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A NEW METHOD FOR THE EVALUATION OF SOLAR CELL PARAMETERS

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Summary

A new method is presented that is capable of resolving the parameters in a double-exponential model with which the electrical characteristics of a crystalline-silicon solar cell are analysed. This method gives not only open-circuit voltage, short-circuit current, fill factor and efficiency, but also diode saturation currents, light-generated current, series resistance and shunt resistance, all from one measurement under AM 1 illumination. The experimental set-up used for *I-V* measurement and automated data handling is described. A fast computer fit procedure is introduced which resolves all parameters from one measurement. The errors in the parameter values obtained are studied. A comparison of these values for a number of *I-V* measurements of solar cells with different internal physical properties is given, in order to illustrate the utility of the method for unravelling various electrical processes in a solar cell.

1. Introduction

The *I-V* characteristics of a crystalline-silicon solar cell can be represented by a two-diode model [1-5]. In this model the various recombination and generation processes in the solar cell under illumination are represented by two diodes with different exponential behaviour. In addition, the light-induced current and the series and shunt resistance are included. Figure 1 shows the electrical equivalent circuit of this model. The corresponding *I-V* characteristics are given by the implicit expression

$$I(V) = I_L - I_{01}(\exp(\gamma(V + IR_{se})) - 1)$$
$$- I_{0m}\left(\exp\left(\frac{\gamma}{m}(V + IR_{se})\right) - 1\right) - \frac{V + IR_{se}}{R_{sh}} \tag{1}$$

where $\gamma = e/kT$, and R_{se} and R_{sh} (series and shunt resistance respectively), I_{01} and I_{0m} (diode saturation currents), m (diode factor) and I_L (generated
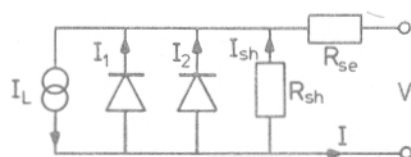
Fig. 1. Electrical equivalent circuit of a crystalline-silicon solar cell under illumination.

current) are free parameters; e is the elementary charge, k the Boltzmann constant and T the absolute temperature.

Usually m is chosen to be 2.0. In this case, in a first approximation the first diode (with ideal exponential behaviour) mainly represents the diffusion current, which is influenced by the properties of neutral regions in the cell. The second diode can then be related to the generation/recombination current which finds its origin in the depletion area. Therefore this model is very useful for the study of electrically active defects in p–n junction devices like solar cells. This model is of interest especially when both diodes are of significant importance, *i.e.* for cells in which defect-induced processes in the depletion area play a role (*e.g.* cells made by ion implantation and laser annealing [6,7], texturized (poly-Si) [8] cells, etc.). In some cases m values different from 2.0 are used in this model. However, it then seems difficult to clearly attribute both diodes to specific physical processes in the junction.

Several methods have been proposed for the determination of the free parameters in this model from an I-V measurement. However, these methods either require measurements over a wide dynamic range (over four orders of magnitude) [5,9] or are based on multiple measurements [10] and usually yield values for only some of the parameters [9–11].

We present here a general approach capable of resolving not only open-circuit voltage, short-circuit current, fill factor and efficiency but also series and shunt resistance, generated current and the diode parameters in an accurate way, from one simple I-V measurement under illumination. I-V curves have been measured automatically over a dynamic range of less than three orders of magnitude. Consequently the experimental set-up is relatively simple. A simplex minimization algorithm [12] is used in a curve-fitting procedure [13] to resolve all parameters. The simplicity of the experimental techniques and the fast and accurate computer evaluation of all cell parameters at once from one measurement makes this method important in an environment in which, during solar cell manufacture (either on a laboratory or an industrial scale), fast feedback of the cell characteristics to the production process is necessary.

