THE INTERACTIVE COMPUTER PROGRAM TO FIT I-V CURVES OF SOLAR CELLS

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ABSTRACT: Computer program has been developed to fit illuminated I-V curves of solar cells. The main effort has been put to achieve reliable fit rather then the optimum speed. A concept of a new weight factor modifying an object function has been introduced. I-V curves of the cells fabricated and measured in different laboratories were analysed. Results are compared with other concepts of the object functions. It is shown that the best fit is achieved with the exponential weight which gives the best linearization of the I-V curves in respect to the parameters being calculated.

1. INTRODUCTION

I-V curve of any illuminated solar cell is commonly described by either of three theoretical diode models defined as follows:

SEM (Single Exponential Model):

$$(1)\quad I = I_{ph} - I_s\left[\exp\left(\frac{V+I\cdot R_s}{AV_t}\right)-1\right] - \frac{V+I\cdot R_s}{R_{sh}}$$

DEM (Double Exponential Model):

$$(2)\quad I = I_{ph} - I_{s1}\left[\exp\left(\frac{V+I\cdot R_s}{V_t}\right)-1\right] - I_{s2}\left[\exp\left(\frac{V+I\cdot R_s}{2V_t}\right)-1\right] - \frac{V+I\cdot R_s}{R_{sh}}$$

VDEM (Variable Double Exponential Model):

$$(3)\quad I = I_{ph} - I_{s1}\left[\exp\left(\frac{V+I\cdot R_s}{V_t}\right)-1\right] - I_{s2}\left[\exp\left(\frac{V+I\cdot R_s}{AV_t}\right)-1\right] - \frac{V+I\cdot R_s}{R_{sh}}$$

where the parameters to be found are Iph - generated photocurrent, R_s and R_{sh} - series and shunt resistance, respectively, I_s, I_{s1}, I_{s2} - saturation currents and A is diode ideality factor; V_t is equal to kT/e where k, e and T have their usual meaning.

SEM and DEM models (nomenclature taken after Charles et al. [1]) require finding five independent parameters whereas in the case of VDEM there are six of them.

Double exponential model is most closely related to the physical phenomena in solar cells under low injection conditions. Usually A is chosen as equal 2.0 and in such case first diode represents diffusion current which is influenced by the neutral regions, either emitter or base, whereas second diode is usually attributed to generation-recombination phenomena within the space charge region of a solar cell. Sometimes A is taken as a variable parameter (VDEM model) giving often values higher than 2.0 which has no physical meaning and is used merely for better numerical fit of the I-V curve.

Assuming the appropriateness of the theoretical model and sufficient quality of measurement, the basic problem when fitting a given experimental characteristic to an analytical model is to define a proper object function for the difference between two characteristics, theoretical and experimental. Then the minimum of this function must be found thus defining the best fit parameters.

Most accurate fitting methods are based on the iterative techniques which require extensive computer calculations. For this reason, until recently, many authors have been looking for fast analytical methods to extract solar cell parameters from the measured data [1,2]. Now, when the relatively fast personal computers are widely available time consuming is not a critical factor and the iterative exact fitting techniques are very attractive for on-hand laboratory use.

The aim of this work was to define an optimum object function to fit illuminated curves of solar cells by introducing an appropriate weight function

2. DEFINING OBJECT MINIMALIZATION FUNCTIONS

The least mean square (LMS) fit given as

$$(4)\quad LMS = \sqrt{\frac{1}{N}\sum_{j=1}^{N}\left[(I_{exp})_j - (I_{theor})_j\right]^2}$$

is known to be an excellent technique when the measured curve has a linear character in respect to the parameters that are to be fitted. Unfortunately this is not the case for I-V curves of solar cells and hence some authors tried to use either more sophisticated fit techniques [3,4,5] or to apply different object functions [1,6]. In order to obtain right relative weight Polman et al. [7] also proposed sampling the current of the cell at equidistant voltage values.

