Pergamon

0038-1101(95)00017-8

Solid-State Electronics Vol. 38, No. 11, pp. 1937–1943, 1995

0038-1101/95 $9.50 + 0.00

EXPERIMENTAL INVESTIGATION OF THE DOUBLE EXPONENTIAL MODEL OF A SOLAR CELL UNDER ILLUMINATED CONDITIONS: CONSIDERING THE INSTRUMENTAL UNCERTAINTIES IN THE CURRENT, VOLTAGE AND TEMPERATURE VALUES

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(Received 24 June 1994; in revised form 11 January 1995)

Abstract—In this paper is presented a new approach for determining the current standard deviation which is used in the current voltage characteristic fitting. The analytical equation has been deduced from propagation of errors theory and it takes into account measurement uncertainties in the current, voltage and temperature values. A conventional monocrystalline silicon solar cell sample has been used to test the theory. We measured several I–V curves under illuminated condition with the temperature varying in the range between −75 and 75°C. We have adopted the chi-square minimization as the error criterion for fitting the experimental curves using the standard deviation proposed in this work. The main advantage of the proposed formalism is that it leads to an improved chi-square value, i.e value physically and statistically more acceptable. We obtain best values for the standard deviation of the parameters from a fitting procedure using the double exponential model. The results show that for a measurement uncertainty of 0.5°C in the temperature, the uncertainty in the current around the open circuit is of about 5% of the short circuit current. Consequently, we conclude that a carefully controlled temperature during measurement is an essential condition for obtaining reliable experimental I–V curves. Tables and figures show the fitted double exponential parameters fitted as a function of temperature, as well as their standard deviations.

NOTATION

α_{n_1}	linear temperature coefficient of the n_1 (K^{-1})
α_{n_2}	linear temperature coefficient of the n_2 (K^{-1})
α_{J_L}	linear temperature coefficient of the photogenerated current (mA/cm^2/K)
$\alpha_{R_{se}}$	linear temperature coefficient of the series resistance (Ω/K)
$\alpha_{R_{sh}}$	linear temperature coefficient of the shunt resistance (Ω/K)
Area	total area of the solar cell (cm^2)
Area$_{\mathrm{met.}}$	metallization area of the solar cell (cm^2)
C_{s1}	saturation current constant to the I_{s1} (mA/cm^2/K^3)
C_{s2}	saturation current constant to the I_{s2} (mA/cm^2/K$^{3/2}$)
E_g	gap energy of the semiconductor (eV)
q	electron charge (C)
I	electric current (mA)
I_L	photogenerated current (mA)
I_m	measured electric current (mA)
I_{s1}	saturation current due to the diffusion of minority carriers into the junction (mA)
I_{s2}	saturation current due to the recombination and generation of carries through defect centers located in the space charge region of junction (mA)
k	Boltzmann constant (eV/K)
N	number of data points read along of the experimental I–V curve
n_1	ideality factor of the first diode at the double exponential model
n_2	ideality factor of the second diode at the double exponential model
p	number of parameters of the analytical model
R_{se}	series resistance of the solar cell equivalent circuit (Ω)
R_{sh}	shunt resistance of the solar cell equivalent circuit (Ω)
S_I	current instrumental uncertainty (mA)
S_T	temperature instrumental uncertainty (°C)
S_V	voltage instrumental uncertainty (mV)
σ_I	current standard deviation due to the current uncertainty (mA)
σ_T	current standard deviation due to the temperature uncertainty (mA)
σ_{Total}	total current standard deviation (mA)
σ_V	current standard deviation due to the voltage uncertainty (mA)
T	temperature of the device during measured (°C)
V	voltage (V)
V_{th}	thermal voltage (V)
χ^2	chi-square
χ^2_{red}	reduced chi-square
γ_1	parameter obtained after derivative of the current by voltage, which is consequence of the implicit form in current of the I–V equation (Ω^{-1})

1. INTRODUCTION

According to Phang and Chan[1] there are two types of algorithms for the determination of model parameters of the current voltage (I–V) characteristic equation. The first uses selected parts of the I–V curves and analytical equations for calculating parameter values (see articles [2] and [3] as examples). The second algorithm uses the full I–V characteristic and involves minimizing some error criterion in order to find the set of parameters values. Although the second approach is more difficult to work with, it is better because it gives the best fit to the experimental curve. Articles [1,4,5] suggest different criteria for obtaining a good fitting. Other authors [4,6,7] have rightly pointed out that the use of any specific criterion of benefit for a good fitting in one part of the I–V curve leads to a reduced fit for the rest of the curve. Phang and Chan[1] have observed that some form of weighting is obviously necessary to give a good fitting over the entire characteristic. The new current standard deviation proposed in this work perhaps may solve this problem, because it works as a true weighting which has a physical interpretation.