2. Experimental procedure

A schematic diagram of the experimental set-up is given in Fig. 2. The solar cells are illuminated by a solar simulator provided with a xenon arc
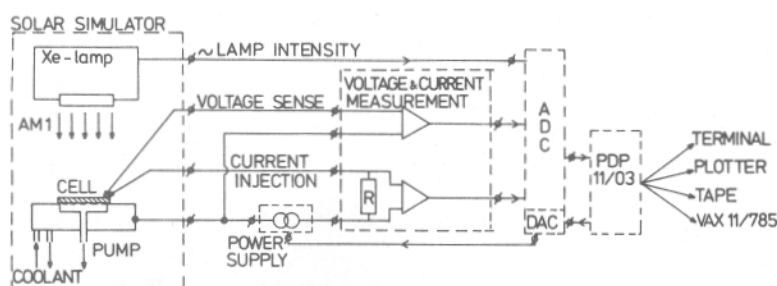
Fig. 2. Experimental configuration used for I-V measurements of solar cells.

lamp. Our set-up is provided with a temperature regulated, gold plated susceptor to which the cells are held using a vacuum. This results in good electrical contact and reduces the rise in cell temperature during measurement to less than 0.5 °C. A reference cell which can be inserted into the light beam is used for intensity calibration at 1000 W m^{-2} of the homogenized AM 1-filtered light beam. Lateral illumination inhomogeneity on the 2 × 2 cm^2 cells is within 2.0%. A signal proportional to the illumination level is measured in the light beam. This signal is used for feedback to the lamp power supply and results in corrections in the lamp intensity in less than 20 ms. It is fed to a 10-bit analogue to digital converter (ADC) connected to a DEC PDP-11/03 microcomputer. By this means accurate monitoring of the lamp stability during a measurement can be achieved. When lamp intensity variations are less than 1.0%, a measurement is considered to be good enough for further interpretation.

Via a 10-bit digital to analogue converter (DAC) the microcomputer triggers a power supply which is in a current circuit with the solar cell. The voltage across this supply sweeps from -1.0 to $+1.0$ V in 10 s. Both current and voltage are sampled, the current by measuring the voltage over a 200 mΩ precision resistance in the circuit with the power supply and the cell, and the voltage in an additional electrical circuit. The measured values are fed to two 10-bit ADCs. In this way 1024 measurements of V and $I(V)$ are stored in the microcomputer. One bit in the ADCs corresponds to 0.6 mA for current (range, -300 to 300 mA) and 2.0 mV for voltage (range, -1.0 to 1.0 V) respectively.

After the measurement of all I-V quadrants, I_{sc} (short-circuit current) and V_{oc} (open-circuit voltage) are estimated (I_{sc} to within 0.05 mA and V_{oc} to within 0.5 mV) by linear interpolation through a few measured points in the area around $V = 0$ and $I = 0$ respectively. The maximum power point is also estimated directly, by searching for the maximum in the V-$I(V)$ product from the measured data set. Fill factor (FF) and efficiency (η) can then easily be calculated. The whole measured curve and all calculated parameters are then automatically plotted. A complete measurement, including estimates of these cell parameters of first interest and the plotting of the

I-V curve, can be achieved within a minute. All data were sent to a DEC VAX-11/785 computer which was used for the further evaluation.

3. Curve-fitting procedure

In order to determine values for the free parameters of the model so that the theoretical curve as given in eqn. (1) fits the measured one, a simplex minimization method is used. In this method [12], a search is made through parameter space to minimize a χ^2 value [13] defined as

$$\chi^2 = \sum_{i=1}^{N} \frac{1}{N-5} \left(\frac{I_{\mathrm{meas},i} - I_{\mathrm{calc},i}}{\sigma_I} \right)^2 \tag{2}$$

where N is the total number of measured points, $I_{\mathrm{meas},i}$ the measured I value and $I_{\mathrm{calc},i}$ the calculated I value, σ_I being the standard deviation in I_{meas}. In this summation the current residues are scaled by a constant factor, the standard deviation in I_{meas}, determined by fluctuations in the lamp intensity during a measurement which give rise to variations in the measured current. When the current is sampled at equidistant voltage values, the right relative weight is obtained for all measurements. For higher positive voltages the measured point density becomes exponentially lower but this is compensated by the exponentially increasing contribution of the measured points to χ^2 for increasing voltage. A good fit of the theoretical curve to the measurements is obtained when χ^2 is near unity; then discrepancies between fit and measurements are near σ_I.

The search through parameter space starts at parameter values calculated as follows, assuming $R_{\mathrm{se}} \ll R_{\mathrm{sh}}$.