The most frequently modification of the LMS is an object function defined as follows

$$\text{(5)}\quad SD = \sqrt{\frac{1}{N}\sum_{j=1}^{N}\left[(I_{exp})_j - (I_{theor})_j\right]^2 / \left(I_{exp}\right)_j^2}$$

and it is usually referred as Standard Deviation (SD)

The use of both these criteria however, tends to a very good fit to the part of the curve near the open circuit region at the expense of the quality of fit in the short circuit region

Chan et al [6] proposed an original object function, hereafter referred as "Area", where minimisation is taken over the area which can be found between experimental and theoretical curves, i.e.

$$\text{(6)}\quad \Delta A = \sum_{j=1}^{N-1}\frac{1}{2}\times ABS\left[(I_{th})_j + (I_{th})_{j+1} - (I_{exp})_j - (I_{exp})_{j+1}\right]\times\left[(V_{exp})_{j+1} - (V_{exp})_j\right]$$

and when we define the total area under the measured curve as

$$\text{(7)}\quad Area = \sum_{j=1}^{N-1}\frac{1}{2}\times\left[(I_{exp})_j + (I_{exp})_{j+1}\right]\times\left[(V_{exp})_{j+1} - (V_{exp})_j\right]$$

then a parameter ε describes the quality of the fit

$$\text{(8)}\quad \varepsilon = \frac{\Delta A}{Area}\times 100\%$$

Parameter ε as defined in Eqn. (8) has been used in this work to estimate the final quality of fit for different object functions.

2.1. SIMPLE ALGORITHM TO DEFINE WEIGHT FACTOR FOR OBJECT FUNCTIONS:

Let us define factor as an array of number values that are used to modify LSM value given by (4). It is calculated in such way that its values are always in the range <0..1> regardless what is the range and number of the data taken into calculations. It is always recalculated whenever the set of experimental data is changed. This allows to avoid confuses with overflow problems during calculations and to compare quality of fit for different object functions. The whole procedure may be described briefly as follows (the assumption is made that the experimental points are labelled consecutively starting from the negative voltage values):

Step 1°: TRANSFORMATION OF MEASURED DATA VALUES i.e. all voltage values of the measured curve are transformed proportionally to the values within <Max..1> according to the following formula:

$$(V_{tr})_j = \frac{Max}{A\cdot(V_{exp})_j + B}$$

(9) where

$$A = \frac{Max - 1}{(V_{exp})_N - (V_{exp})_1} \quad\text{and}\quad B = Max - A\cdot(V_{exp})_1$$

where Max is an arbitrary positive number, chosen as 10 in a program, and $(V_{exp})_1$ and $(V_{exp})_N$ are the lowest and highest values of measured voltage, respectively.

2° CALCULATION OF A WEIGHT FACTOR ARRAY:

(10) SD: $(factor)_j = 1$

(11) SD(modif.): $(factor)_j = (V_{exp})_j / Max$

(12) Logarithmic: $(factor)_j = Ln[(V_{exp})_j] / Ln(Max)$

(13) Exponential: $(factor)_j = 1 - 1.72/[Exp(V_{exp})_j - 1]$

where j is an index of the I-V data point. The object function is calculated as follows:

$$\text{(14)}\quad SD(modif.) = \sqrt{\frac{1}{N}\sum_{j=1}^{N}(factor)_j\times\left[(I_{exp})_j - (I_{theor})_j\right]^2}$$

Object function modified by factor equal to unity, Eqn. (10), is in fact equivalent to SD given by (4).

Once the object function is defined SIMPLEX DOWNHILL method [8] is used to minimise it.

3. RESULTS

Results of fitting are presented for the cells measured in either of three different laboratories, i.e. Solar Lab, TU Wrocław (Poland), IMEC, Leuven (Belgium) or Solar Experimental Station, Kozy (Poland).

The meanings of denotations on the plots are as follows:

=1	- LMS, Eqn. (4);
1/Imeas	- Eqn. (5);
Area Dev.	- Eqn. (6);
Exponential	- Eqns. (13) and (14);
Logarithmic	- Eqns. (12) and (14);
1/Imeas.normalized	- Eqns. (11) and (14);

The relative error of fit defined as

(15) $dI/I_{meas} = (I_{meas} - I_{theor})/I_{meas}$

s shown under each I-V curve as it is een on the screen of the computer in the ourse of calculations.

