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A new approach to the extraction of single exponential diode model parameters

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ABSTRACT

A new integration method is presented for the extraction of the parameters of a single exponential diode model with series resistance from the measured forward *I-V* characteristics. The extraction is performed using auxiliary functions based on the integration of the data which allow to isolate the effects of each of the model parameters. A differentiation method is also presented for data with low level of experimental noise. Measured and simulated data are used to verify the applicability of both proposed method. Physical insight about the validity of the model is also obtained by using the proposed graphical determinations of the parameters.

1. Introduction

Parameter extraction in diode and solar cells has been an active research topic for many years [1–15]. Some methods are based on optimization of the measured current-voltage characteristics [2,5] while other methods have proposed new functions [1,3,12,16–22], which eliminate the effects of one parameter. Some of these functions [3,12,16–22] are based on integration and as a means to reduce the extraction uncertainties arising from the probable presence of noise in the measured data. On the other hand, graphical methods have been used for the evaluation of series resistance in solar cells [23,24] as well as for the calculation of majority carrier density of semiconductors with multiple donors and acceptors [25,26].

In this article, we present two new methods to evaluate the parameters of an idealized single-exponential diode with a parasitic series resistance. These methods are based on functions which isolate the effects of each parameters. The first method is described in Section 3 and is based on the integration of the current with respect to the voltage while the second method uses differentiation and is presented in Section 4. The integration method is recommended for measured data with high level of experimental noise. Both methods plot the extracted parameters as a function of the current, and the validity of the model is clearly illustrated in the region in which the parameters are nearly a constant. On the other hand, classical optimization methods, which are the best to minimize quadratic errors, could yield to erroneous parameters if the model is used in invalid region.

2. Integration of the measured forward bias data

Consider a single-exponential diode with a parasitic series resistance R whose *I-V* characteristics may be described by [1,12]:

$$I = I_0\left[\exp\left(\frac{V-RI}{n\,v_{th}}\right)-1\right] \tag{1}$$

where V is the terminal voltage, I_0 is the reverse saturation current, n is the so-called diode quality factor, and $v_{th} = k_B T/q$ is the thermal voltage. The current can be explicitly solved from implicit Eq. (1) making use of the Lambert W function [6,15], while the terminal voltage can be explicitly solved using elementary functions [2,5,12]:

$$V = RI + n\,v_{th}\ln\left(1+\frac{I}{I_0}\right). \tag{2}$$

Following the pioneering idea of using numerical integration for parameter extraction [3], the drain current may be integrated by parts using the voltage expression in (2) and performing the algebraic manipulations:

$$\begin{aligned}\int_0^V IdV &= VI-\int_0^I VdI\\ &= I\left[RI + n\,v_{th}\ln\left(1+\frac{I}{I_0}\right)\right]\\ &\quad-\left[\frac{R}{2}I^2 + n\,v_{th}(I+I_0)ln\left(1+\frac{I}{I_0}\right)-n\,v_{th}(I+I_0)\right]\\ &= \frac{R}{2}I^2 + n\,v_{th}I - I_0 n\,v_{th}\left[\ln\left(1+\frac{I}{I_0}\right)-1\right]\end{aligned} \tag{3}$$

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For values of forward current $I >> I_0$ the effect of I_0 on the integral is negligible, so that the last term of the RHS (Right-Hand Side) of (3) may be neglected. Thus, the integral of the forward current turns out to be approximately described by a simple second order polynomial on I whose coefficients are directly and independently determined by two of the diode's parameters: R and n [17,18]:

$$\int_0^V IdV \approx \frac{R_s}{2}I^2 + n v_{th} I. \tag{4}$$

The two coefficients of this second order polynomial defined by the RHS of (4) may be adjusted by optimization to fit the numerical integral of the forward current data specified by the LHS (Left-Hand Side) of (4). Such optimization would directly extract the values of two of the diode's parameters: R and n.

On the other hand, it is also possible to remove the effect of the parasitic series resistance R using integration of the measured forward bias data. This may be easily done through the use of the "Integral Difference Function," which is defined as [19,20]:

$$D(V,I) \equiv \int_0^I VdI - \int_0^V IdV = IV - 2\int_0^V IdV, \tag{5}$$

where D has units of "electric power." Applying function D to the case of a single-exponential diode model with series resistance and restricting the analysis to values of forward current $I >> I_0$, substitution of (2) into (5) yields [19,20]:

$$D = (I + 2I_0) n v_{th} \ln(I/I_0 + 1) - 2n v_{th} I \approx I n v_{th}[\ln(I/I_0) - 2], \tag{6}$$

which is an expression that contains two of the diode's parameters: I_0 and n, but does not contain R. Dividing (6) by the current yields another auxiliary function, called G:

$$G \equiv D/I \equiv V - \frac{2}{I}\int_0^V IdV \approx n v_{th}[\ln(I/I_0) - 2]. \tag{7}$$

It is interesting to note that function G expressed by (7) is very similar to the expression for the voltage of an intrinsic diode ($R = 0$) which according to (2) is: $n\, v_{th} \ln(I/I_o + 1)$.

