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I–V methods to extract junction parameters with special emphasis on low series resistance

A. Kaminski*, J.J. Marchand, A. Laugier

Institut National des Sciences Appliquées, Laboratoire de Physique de la Matière, UMR CNRS 5511; Bât 502, 20 avenue A. Einstein, 69621 Villeurbanne cedex, France

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Abstract

We compare different I–V methods to extract junction parameters with a special emphasis on low series resistance determination. We have established the first method, the second method is based on the derivative (we use three formulae derived from $\mathrm{d}V/\mathrm{d}I$), the third method based on the integral ($\int I\mathrm{d}V$) and the final one which is the method of Lee et al. (Lee TC, Fung S, Beling CD, Au HL. J Appl Phys 1992;72:4739). The comparison is performed using a simulated case with random noise. The above methods give good results, especially the derivative although it is dependent on voltage step. The latter is not the case with our method. In addition this latter method is very simple to use.

We also deal with a solar cell with two exponential conduction processes and a shunt resistance. The fitting of the curve gives good results and our method permits to determine the boundary between the two processes and to obtain good initial values for a numerical fit of the whole curve.

1. Introduction

In junctions, there always exists a series resistance (R_s), whose evaluation is difficult especially at small values. Many methods used to find the series resistance and the junction parameters have been described before. For example Norde [1] supposes that the conduction process is known, namely diffusion, and uses a special function giving a minimum. The position of this minimum gives R_s. This method is not valid for general cases with different conduction processes and the determination of a minimum is not very accurate. The above method has been improved by Lien et al. [2], but the technique of the minimum of the function remains with its lack of accuracy. Lee et al. [3] use the same kind of method but without this minimum problem. Werner [4] uses three formulae based on the derivative and the current. Ortiz-Conde et al. [5] use an integration in order to extract the parameters. Some of these methods have been compared by the authors. For example, Aubry et al. [6] have compared four different ones, Evangelou et al. [7] three and Lyakas et al. [8] two. Other methods, more specific for photovoltaic applications, use either I–V curves under illumination [9–12] or both under dark conditions and illumination [13–15].

When R_s is low (like, for example, in large area solar cells), it becomes very hazardous to determine it with accuracy. In order to precisely calculate R_s, we need high currents. However, physical models are no longer valid under high injection conditions and furthermore junction heating intervenes. In this paper we present a method to extract parameters under dark conditions conditions [16] with a special emphasis on

* Corresponding author. Fax: +33-4-7243-8531.
E-mail address: annek@insa.insa-lyon.fr (A. Kaminski)

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low series resistance determination. We compare this method to three other methods in order to underline its advantages. The first method is based on the integral ($\int I \mathrm{d}V$). It is studied and completed since our formulation is more general than the one known in literature [5]. The second method concerns the use of the derivative (we compare three formulae) [4] and the third one is the Lee et al. method [3]. These four methods are compared with a simulated case. In the second part, we deal with the case of a solar cell with two exponential conduction processes.

2. Determination of low series resistance and junction parameters

We consider that the I–V curves can be described by a general equation

$$I = I_s[e^{\alpha(V - IR_s)} - 1], \tag{1}$$

in which R_s is the series resistance, α the coefficient of the exponent, may be q/nkT for diffusion process, generation–recombination or an intermediate process; I_s is the saturation reverse current and n an ideality factor.

2.1. Improved methods

2.1.1. Our method

This method concerns directly the usual measured I–V data.

By writing the relation in Eq. (1) in its logarithmic form, we have demonstrated that [16]

$$Y = \alpha(-R_s + X) \quad \text{for } I \gg I_s, \tag{2}$$

with $Y = (\ln(I/I_0))/(I - I_0)$ and $X = (V - V_0)/(I - I_0)$ and (V_0, I_0) is a point of the I–V curve.

When R_s is low or when multiple conduction processes intervene, the determination of R_s value becomes hazardous. To get a better accuracy we consider a set of I_i– V_i data giving rise to a set of X–Y values, with i varying from 1 to N. We use satisfactory currents for a reasonable weight of R_s, these ones ranging from $I = I_{i0}$ to I_N, that is $n = N - i0 + 1$ pairs of I–V data. Then, we calculate X and Y values for $I_0 = I_{i0}$ and $I = I_{i0+1}$ up to $I = I_N$. This gives $(n-1)$ pairs of X–Y data. We start again with $I_0 = I_{i0+1}$ and $I = I_{i0+2}$ up to I_N and get (n-2) additional X–Y data, and so on, up to $I_0 = I_{N-1}$. Finally, we obtain $n(n-1)/2$ pairs of X–Y data that means more values for the linear regression. The linear regression of Eq. (2) gives α and R_s.

The most interesting point with this method is the fact that we do not have any limitation conditions on the voltage hop and it is very easy to use.

At last, when we know R_s, whatever the method involved, the reverse saturation current is obtained by plotting ln I versus $(V - IR_s)$.