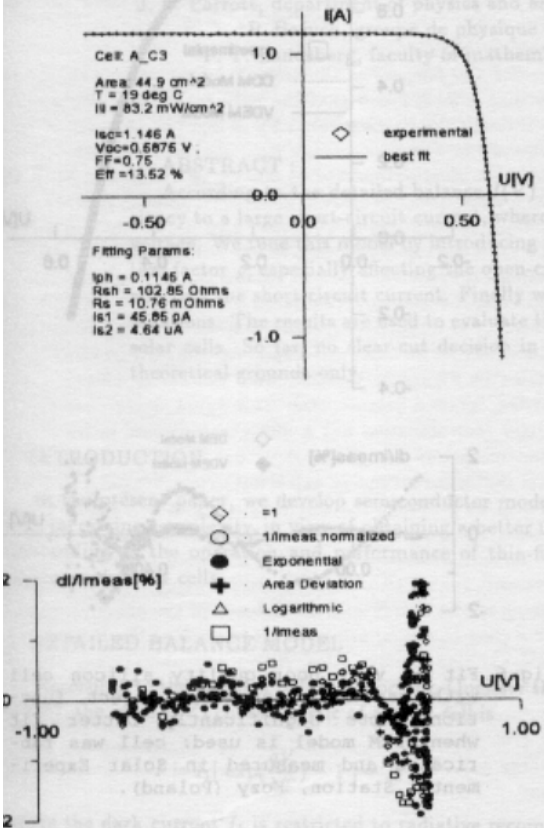

Fig.1 Typical fit (DEM) and a relative fit error dI/I_{meas} for medium quality silicon cell with use of different object functions; cell was manufactured in Solar Experimental Station in Kozy (Poland) and measured in Solar Lab, TU Wrocław.

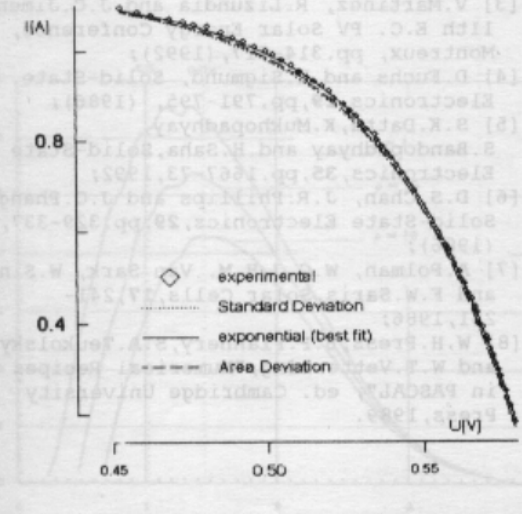

Fig.2 Small fragment of the I-V curve from Fig.1 showing subtle differences in the quality of fit for different object functions.

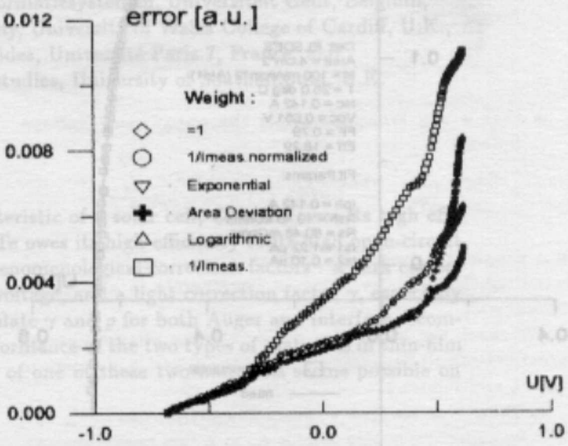

Fig.3 Plot of increment of ΔA as defined by (6) and calculated for I-V curves from Fig.1 showing almost linear dependence for the exponential-type object function.

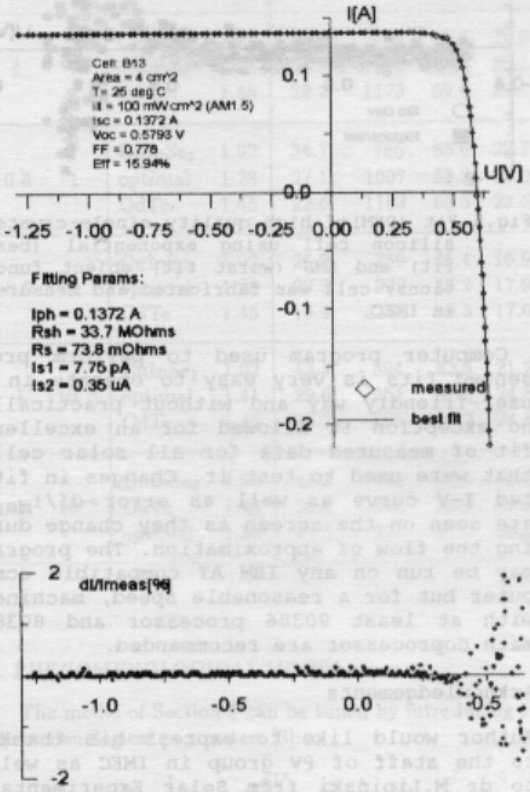

Fig.4 Fit (DEM) of high quality multi-crystalline silicon cell using exponential object function; note the extended range of voltage and current measured and preferential density of data points taken in the range of "flat" part of the I-V curve; cell was fabricated and measured in IMEC.