In this work we have adopted the chi-square value, which is given by eqn (1), as the error criterion for fitting the experimental I–V characteristic. The χ^2 minimization technique is also called weighted least squares fitting and it has two important advantages. It allows one to determine the goodness of the fitting[8] and also to calculate the standard deviations of the parameters[10]:

$$\chi^2 = \sum^{N} \left(\frac{I_{\mathrm{ex}} - I(V_i)}{\sigma_I} \right)^2 \qquad (1)$$

σ_I is the standard deviation of the current measured and it is obtained as a function of the experimental set-up. This method has been used by many researchers for fitting the solar cell I–V experimental curve[5].

This article is aimed at giving a correct interpretation to the current standard deviation, which is not merely the experimental uncertainty in the electric current value. Nowadays laboratories are equipped with programmable electronic multimeters and automatic data collection systems. Consequently the current and voltage values can be obtained with an accuracy better than 0.01% with 4 or 5 significant digits. This represents an improvement in the quality of experimental I–V curves, but it is more difficult to fit such curves because the chi-square values obtained in the fitting are larger than expected. According to Bevington [8, p. 89] for any physical experiment the value of χ^2 should be approximately equal to the degree of freedom, which is the number of data points minus the number of parameters of the equation used to fit these data points. High values of χ^2 indicate larger deviations than expected in the set of parameter values obtained in the fitting. Table C-4 of Ref. [8] gives the probability that a random sample of data points would yield a value of χ^2 larger than expected. If the probability is nearly equal to 1, the assumed distribution describes the spread of data points quite well. If the probability is small, either the assumed distribution is not a good estimate of the parent distribution or the data are not a representative sample. Additionally, we can also say that the adopted model may not be correct. Sometimes it is convenient to verify the value of this probability in the table to check the goodness of the fitting. If the value is higher than 1% we can think that the fitting parameter values have a good chance to be close to the true values of the mathematical model. From now on we will work with the reduced χ^2 value to simplify the reading of the probability in this table. The reduced chi-square is given by eqn (2). To achieve a good fitting the expected value of the reduced χ^2 should be around unity:

$$\chi^2_{\mathrm{red}} = \frac{\chi^2}{N-p}. \qquad (2)$$

We have used the double exponential model for extracting the parameters from the experimental I–V curves. By a preliminary fitting of the characteristic measured in the Stuttgart University we obtained χ^2_{red} values higher than unity. Naturally, after this fact a good question was immediate: Is the double exponential model correct? Fortunately, it is still correct. By error propagation theory [8, Chap. 4] we concluded that the current standard deviation given by eqn (1), which was considered being only the accuracy of the experimental current value, was not a good approach. This occurred because the current deviation σ_I is also a function of voltage and temperature. With the purpose of solving the problems here mentioned, we adopted a new expression for σ_I, given by eqn (3), considering the error propagation theory. We now call it by "total current standard deviation" because it has a current, voltage and temperature contributions. This new approach is physically more realistic and gives best results for the chi-square reduced value. In eqn (3) the cross terms have not been considered because the parameters are uncorrelated:

$$\begin{aligned} \sigma^2_{\mathrm{Total}} &= \sigma^2_I + \sigma^2_V + \sigma^2_T \\ &= S^2_I + \left(S_V \frac{\partial I}{\partial V} \right)^2 + \left(S_T \frac{\partial I}{\partial T} \right)^2. \end{aligned} \qquad (3)$$

Equation (3) does not take into account systematic errors such as wrong temperature measurements. These kinds of errors can be avoided with specific calibration methods, which are not the subject of this work. The terms S_I, S_V and S_T are random uncertainties in the current, voltage and temperature. They may be obtained from the measurement system.

