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AN IMPROVED TECHNIQUE FOR THE DETERMINATION OF SOLAR CELL PARAMETERS

SWAPAN K. DATTA
Department of Physics, City College, Calcutta 700 009, India
and
K. MUKHOPADHYAY, S. BANDOPADHYAY and H. SAHA
Department of Electronics and Telecommunication Engineering, Jadavpur University, Calcutta 700 032, India

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Abstract—An improved method based on a computer-aided curve fitting technique for the simultaneous determination of the different solar cell parameters (R_s, R_{sh}, A, I_0 and I_{ph}) from single illuminated I–V characteristics has been developed. The technique is very fast and precise. It gives realistic values of the parameters for solar cells of various qualities and at different levels of illumination. The validity of the method has been checked by comparing it with the values of some of the parameters measured directly by other methods.

NOTATION

V_{oc}	open circuit voltage
I_{sc}	short circuit current
A	diode quality factor
R_s	series resistance
R_{sh}	shunt resistance
I_{ph}	photogenerated current
F.F (or FF)	fill factor
I_o	reverse saturation current
k	Boltzmann constant
T	absolute temperature
q	electronic charge
I_m	current at the maximum power point
V_m	voltage at the maximum power point

1. INTRODUCTION

Evaluation of solar cell parameters from I–V characteristics provides useful guidance about modeling and the direction in which further improvements have to be made. The I–V characteristics of a crystalline silicon solar cell can be represented either by a two diode model[1–3] or by a single diode lumped parameter model[4–6]. The single diode model is however the most popular approximation for solar cells which are under normal operating conditions[4–5]. The determination of solar cell parameters (R_s, R_{sh}, A, I_o and I_{ph}) has been the subject of investigation of a number of workers. Some of the methods involve measurements of illuminated I–V characteristics at different light intensities[7], while others utilize dark and illumination measurements[8] and the rest use data extracted from a single illuminated I–V curve[3,6,9–10]. However, most of the methods yield values for only some of the parameters and in some cases, the evaluation of parameters is based on an analysis ignoring the role of R_{sh} which is not always permissible. A few methods based on curve fitting technique have been proposed for the simultaneous determination of all the parameters from an I–V measurement[3,6]. However, in some cases, the parameter values determined by the least square (L.S.) technique turn out to be unrealistic although a mathematical fit is obtained[6]. In other cases, a first order polynomial is used in the region of I_{sc} and V_{oc} to calculate the shunt resistance and to utilize a relation between R_s and A[3]. However, this requires very accurate measurements ranging over at least three orders of magnitude in the open circuit voltage and short circuit current region of the cell and may lead to inconsistency in the event of an inaccurate determination of the slopes at V_{oc} and I_{sc}. In any case, there is no reported data to test the suitability of these methods over a range of illumination intensities and for different qualities of cells evidenced by a range of fill factors.

In this paper, we have developed a simple, rapid and accurate method for the on-line extraction of solar cell single-diode model parameters from a single automated I–V measurement under illumination. This method is also based on the L.S technique but it eliminates the determination of slope at V_{oc} and I_{sc}. Instead, it utilizes the more convenient guiding relation between A and R_s at the maximum power point. This quick and accurate computer evaluation of all the parameters has been applied for a wide range of illumination intensities from 20 to 100 mW/cm^2 and for different cells with fill factors varying in the range of 0.40–0.78 and efficiency varying in the range of 6–16.5%. The validity of the extracted parameters has been checked by comparing it with the value obtained by alternative direct experimental measurement and also by computing theoretically the fill factors of the cells using these extracted

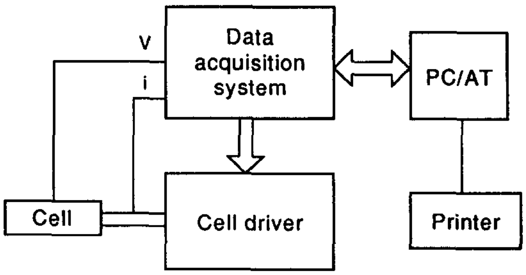


Fig. 1. Schematic diagram of the experimental set up.

parameters and then comparing them with the experimentally determined fill factors.

2. EXPERIMENTAL PROCEDURE

The schematic diagram of the experimental set up is shown in Fig. 1. It consists of a light source, a cell driver circuit, a Keithley 570 Data Acquisition System (DAS), and a microcomputer (PC-AT). The microcomputer supervises system operation through the interface card of System 570. The interface card contains data, address bus buffers, address decoding circuit and users program. The light source is an ELH tungsten halogen lamp.