From eqn. (1) it can be derived that

$$\left(\frac{\partial I}{\partial V} \right)_{I=I_{\mathrm{sc}}} = -\frac{1}{R_{\mathrm{sh}}} \tag{3}$$

Therefore R_{sh} is estimated by calculating the slope of a first-order polynomial through 20 measured points around $V = 0$. The intercept of the calculated polynomial with the axis $V = 0$ (I_{sc}) can be chosen as a starting value for I_{L}.

It is evident that slight variations in m result in a large variation in the shape of the calculated curve. Therefore the first estimates of the parameter values as described in this paragraph are all calculated at a certain fixed value of m. For reasons given earlier in Section 1, $m = 2$ is used.

When it is assumed that both diode currents are of the same order of magnitude at $V = V_{\mathrm{oc}}$, starting values for I_{01} and I_{02} can be determined in the following way. From eqn. (1) it is derived that at $V = V_{\mathrm{oc}}$ the sum of the diode currents approximates I_{L}.

$$I_{\mathrm{L}} \approx I_{01}(\exp(\gamma V_{\mathrm{oc}}) - 1) + I_{02}\left(\exp\left(\frac{\gamma}{2}(V_{\mathrm{oc}})\right) - 1\right) \tag{4}$$

For determination of starting values both diode contributions are taken to be the same and it is estimated that

$$I_{01} = \frac{1}{2} \frac{I_L}{\exp(\gamma V_{oc})}$$

and

$$I_{02} = \frac{1}{2} \frac{I_L}{\exp\left(\dfrac{\gamma}{2} V_{oc}\right)}$$

(5)

For V_{oc} the estimate obtained from the measurement is used as described in section 2, and for I_L the starting value calculated as described above is used.

From the slope of the I-V curve at $V = V_{oc}$ a starting value for R_{se} can be determined. This can be done in a simple way when a one-diode approximation is used. The corresponding I-V characteristic is given by

$$I(V) = I_L - I_{0n} \left(\exp\left(\frac{\gamma}{n} (V + IR_{se})\right) - 1 \right) - \frac{V + IR_{se}}{R_{sh}}$$

(6)

By substituting $n = 1$ and $n = 2$ in this equation, two R_{se} values can be calculated. As our model is a superposition of two diodes with $n = 1$ and $n = 2$ respectively, these values can be used as boundary values for R_{se}. First, in a way similar to the calculation of the starting values for I_{01} and I_{02}, an estimate of I_{0n} is determined

$$I_{0n} = \frac{I_L}{\exp\left(\dfrac{\gamma}{n} V_{oc}\right)}$$

(7)

From eqn. (6) it is possible to derive

$$\left(\frac{\partial I}{\partial V}\right)_{V = V_{oc}} = - \left(R_{se} + \frac{1}{\gamma I_{0n} \exp\left(\dfrac{\gamma}{n} V_{oc}\right)} \right)^{-1}$$

(8)

Substitution of eqn. (7) in eqn. (8) yields

$$\left(\frac{\partial I}{\partial V}\right)_{V = V_{oc}} = - \left(R_{se} + \frac{1}{\dfrac{\gamma}{n} I_L} \right)^{-1}$$

(9)

so that the following can be estimated

$$R_{se} = - \left(\left(\frac{\partial I}{\partial V}\right)_{V = V_{oc}} \right)^{-1} - \left(\frac{\gamma}{n} I_L\right)^{-1}$$

(10)

when $(\partial I/\partial V)_{V=V_{oc}}$ is calculated. This is done by calculating the slope of a first-order polynomial through 20 measured points around $V = V_{oc}$. When $n = 1$ is taken in eqn. (10) an underestimate of R_{se} is obtained; an overestimate is obtained when $n = 2$. As a starting value for the double-exponential model the average of these boundary values is taken.

With these calculated first estimates for the five parameters R_{sh}, I_L, I_{01}, I_{02} and R_{se} the minimization procedure is started. The fastest convergence is obtained when evaluation of R_{sh} and I_L is started in the region $V = (-1.0, 0.25V_{oc})$. When these variables are determined accurately the convergence procedure continues in both the first and the fourth quadrant with a variation of the parameters I_{01}, I_{02} and R_{se}. The fit procedure is completed by varying all parameters to minimize χ^2 for all quadrants together. In total about 150 steps through parameter space turned out to be sufficient for an accurate determination of the parameters.