The current vs voltage expression, eqn (4), given by the double exponential model has seven parameters and they may be extracted from the fitting. This model is based on the equivalent circuit with two diodes. The first exponential simulates the diffusion process of the minority carriers into the depletion layer. The second exponential corresponds to the carrier recombination in the space charge region of the junction[2]:

$$I = I_{s1}\left(\exp\left(\frac{V - IR_{se}}{n_1 V_{th}}\right) - 1\right) + I_{s2}\left(\exp\left(\frac{V - IR_{se}}{n_2 V_{th}}\right) - 1\right) + \frac{V - IR_{se}}{R_{sh}} - I_L \quad (4)$$

where $V_{th} = kT/q$ is the thermal voltage of the device.

The chi-square minimization criterion was used for fitting the experimental I–V curves and this minimum gives the best set of eqn (4) parameters values. This task is carried out by a computational program which uses the downhill method in multidimensions and parabolic interpolation[9].

2. GENERAL FORMULATION

The second term on the right-hand side of eqn (3) is a function of the voltage uncertainty and the derivative is given by eqn (5). In this equation we use the same notation as in [10]. The λ_1 expression is given by eqn (6) and it is a consequence of the implicit form of eqn (4) regarding the current:

$$\frac{\partial I}{\partial V} = \frac{\lambda_1}{1 + \lambda_1 R_{se}} \quad (5)$$

$$\lambda_1 = \sum_{i=1,2} \frac{I_{si}}{V_{th}} \exp\left(\frac{V - IR_{se}}{n_i V_{th}}\right) + \frac{1}{R_{sh}}. \quad (6)$$

Equation (4) has explicit and implicit temperature dependencies. Equation (7) gives the saturation current terms[2,6]. It was derived using a well-known expression for the energy gap of silicon as a function of temperature[11], which is given by eqn (8):

$$I_{si} = \text{Area}\, C_{si} T^3 \exp\left(-\frac{E_g}{n_i kT}\right) \quad (7)$$

$$E_g = E_g(0) - \frac{\alpha T^2}{T + \beta}. \quad (8)$$

The constants C_{s1} and C_{s2} are independent of temperature and $E_g(0) = 1.17$ eV, $\alpha = 0.473$ meV/K and $\beta = 636$ K. The derivative of the saturation currents with respect to temperature is given by eqn (9):

$$\frac{\partial I_{si}}{\partial T} = \frac{I_{si}}{T}\left(3 + \frac{E_g}{kT} - \frac{\partial E_g}{k\,\partial T}\right). \quad (9)$$

We have considered that the photogenerated current, the quality factors and the series and shunt resistancies are linear functions of temperature. Their expressions are shown in eqns (10), (11), (12), (13) and (14). They are first order approximations[12]:

$$J_L = J_L(300\ \text{K}) + \alpha_{J_L}(T - 300\ \text{K}) \quad (10)$$

$$n_1 = n_1(300\ \text{K}) + \alpha_{n_1}(T - 300\ \text{K}) \quad (11)$$

$$n_2 = n_2(300\ \text{K}) + \alpha_{n_2}(T - 300\ \text{K}) \quad (12)$$

$$R_{se} = R_{se}(300\ \text{K}) + \alpha_{R_{se}}(T - 300\ \text{K}) \quad (13)$$

$$R_{sh} = R_{sh}(300\ \text{K}) + \alpha_{R_{sh}}(T - 300\ \text{K}). \quad (14)$$

The derivative of the current with respect to temperature is given by eqn (15):

$$\begin{aligned}\frac{\partial I}{\partial T} = \frac{1}{1 + R_{se}\lambda_1}\Bigg(&\sum_{i=1,2}\left(\exp\left(\frac{V - IR_{se}}{n_i V_{th}}\right) - 1\right)\frac{\partial I_{si}}{\partial T} \\ &- (\lambda_1 - 1/R_{sh})\frac{V - IR_{se}}{T} \\ &- \sum_{i=1,2}\frac{V - IR_{se}}{V_{th}}\frac{I_{si}}{n_i^2}\exp\left(\frac{V - IR_{se}}{n_i V_{th}}\right)\frac{\partial n_i}{\partial T} \\ &- I\lambda_1\frac{\partial R_{se}}{\partial T} - \frac{V - IR_{se}}{R_{sh}^2}\frac{\partial R_{sh}}{\partial T} - \frac{\partial I_L}{\partial T}\Bigg).\end{aligned} \quad (15)$$