The cell driver acts as a variable load across the illuminated cell and the electronic load[12] varies from open circuit condition to short-circuit condition of the illuminated cell after getting a triggered pulse from the system 570. The total scanning time is 2–3 s depending upon the settings of scanning time interval through users software. During the scanning, voltage and current are sampled and values are fed to the two input channels of DAS. The signals are processed and routed to the 12 bit A/D converter, allowing the signals to be resolved into 4096 steps. Once the signal is converted, the digital data is fed over the system data bus back to the computer. One bit in the A/D inverter corresponds to 0.5 mA for current (range 0–2 A) and 0.5 mV for voltage (range 0–1.0 V), respectively.

The voltage and current data are stored in the computer and through users' software, the values of I_{sc}, V_{oc}, V_m, I_m, and F.F. are estimated and automatic plotting of measured (I–V) characteristics is obtained within 10 s although the cell needs to be illuminated for only 2–3 s which is the period of scanning. The five physical parameters of the cell are then estimated following the analysis of the (I–V) characteristics and curve fitting procedure, within a minute using a PC-286 microcomputer. For faster systems, it will take less time. The details of the curve-fitting procedure is indicated in Section 3. The theoretical I–V curve computed using these five extracted parameters is also drawn and compared with the experimental I–V curve using the same users software.

3. ANALYSIS OF THE CURRENT-VOLTAGE CHARACTERISTICS AND CURVE-FITTING PROCEDURE

The standard equation of the illuminated output I–V characteristics curves of a solar cell can be written in the single diode one-exponential model as[11]

$$I = I_{ph} - I_o[\exp\{(q/AkT)(V + IR_s)\} - 1] - (V + IR_s)/R_{sh}. \quad (1)$$

Equation (1) contains five parameters I_{ph}, I_o, A, R_s, and R_{sh}, of which only three are independent since the two parameters, I_{ph} and I_o can be expressed as follows

$$I_{ph} = \frac{BI_{sc} - (V_{oc}/R_{sh})\phi}{1 - \phi} \quad (2)$$

and

$$I_o = \frac{BI_{sc} - (V_{oc}/R_{sh})}{\exp(qV_{oc}/AkT)[1 - \exp\{(q/AkT)(I_{sc}R_s - V_{oc})\}]} \quad (3)$$

where

$$B = 1 + (R_s/R_{sh})$$

and

$$\phi = [\exp(qI_{sc}R_s/AkT) - 1]/[\exp(qV_{oc}/AkT) - 1].$$

Equation (1) can be rewritten as

$$I = (1/B)\{I_{ph} - (V/R_{sh})\} - (I_o/B)[\exp\{(q/AkT)(V + IR_s)\} - 1]. \quad (4)$$

The procedure starts with the search for R_{sh} through the parameter space of A, R_s and R_{sh} in the short circuit region since R_{sh} significantly affects only this region of the I–V curve.

By applying the least squares method to eqn (4), we get an expression for R_{sh} as

$$R_{sh} = \frac{a_1}{b_1 - c_1 + d_1} - R_s \quad (5)$$

where

$$a_1 = \sum_i [V_i - V_{oc}\exp\{(q/AkT)(V_i + I_iR_s - V_{oc})\}]^2$$

$$b_1 = \sum_i (I_{sc} - I_i)V_i$$

$$c_1 = \sum_i \{I_{sc}V_i + V_{oc}(I_{sc} - I_i)\} \times \exp[(q/AkT)(V_i + I_iR_s - V_{oc})]$$

$$d_1 = \sum_i I_{sc}V_{oc}\exp([2q/AkT)(V_i + I_iR_s - V_{oc})]$$

and I_i, V_i are the measured curent and voltages.

To find the values of A and R_s, we note that the variations in the values of A and R_s significantly affect only the portion of the I–V curve extending from the open-circuit voltage region to the maximum power point region. In this region, the current varies over a wide range for small changes in voltage and it would therefore be a better approach to express the load voltage V in terms of the current I by rewriting eqn (1) in the form

$$V = [V_{oc} - IR_s] + (AkT/q)\ \ln\{\mathrm{Arg}(I, V)\} \quad (6)$$

where

$$\mathrm{Arg}(I, V) = \left[\frac{I_o + I_{ph} - BI - (V/R_{sh})}{BI_{sc} - (V_{oc}/R_{sh})}\right] \times [1 - \exp\{(q/AkT)(I_{sc}R_s - V_{oc})\}].$$