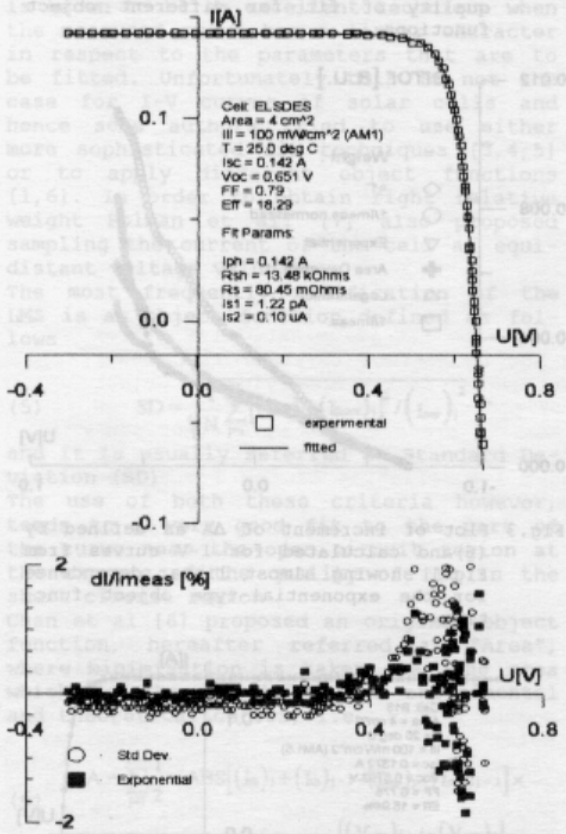

Fig.5 Fit (DEM) of high quality single-crystal silicon cell using exponential (best fit) and LMS (worst fit) object functions; cell was fabricated and measured in IMEC.

Computer program used to perform presented fits is very easy to operate in a user-friendly way and without practically no exception it allowed for an excellent fit of measured data for all solar cells that were used to test it. Changes in fitted I-V curve as well as error dI/I_{meas} are seen on the screen as they change during the flow of approximation. The program may be run on any IBM AT compatible computer but for a reasonable speed, machines with at least 80386 processor and 80387 math coprocessor are recommended.

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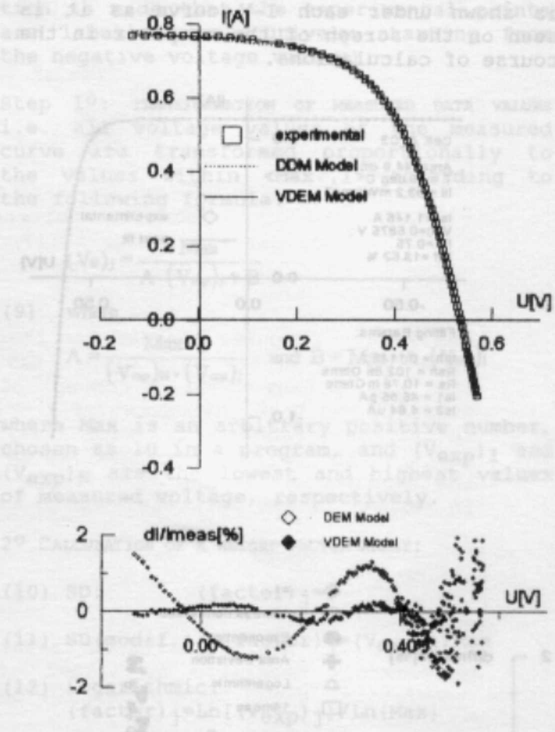

Fig.6 Fit of very poor quality silicon cell with use of exponential object function; note significantly better fit when VDEM model is used; cell was fabricated and measured in Solar Experimental Station, Kozy (Poland).

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