A numerical simulation of this theory was carried out in order to understand the effects of the current, voltage and temperature experimental uncertainties on the current standard deviation. We considered the following values: $T = 25$ C, Area $= 4\ \text{cm}^2$, $I_L = 150$ mA, $J_{s1} = 10^{-8}\ \text{mA/cm}^2$, $n_1 = 1$, $J_{s2} = 10^{-4}\ \text{mA/cm}^2$, $n_2 = 2$, $R_{se} = 100\ \text{m}\Omega$, $R_{sh} = 1\ \text{k}\Omega$, $\alpha_{J_L} = 0.02\ \text{mA/cm}^2\ \text{K}$, $\alpha_{n_1} = 10^{-4}/\text{K}$, $\alpha_{n_2} = 10^{-4}/\text{K}$, $\alpha_{R_{se}} = 1\ \text{m}\Omega/\text{K}$ and $\alpha_{R_{sh}} = 1\ \Omega/\text{K}$. The following experimental uncertainties were adopted in this simulation: $S_I = 0.1$ mA, $S_V = 0.2$ mV and $S_T = 0.5$ C. In Fig. 1 the logarithm of the absolute values of the electrical current, current standard deviation, voltage standard deviation, temperature standard deviation and total current standard deviation given by eqn (3) are plotted against voltage. The values of 1 and 10%J_{sc} are also shown.

The temperature standard deviation curve shows a singularity because the derivative of the current with respect to temperature changes its sign. Furthermore, we can see from Fig. 1 that the total current standard deviation, which is used in the equation for χ^2, is higher than 1% of J_{sc} at voltages larger than the maximum power voltage.

3. EXPERIMENT

The sample used in this study is a space-qualified monocrystalline silicon solar cell produced at the Research Laboratory for Materials and Sensors of the Space Research Institute (INPE – LAS) in Brazil. It is a $n^+ - p$ structure with a total area of 4 cm^2 and was prepared by conventional thermal diffusion of phosphorus and had Ti/Pd/Ag front metallization and Al/Ti/Pd/Ag back metallization. The solar cell No. 53 used in this work has been randomly selected from a solar cell lot which has been manufactured to supply the Solar Cell Experiment of the first Brazilian Satellite (Ref. [13] contains more details about this device).

In order to measure of the I–V characteristic, the solar cell was divided in small pieces with a total area of 0.25 cm^2. The experimental I–V curves were recorded by using an automated data collecting

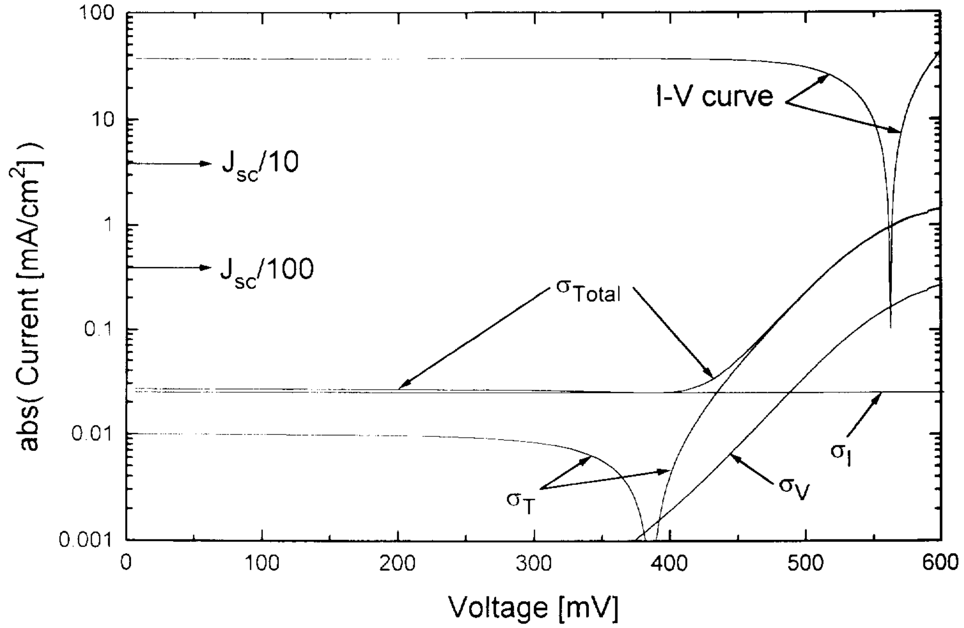

Fig. 1. Standard deviations as a function of voltage calculated by numerical simulation.

system at the Institut für Physikalische Elektronik at the University of Stuttgart and the temperature was varied between −75 and 75°C. Each curve has approx. 50 points and the illumination was provided by an ELH light source calibrated for around Air Mass Zero intensity (135.3 mW/cm^2). The metallization grid in each piece has an area of 0.05 cm^2.

