving the system of nonlinear equations using the some parameters given in experiment results. The second method is based on the least squares algorithm. This technical represent an extraction process of rapid and accurate parameters. The values of the physical parameters extracted by the two methods are in good agreement with the experimental values and with literature. The application of the both methods can be extended to components having same five parameters such as solar cells.

Conflict of Interest

The authors have not declared any conflict of interest.

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