Table 1
Extracted values of R_s and α by different methods, from a simulated case (with $R_s = 10$ mΩ and $\alpha = 40$ V^{-1})

	α (V^{-1})	R_s (mΩ)
Our method	39.8	9.86
Werner method A [4]	40.08	10.03
Werner method B [4]	41.41	11.25
Werner method C [4]	40.31	10.25
Modified integral	40.85	10.65
Lee et al. method [3]	40.11	10.1

2.1.2. Method using the integral

The integration of Eq. (1) gives

$$\int_{V_0}^{V} (I + I_s)\mathrm{d}V = \int_{V_0}^{V} I_s e^{\alpha(V - IR_s)}\mathrm{d}V. \tag{3}$$

Ortiz-Conde et al. [5] have already calculated this integral and established a linear relation for parameters extraction but for $V_0 = 0$ which is a limitation. In order to generalize this formula, we have used Eq. (3) and obtained

$$\frac{1}{I - I_0}\int_{V_0}^{V} I\,\mathrm{d}V = \frac{1}{\alpha} + \frac{R_s}{2}(I + I_0) \quad \text{for } I \gg I_s. \tag{4}$$

Eq. (4) is more interesting than the previous relation because, in the case of two conduction processes for example, we can extract the parameters for an I–V range where one conduction process dominates and have a better accuracy.

$$\text{Taking } y = \frac{1}{I - I_0}\int_{V_0}^{V} I\,\mathrm{d}V \quad \text{and } x = \frac{I + I_0}{2}, \quad \text{we get } y = \alpha^{-1} + R_s x. \tag{5}$$

If we consider a part of the I–V curve extending from $I_A(V_A)$ to $I_B(V_B)$ with increasing values containing N pairs of data, then $V_0 = V_A$ and V is given by all the others values up to $V_B(I_B)$. We get (N-1) values of y and x. The linear regression of Eq. (5) gives α and R_s.

The numerical integration can be obtained by the means of the trapezoidal method. In that case, since we consider that the curve can be approximated by a straight line between two successive I–V pairs of data, the voltage hop must be as small as possible to have the best accuracy.

Another relation containing the integral has been proposed by Garcia Sanchez et al. [17]. It presents the advantage of being independent of the series resistance

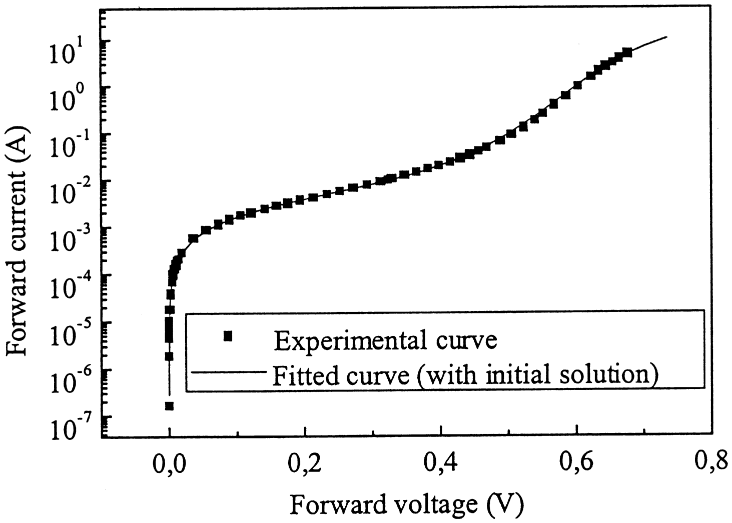

Fig. 1. Experimental and fitted forward dark I–V curve of a 100-cm^2 solar cell.

but it also necessitates the calculation of the integral from $V=0$ V, which is a limitation.

2.2. Comparison of the methods with a simulated case

We have compared the preceding methods with the method of Lee et al. [3] and Werner three derivative formulations [4]: (A) G/I_d versus G, where $G=dI_d/dV$, (B) R_{rd} versus $1/I_d$, where R_{rd} is the differential difference of the I–V curve and (C) I_d/G versus I_d. These methods have been tested on a simulated I–V curve with one exponential and a series resistance. We have taken: $R_s = 10$ mΩ, $\alpha = 40$ V^{-1} and $I_s = 10^{-9}$ A. This could correspond to a 100 cm^2 solar cell [18,19]. In Table 1, we present the values of R_s and α found with the different methods for a current range of 0.2 A$-$2 A and a round-up on the current values in order to simulate experimental noise.

The best results are obtained with the Werner formula A of the derivative. However, for the numerical derivative, small voltage steps are necessary. Lee et al.'s method also gives good results but it necessitates a nonlinear curve fit. Our method 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. Moreover, values extracted are obtained with a satisfactory precision considering the simplicity of the method.