Kaminski et al. [16] generalized this method in 1997 by allowing an arbitrary nonzero lower integration limit. In 2005 Tan et al. [10] extended function G by including the presence of a parallel parasitic resistance.

3. A method based in the integration of the measured forward bias data

In the previous section we presented the expression for G that contains two of the diode's parameters, I_0 and n, but does not contain R. Next, we will define a new function, which we call ΔG, as a means to also remove the effect of I_o, leaving only one parameter to be determined, n. The function is defined as the difference:

$$\Delta G(V,I) \equiv G(V,I) - G(V_R,I_R) \tag{8}$$

where (V_R, I_R) is a reference point of the I-V characteristic to be selected. Then, since parameters I_0 and n of the model described by (1) are assumed to have constant values throughout the entire forward *I-V* characteristics, and because (7) is a logarithmic function, substitution of (7) into (8) yields:

$$\Delta G(V,I) = n v_{th} \ln(I/I_R). \tag{9}$$

In order to use this ΔG function to extract the diode's parameters, the procedure to follow is:

First: Function G is numerically calculated using the integration in (7).

Second, Function ΔG is evaluated for some selected value of I_R using (8).

Third, Parameter n is obtained from (9) as:

$$n = \frac{\Delta G(V,I)}{v_{th}\ln(I/I_R)}, \tag{10}$$

and plotted as a function of the forward current.

Fourth, After having found the value of n, I_o is obtained using (7) as:

$$I_0 = \frac{I}{\exp\left(\frac{G}{n v_{th}} + 2\right)}, \tag{11}$$

and plotted as a function of the current.

Fifth and last, Parameter R is evaluated with (2) using the already extracted values of n and I_o:

$$R = \frac{V}{I} - \frac{n v_{th}}{I}\ln\left(\frac{I}{I_0} + 1\right) \approx \frac{V}{I} - \frac{n v_{th}}{I}\ln\left(\frac{I}{I_0}\right), \tag{12}$$

and plotted as a function of the current.

It is important to check that the resulting curves of n, I_o and R as plotted versus I should approach constant values, indicating that the assumed model of a single-exponential diode with parasitic series resistance is an adequate description of the actual *I-V* characteristics of the measured real device within the range of interest.

3.1. Verification of the procedure using simulations

The top part of Fig. 1 shows a simulated diode's *I-V* characteristics using equation (1), with a 10 mV step size, and the parameters previously reported in [5,12]: $n = 1.05$, and $I_o = 0.58$ nA and $R = 33.4\ \Omega$. Function G is calculated using the numerical integration of the simulated data as described by (7). We note that G is linearly proportional to the logarithm of the current as soon as few points are calculated in the

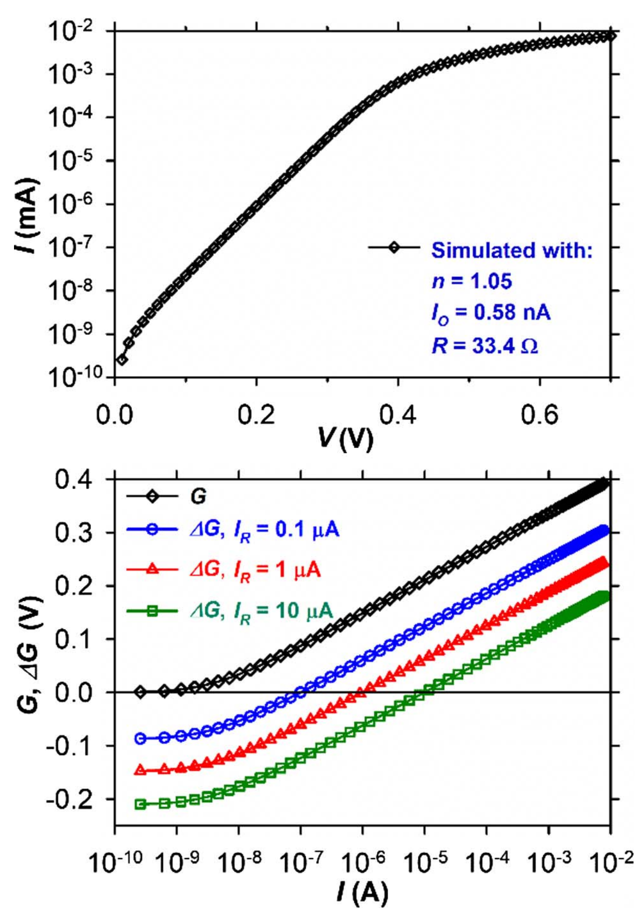

Fig. 1. Top: Simulated *I-V* characteristics of a silicon diode. Bottom: Functions G and ΔG as a function of the logarithm of the current calculated from the simulated *I-V* characteristics. Notice that the curves become straight lines as soon as $I >> I_0$.