4. Results

Results are shown for I-V measurements of solar cells made by ion implantation and laser annealing [6,7] of 2×2 cm^2 mono-crystalline Si samples.

MEASURED	
V_{oc} (mV)	561.
I_{sc} (mA)	80.3
FF	0.75
η (%)	8.5

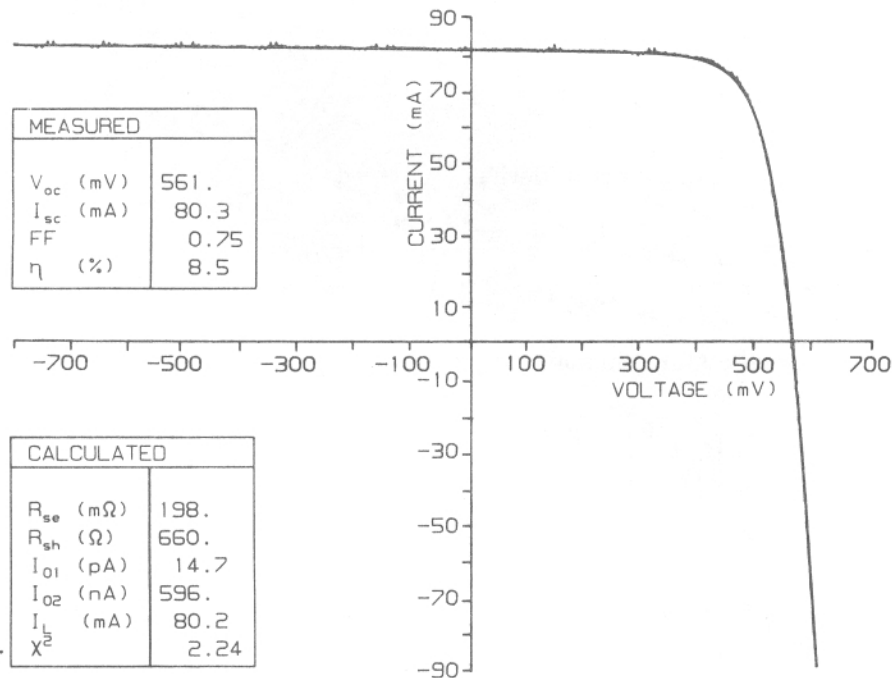| CALCULATED	
R_{se} (mΩ)	198.
R_{sh} (Ω)	660.
I_{01} (pA)	14.7
I_{02} (nA)	596.
I_L (mA)	80.2
χ^2	2.24

Fig. 3. Typical example of a measured I-V curve and the calculated fit curve for the double-exponential model.

4.1. Convergence

The results were found to be independent of the starting values. In Fig. 3 a typical example of a measured I-V curve and the calculated fit curve are shown. A χ^2 value of 2.24 was obtained from which it is apparent that our model gives a relatively good description of the measured I-V curve.