3. Case of a solar cell with two exponential processes, a shunt resistance and a series resistance

In the case of solar cells, it is necessary to obtain a very low series resistance because it plays an important part on the fill factor and efficiency [20]. For example, for a 100 cm^2 solar cell with a 20 mΩ series resistance and 3 A short circuit current, the voltage loss could reach 60 mV for a bias of 0.6 V, that is to say 10% approximately. Consequently, I–V methods must allow an accurate determination of a low series resistance to improve solar cell technology. However, in the case of solar cells, it is recommended to use low current densities because phenomena like junction heating, high injection phenomena and current crowding effects intervene if we are working at higher values of current [21–23]. This increases the difficulty to extract low series resistance. Garcia Sanchez et al. [24] have already presented a method to calculate the double-exponential model parameters but they neglect the shunt resistance. In this part we will present the way we proceed.

The two exponential I–V curve is modeled by the following equation [20]

$$I = I_{s1}(e^{(\alpha_1(V-IR_s))}-1)+I_{s2}(e^{(\alpha_2(V-IR_s))}-1) + \frac{V-IR_s}{R_{sh}}, \quad (6)$$

with $\alpha_i = q/(n_i kT)$, n_i the ideality factor, I_{si} the saturation current, R_s the series resistance and R_{sh} the shunt resistance.

In this case the determination of the different parameters is more difficult because the lower part of the curve (low currents) influences the higher part (high currents) and vice versa.

For the parameters extraction, we separate the curve in two parts: the higher part includes the influence of

Table 2
Extracted parameters from the experimental 100 cm^2 solar cell I–V curve

	I_{s1} (A)	n_1	I_{s2} (A)	n_2	R_{sh} (Ω)	R_s(mΩ)
Extracted values	$1.86{\cdot}10^{-8}$	1.3	$1.6{\cdot}10^{-4}$	3.5	80	5.7
Refined fit with Levenberg– Marquardt algorithm	$4.317{\cdot}10^{-9}$	1.2	$1.8{\cdot}10^{-4}$	3.6	83	5.45

series resistance and of the first exponential, and the lower part includes the shunt resistance and the second exponential.

We consider that, for the higher part of the I–V characteristic, the curve can be fitted by the following relation:

$$I = I_{s1}(e^{(\alpha_1(V - IR_s))} - 1). \tag{7}$$

R_s, α_1 and I_{s1} are extracted using our method. The boundary between the two regions is obtained when we have a good correlation factor for the linear regression of Eq. (2).

For the lower part of the curve, we use the following equation:

$$I = I_{s2}(e[\alpha_2(V - IR_s]) - 1) + \frac{V - IR_s}{R_{sh}}. \tag{8}$$

In order to calculate the second exponential parameters and the shunt resistance, we use the method presented in Ref. [16].

An example of experimental I–V curve (obtained on a 100 cm^2 solar cell), fitted by the previous relations is presented in Fig. 1 and one can see that it gives very good results. The extracted values are given in Table 2. Solar cell used for the measurement is a 100 cm^2 industrial multicrystalline silicon solar cell (average grain area is 1 cm^2) with submicronic junction ($x_j < 0.3$ μm). The basic component is a n^+p junction. The surface of the cell is anisotropicaly texturized (the silicon wafer has been submitted to a NaOH chemical etching giving to the surface a pyramidal aspect and improving photons absorption). A SiO_2 layer is used for surface passivation and TiO_2 is used as antireflection coating. Front and back grid metallizations are screen printed and annealed at the end of the process. The solar cell thickness is 200 μm.

For each value of the curve, we have calculated the relative error. It is contained between 4 and 15%, which is good if we consider that we have fitted the curve with six unknown parameters. The biggest error (15%) is situated in the region of influence of the first exponential (approximately 0.5 and 0.6 V for the example presented in Fig. 1). This is due to the fact that we first determine the parameters of the part of the curve present at higher voltages, neglecting the second exponential. Therefore the value of α_1 and in consequence of ideality factor is overestimated and that explains the biggest error in this region of the I–V characteristic.

This fit could be more refined by using this solution as an initial solution for a nonlinear curve-fitting using the Levenberg–Marquardt algorithm [25]. New values are presented in the second line of Table 2. The previous remark is confirmed by this fit. However, for a fit with six parameters, an initial solution is necessary and in this paper we present a method to obtain it. Moreover the initial value of R_s is nearly similar to the final value.

The device presents high values of ideality factor (especially n_2). This has been explained by the presence of different conduction processes [19] like trap assisted tunneling [20,26,27], Poole–Frenkel effect [28] or recombination [29].

4. Conclusion

We have compared four methods to extract junction parameters: our method, the integral, the derivative and the Lee et al. method. Our formula for the integral is more interesting than the previously published one, because we can use it for a segment of the I–V curve starting from any I value. Our method presents the advantage of being independent of voltage step and it is easy to use. The fitting of an I–V curve with two exponential conduction processes gives good results and our method permits to determine the boundary between the two processes and to simplify the extracting procedure.

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