The experimental current, voltage and temperature uncertainties adoped in this work were 0.01% of full scale and 0.5°C, respectively.

4. RESULTS

At first we fitted the I–V curves only considering the measurement uncertainty in the current. The second and third terms of eqn (3) were assumed to be zero. Table 1 gives the results of this fitting, which have neither temperature nor voltage corrections. The parameters are from eqns (7), (10) (14). The reduced chi-square values obtained in the fitting of these curves, where only measurement uncertainty in current was taken into account, had an average value of $(2.3 \pm 2.1)10^2$. We expected a value around unity.

The χ^2_{red} values obtained in the fitting of the I–V curve, which were around a thousand, and the χ^2_{red} of Table 1 indicate that there is something wrong, because the probability for obtaining a reduced chi-square value larger than 50 is less than 0.001%. Consequently, there is a probability less than 0.001% that the value of the Table 1 will be correct.

Considering the theory proposed in this article the evaluated chi-square values of the double exponential model are given in Table 2. These values were obtained after five iterations of the linear coefficient parameters, because in order to adjust the I–V curve was used in these values. In the first iteration we guessed on an initial set of values. In the second iteration we used the values obtained in the first and so on. The process requires some iterations to converge. Table 3 shows the values of the linear coefficients obtained in this iterative process. The reduced chi-square values obtained in the fitting of these curves, where measurement uncertainties in current, voltage and temperature were taken into account, had an average value of 0.7 ± 0.5

Figure 2 shows the series resistance values as a function of temperature obtained with the conventional fitting method (●). The current standard deviation was estimated by taking into account only the experimental current uncertainty. We made an attempt to adjust a straight line to the points, which

Table 1. Values of the double exponential parameters obtained with the conventional fitting procedure

	Parameter value	χ^2_{red}
J_1	$(37.3289 \pm 0.0010) + (2.778 \pm 0.002)10^{-2}(T - 300\ K)$	1.76×10^4
C_{s1}	$(1.7720 \pm 0.0010)10^2$	8.1×10^4
n_1	$(1.01381 \pm 0.00007) + (8.46 \pm 0.10)10^{-5}(T - 300\ K)$	1.26×10^5
C_{s2}	138.2 ± 0.2	7.4×10^5
n_2	$(1.9154 \pm 0.0004) - (6.26 \pm 0.07)10^{-4}(T - 300\ K)$	7.9×10^2
R_{se}	$(0.9920 \pm 0.0004) + (3.455 \pm 0.005)10^{-3}(T - 300\ K)$	5.9×10^4
R_{sh}	$(1.83 \pm 0.02) + 10^4 - (25 \pm 7)(T - 300\ K)$	139

Table 2. Values of the double exponential parameters obtained applying the theory of this work

	Parameter value	$\chi^2_{red.}$
J_1	$(37.167 \pm 0.002) + (2.590 \pm 0.004)10^{-2}(T - 300\ K)$	8.9×10^2
C_{s1}	$(2.6 \pm 0.3)10^4$	1.71
n_1	$(1.049 \pm 0.014) + (4.7 \pm 1.8)10^{-4}(T - 300\ K)$	0.93
C_{s2}	98 ± 16	1.75
n_2	$(2.13 \pm 0.09) - (1.5 \pm 1.1)10^{-3}(T - 300\ K)$	1.25
R_{se}	$(1.21 \pm 0.05) + (6.0 \pm 0.7)10^{-3}(T - 300\ K)$	1.31
R_{sh}	$(1.70 \pm 0.09)10^4 + (11 \pm 11)(T - 300\ K)$	2.6

Table 3. Values of the linear coefficient parameters used in the fitting of the I–V curves with an iterative process