When so many parameters are involved, investigation of the uniqueness and errors in the values found is a problem of interest. This problem has been studied for the double-expontial model with $m = 2$. The contour plots in Fig. 4a–c show how changes of the parameters I_{01}, I_{02} and R_{se} around the calculated (minimal χ^2) values are related to each other via constant χ^2. The results indicate the existence of one clear minimum for χ^2. Similar calculations have been performed for I_L and R_{sh} yielding similar results. It is con-
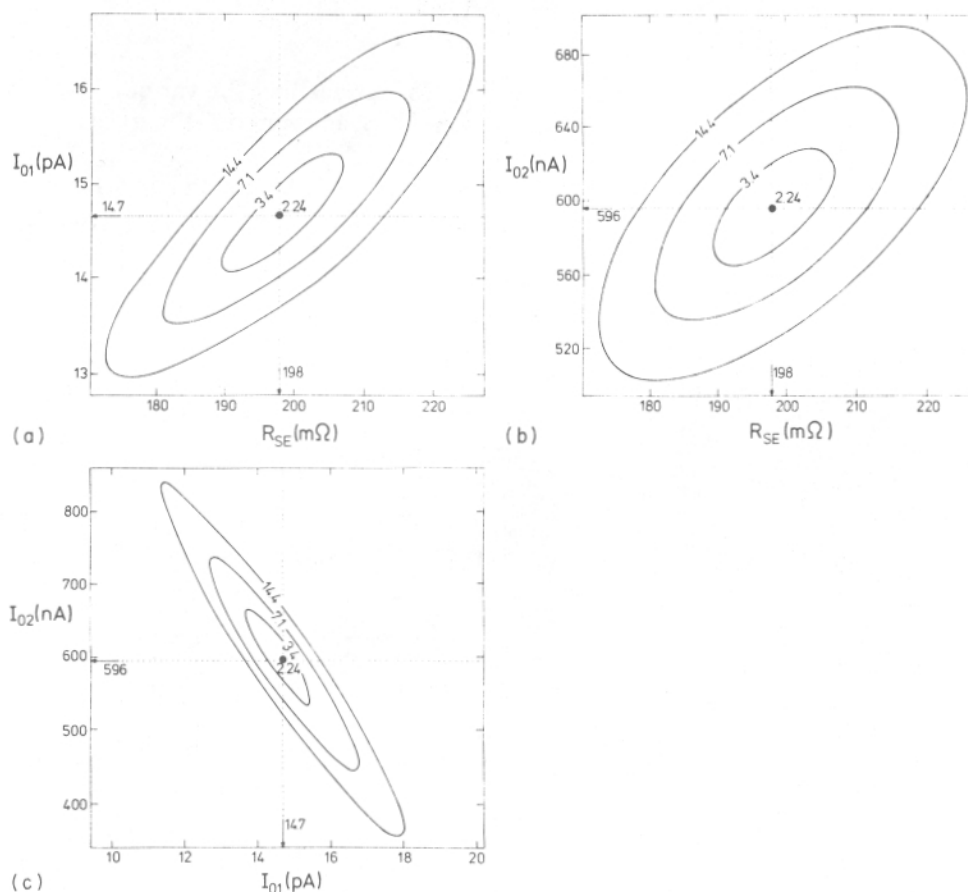

Fig. 4. χ^2 contour plots for R_{se}, I_{01} and I_{02}: (a) I_{01} vs. R_{se}; (b) I_{02} vs. R_{se}; (c) I_{02} vs. I_{01}. Contours correspond to χ^2 values of 3.4, 7.1 and 14.4 respectively; $\sigma_I = 0.3$ mA; $\chi_{min}^2 = 2.24$.

cluded that there is one unique parameter set related to a found minimum value of χ^2.

For the final evaluation of the errors in the calculated parameter values two types of error have to be taken into account. Firstly a statistical error due to scatter in the data, which in our case can be neglected in view of the minimum χ^2 value of 2.24 [13]. Secondly a physical error should be taken into account, related to the question as to how well a mathematically determined fit curve for a model with a limited number of free parameters describes the physical measurement. Due to the specific definition chosen for χ^2 and the limitations of the model, a curve-fitting procedure as described here can yield parameter values which are slightly different from their real physical values. By comparing the measured curve to plots of I-V curves calculated with parameter values slightly different from the optimum, it was found that the accuracy for I_{01} and I_{02} is better than 7%, for R_{se} better than 5% and for I_L and R_{sh} better than 0.5%.

4.2. Parameter determination

To show the utility of the method for unravelling the various electrical processes in a solar cell, additional examples of measured I-V curves and the calculated fit curves are given in Figs. 5-7.