An examination of eqn (6) and the I–V curve in the above mentioned region reveals that the second term in eqn (6) is much smaller than the first term and can be treated as a correction factor which progressively contributes significantly as the maximum power point region is approached. It can also be seen that in this region, the lower the value of R_{sh}, the higher is its influence in shaping the nature of the I–V curve. By applying the least squares method to get the best suitable value of A assuming the variation of logarithm factor [ln(Arg(I, V))] to be negligible with respect to the variations in A, we get

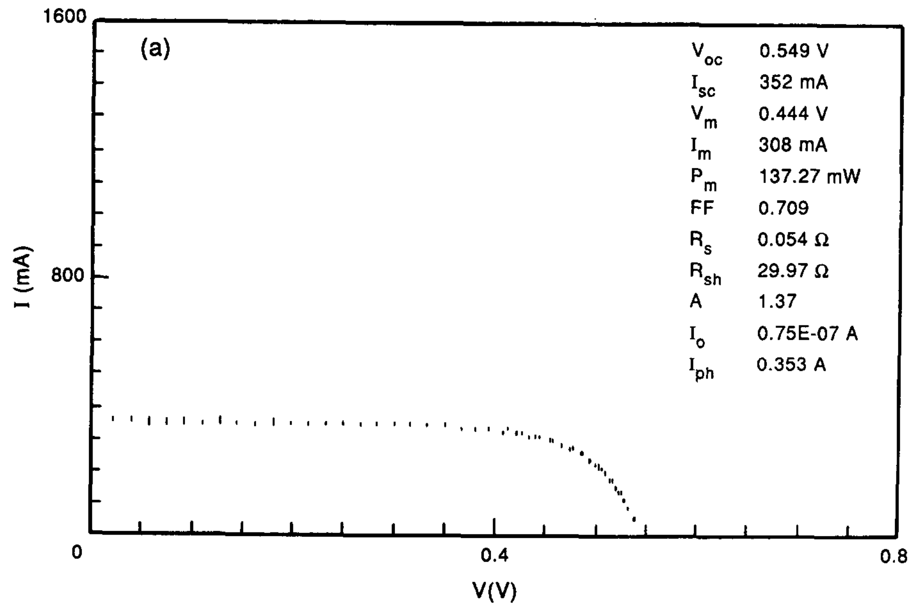
$$A = (q/kT)\cdot[(a_2 + b_2R_s)/c_2] \quad (7)$$