Condition	α_{J_L}	α_{n_1}	α_{C_2}	α_{R_s}	$\alpha_{R_{sh}}$
Initial	0.023	0	0	0	0
After 1st	0.026	0.000086	0.00049	0.0068	23
After 2nd	0.026	0.00038	0.00076	0.0060	18.6
After 3rd	0.026	0.00043	0.00090	0.0059	13.7
After 4th	0.026	0.00053	0.00138	0.0058	11.5
After 5th	0.026	0.00047	0.00147	0.0060	10.9

is the solid line shown in the figure. The reduced chi-square obtained in this linear regression is too high. We concluded that the problem was not in the values of the points but in the standard deviations, which are much lower than expected. The series resistance standard deviations of Fig. 2 (●) are so small that they do not appear in the figure. The problem is that only the experimental current uncertainty was considered in this case.

Figure 2 shows also the points obtained considering the theory of this article, which are shown as (○). These values were obtained considering the experimental uncertainties in the current, voltage and temperature. We can see that now it is possible to adjust a straight line (- -) to these points if one considers their uncertainties. The chi-square value of this curve is 1.31. It represents a good fit because the curve lies entirely inside any standard deviations.

Figures 3 and 4 show the equivalent results for the saturation current constant (C_{02}) and for the ideality factor (n_2), respectively. The saturation current constants were determined by the least square method using the standard deviations. The squared uncertainties work as weights for obtaining the mean. For example, in Fig. 3 we can see that the mean of the open circles is represented by dashed line and it is nearest to the points with small standard deviations. The same fact takes place with the solid points in this figure, where the constant obtained by the least square method is the solid line. The error bars of the solid points are smaller than the size of the points in the graph. The linear regressions in Fig. 4 were also obtained with the least square method, considering the standard deviations as weights.

The photogenerated current density was obtained by using the conventional method and by the method of this work. The reduced chi-square values in both cases were larger than unity (see Tables 1 and 2) because oscillations in the luminosity intensity during the measurements were not considered in the theory.

5. CONCLUSIONS

The experimental I–V curves measured at IPE—Stuttgart University were treated with a conventional fitting method and with a method proposed in this article. The essential difference between both methods lies in the functional form of the current chi-square equation. In the first method only experimental uncertainty in the current is considered, i.e. only the first term in eqn (3) is different from zero. In the second case all terms of this equation were considered. We adopted a temperature uncertainty of 0.5 C.

Obtaining good values for the double exponential model parameters is relevant for understanding the behavior of solar cell devices as a function of any specific variable, which can be temperature, incident light intensity, radiation damage or annealing. It is also relevant for appreciating how the manufacturing process alters the values of any parameter, such as

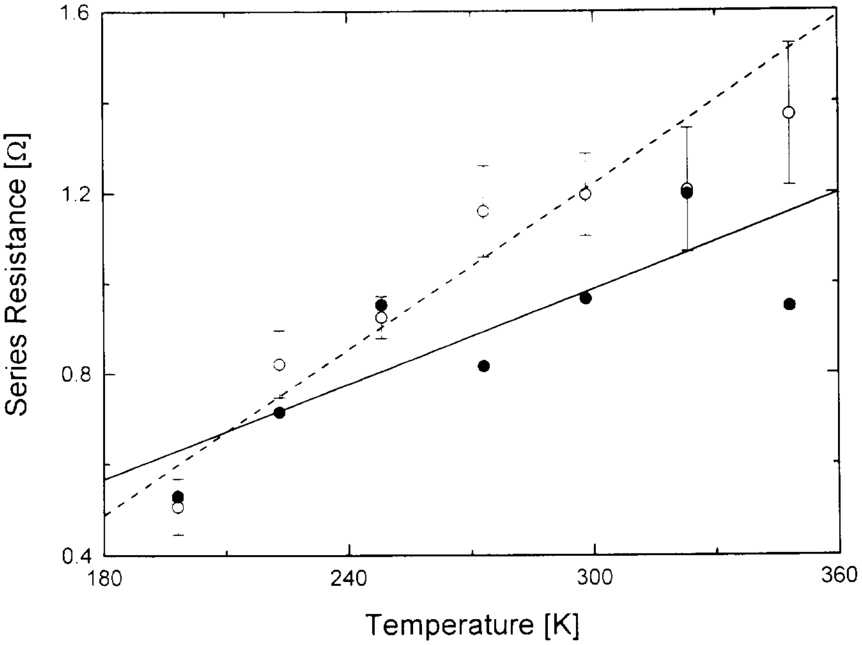

Fig. 2. Series resistance obtained with conventional fitting method (—●—) and with method of this work (○).