Figure 5 shows an I-V measurement of a cell with the relatively low shunt resistance of 73.2 Ω. Even in this case the fit procedure yields good results.
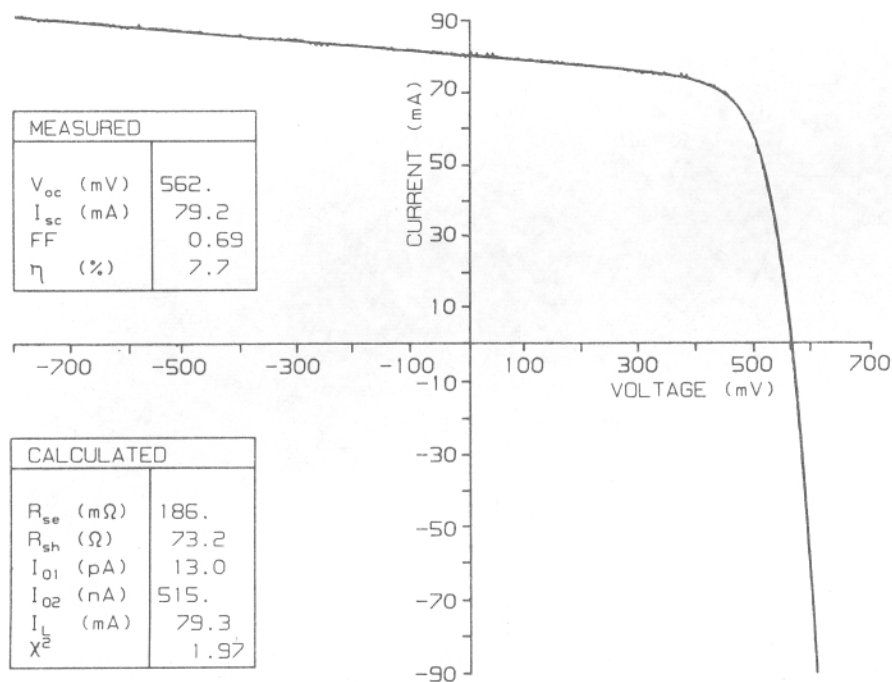

MEASURED	
V_{oc} (mV)	562.
I_{sc} (mA)	79.2
FF	0.69
η (%)	7.7

CALCULATED	
R_{se} (mΩ)	186.
R_{sh} (Ω)	73.2
I_{01} (pA)	13.0
I_{02} (nA)	515.
I_L (mA)	79.3
χ^2	1.97

Fig. 5. Measured I-V curve and calculated fit curve for a cell with low R_{sh}.

MEASURED

	1	2
V_{oc} (mV)	571.	557.
I_{sc} (mA)	77.8	79.8
FF	0.74	0.75
η (%)	8.3	8.3

CALCULATED

	1	2
R_{se} (mΩ)	175.	198.
R_{sh} (Ω)	218.	298.
I_{01} (pA)	9.70	20.4
I_{02} (nA)	451.	453.
I_L (mA)	78.0	79.9
χ^2	1.97	2.64
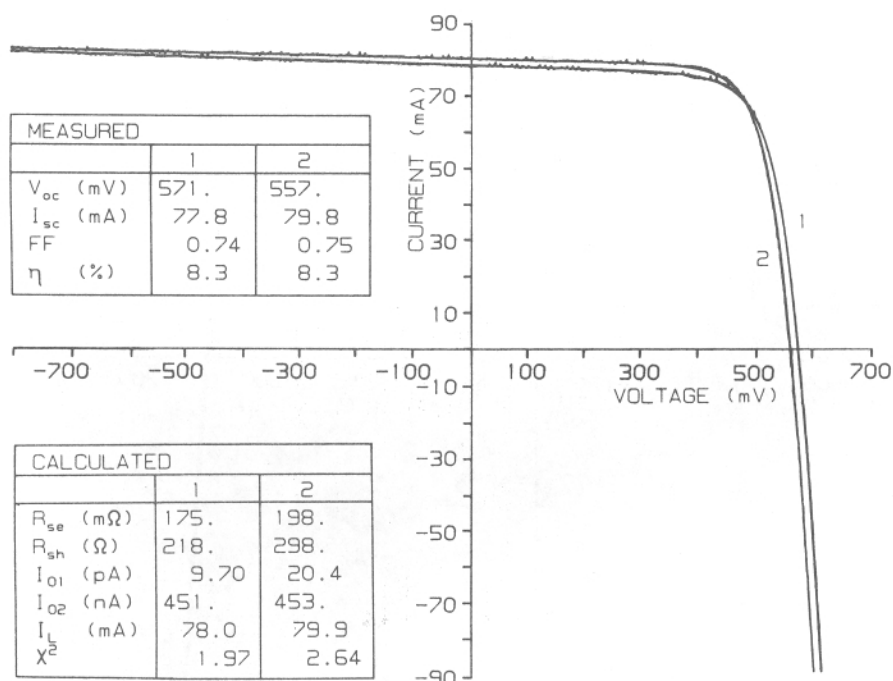
Fig. 6. Measured I-V curves and calculated fit curves for two cells with different I_{01} values.