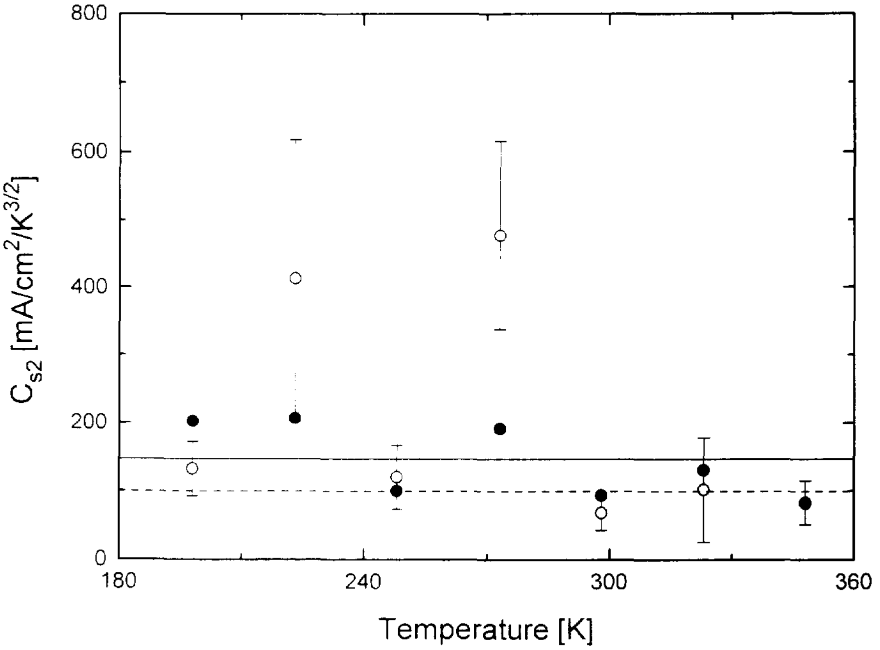

Fig. 3. Saturation current density constant to the I_{s2} obtained with conventional fitting method (—●—) and with method of this work (○ - -).

series resistance or shunt resistance, which are very sensitive to the state of art in solar cell fabrication. Standard deviation values are important for knowing the best function to adjust an experimental curve. For example, Fig. 2 shows the R_{se} as a function of the temperature obtained with our sample, which was calculated with conventional method considering only the current instrumental uncertainty (●). In this figure it is impossible to fit a straight line (- - -) because the difference between the experimental point and the point under the line is several times larger than the series resistance standard deviation. It was calculated with a method already published[10] and it is so small that it does not appear in the graph. The other parameters have the same problem as the series resistance and the $\chi^2_{red.}$ values obtained are listed in Table 1. These values are several orders of magnitude larger than the unity and the probability of the

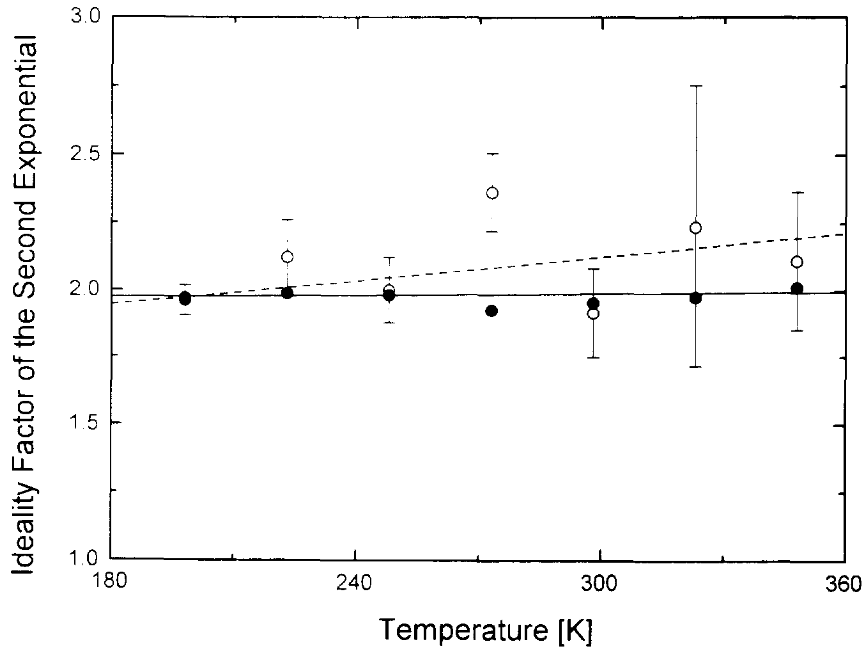

Fig. 4. Ideality factor of the second exponential obtained with conventional fitting method (—●—) and with method of this work (○ - -).

parameter equation as a function of temperature being valid is almost null. This indicates that there is something wrong with the conventional method to extract parameter values of the double exponential model although in the first approximation the straight line would be a good approximation.

Now with the method proposed in this work, we can see in Figs 2–4 that the standard deviations ( ) are higher than obtained with conventional method. This happened because we have considered the correct theory to the current standard deviation of the chi-square, which is used as criterion to fit the experimental I–V curve. Figures 2–4 show that it is possible to adjust a straight line ( ) and this can be confirmed by the values of the χ^2_{red} in Table 2, which are around the unity. This value is acceptable by the goodness of fitting [8, Chap. 10] because it has on the average a probability of 10% that the set of parameter values fitted are true. This probability value, 10%, is a good value in statistic theory.

The fitted photogenerated current curve ( ), which has $\chi^2_{\text{red}} = 8.9 \times 10^2$, indicates an effect that was not considered. As a matter of fact, the solar simulator produces oscillations in the photogenerated current and this effect, the light intensity experimental uncertainty, would have been considered to complete our theory. In any case, this effect does not change the other parameter values obtained in the fitting.

In the numerical simulation of the current standard deviation as a function of voltage considering experimental uncertainties of the current, voltage and temperature (see Fig. 1), we can see that the total current standard deviation value is around 5% of the short circuit current for voltages around an open circuit voltage. This high value of the total standard deviation is caused mainly by the temperature uncertainty and it has the following practical meaning: there are two reasons to measure illuminated solar cell I–V curves in the laboratory. The first is for taking the output parameters of the solar cell (I_{sc}, V_{oc}, I_{mp}, etc.). The second is for extracting parameters by a fitting procedure considering a specific mathematical model, for example the double exponential model one. The first class of measurement does not need to be rigorous with details about temperature stabilization and current voltage accuracy because the output parameters of the I–V curve are less sensitive in the small variations of these physical parameters. On the other hand, the second class of measurement must be done carefully regarding the instrumental uncertainties of the set-up to take their current and voltage points.

This work shows that the parameters and their standard deviations extracted from experimental I–V curves are very sensitive on temperature variations of the devices measured. In our measured I–V curve we adopted an optimistic value to the temperature accuracy of 0.5 C and it has a drastic consequence in the fitting parameters. For example, Fig. 2 shows that the straight line (– –) fits well the experimental points but the theory[14–16] indicates that series resistance is a function of several device parameters. It is sure that the true behvaior of the series resistance is not a linear function of temperature but the temperature-accuracy has to be improved considerably to study this relation. Also, the temperature coefficient of series resistance appears too high if it is considered only as a purely resistive process. We suppose that, probably, there are problems or limitations in the double exponential model and to study this effect it is necessary to better the I–V curves.

Another example is the value of the $\chi^2_{\text{red.}}$ for the saturation current constants in Table 3, they indicate that the Wolf *et al.* approach[6] is still valid, which was used in this work. The theory of Cerofolini and Polignano[17] presents a better approach to the Shockley–Read–Hall generation–recombination mechanism, which corresponds to the second exponential of eqn (4). But this can be tested only by more exact I–V curve measurements mostly concerning the accuracy of the device temperature.

Acknowledgements—One of the authors (NV) is grateful to Conselho Nacional de Pesquisas (CNP_q-RHAE) of Brazil for the award of research fellowship, process number 260173/92-4 (NV). The authors wish to thank Dr Meinolf Blocs for valuable contributions. We acknowledge too Mr Richard Menner and Dr H. W. Schock for stimulating this work and also for measurements performed in his laboratory.

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