Figure 6 shows two I-V measurements of cells with a difference in V_{oc} of 14 mV. As can be seen from the parameter values found, as indicated in the figure, it can be concluded that the low V_{oc} value of curve 2 can be attributed to an increased contribution of I_{01} compared to the value for curve 1. In this case this leads to the conclusion [6] that the emitter region of cell 2 contains more electrically active defects than the emitter region of cell 1.

Figure 7 shows the result of I-V measurements of two cells with a small difference in V_{oc} (only 5 mV). Here again, this difference can easily be related to the difference in the parameter values obtained. From the fit procedure an I_{02} value for curve 2 twice as high as that for curve 1 was obtained. It is therefore concluded that electrically active defects in the depletion area are more pronounced in cell 2 than in cell 1.

The above examples clearly show that our analysis procedure can be used in the optimization of silicon solar cells [6].

5. Conclusions

The method described gives fast convergence to the parameters in a double-exponential model with which the I-V characteristics of a crystalline-silicon solar cell are analysed.
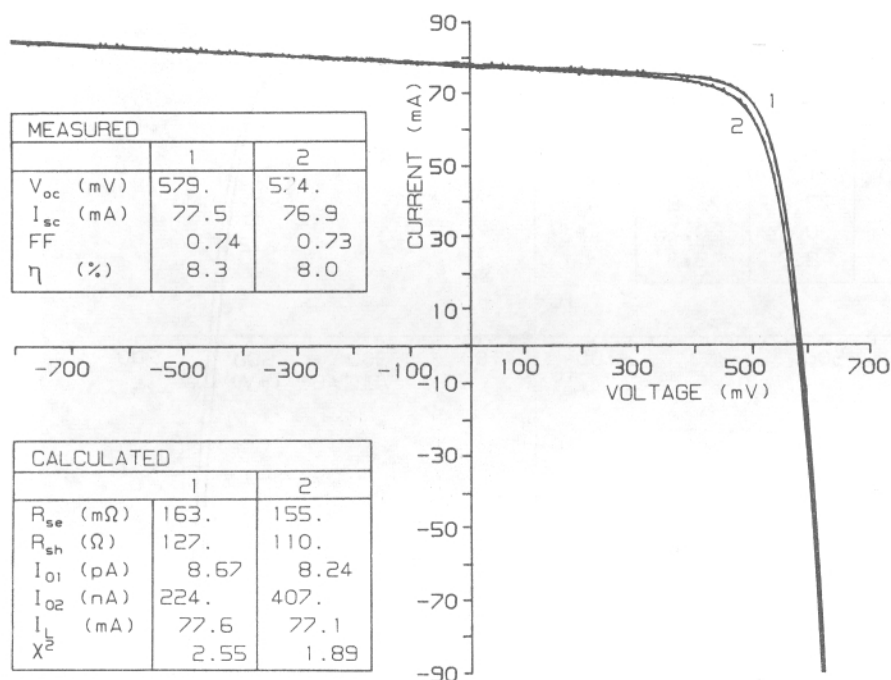
Fig. 7. Measured I–V curves and calculated fit curves for two cells with different I_{02} values.

Accurate parameter values can be determined from one measurement under the conditions relevant for solar cell operation (one sun illumination) and the information of all quadrants of the $I(V)$ curve is used. The good quality of the fit indicates that the model gives a good description of the electrical characteristics of the cell.

The relation of the two-diode model with $m = 2$ to physical processes and the relatively simple experimental techniques used, make this method suitable for the study of electrically active defects in a solar cell. The fast measurement and parameter evaluation are of particular interest when feedback to a production process is necessary.

Acknowledgments

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