where

$$a_2 = \sum_i (V_i - V_{oc})\cdot \ln[\mathrm{Arg}(I_i, V_i)]$$

$$b_2 = \sum_i I_i \ln[\mathrm{Arg}(I_i, V_i)]$$

$$c_2 = \sum_i \{\log[\mathrm{Arg}(I_i, V_i)]\}^2.$$



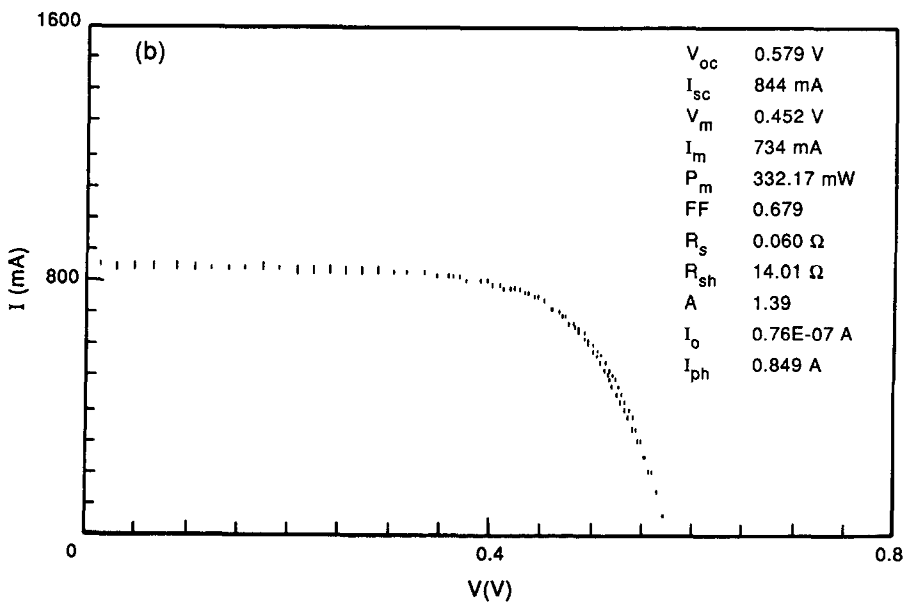


Fig. 2. (a, b) *Caption overleaf.*

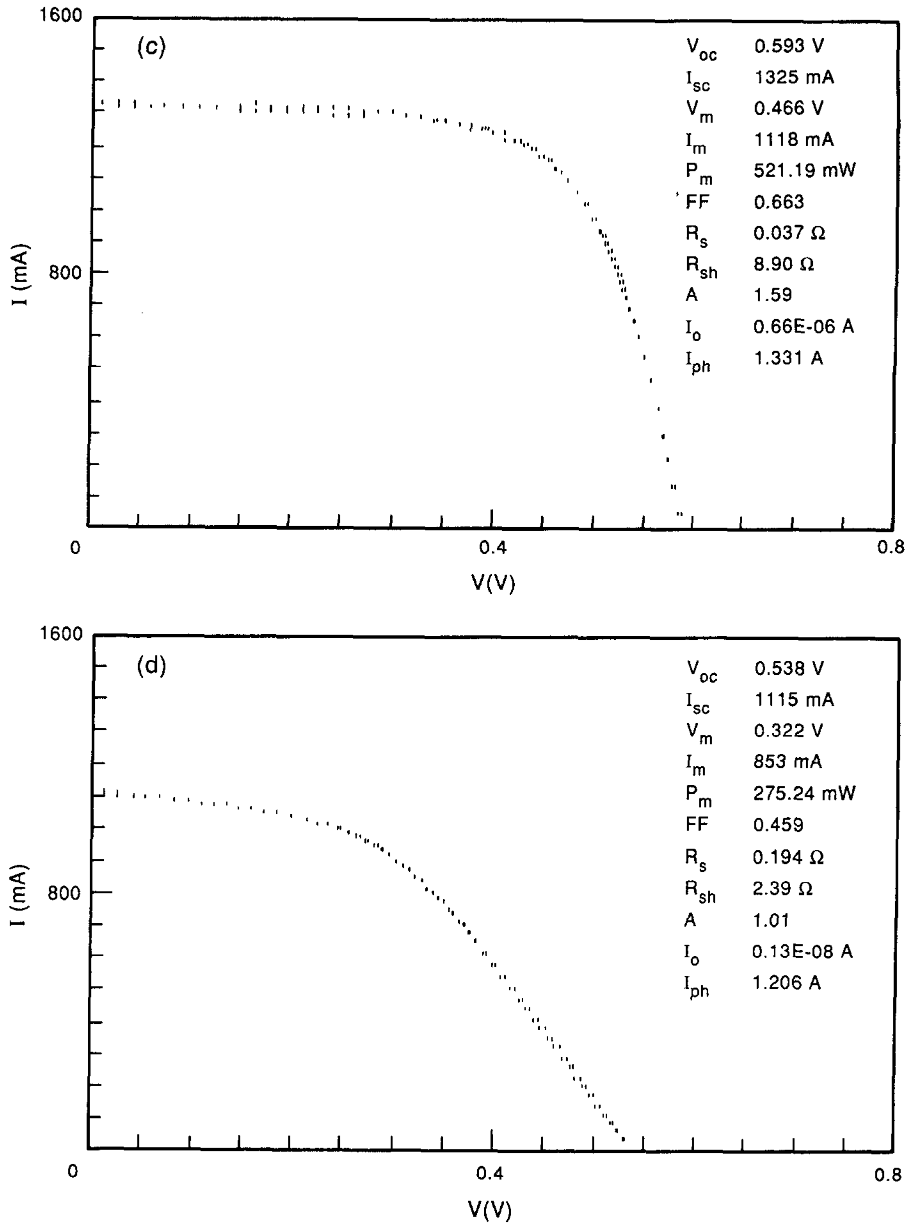


Fig. 2. (c, d).

Fig. 2. Actual and fitted I–V characteristics and different solar cell parameters. (a), (b), (c) are the results of a solar cell at three different illuminations while (d) is for a solar cell with low fill factor and measured at high illumination.

A suitable guiding relation between A, R_s and R_{sh} has been derived using the condition at the maximum power point and is given by

$$R_s = \{(V_{oc} - V_m)/I_m\} - (AkT/qI_m)\ln\left[\frac{BI_{sc} - (V_{oc}/R_{sh})}{\{B(I_{sc} - I_m) + I_o - V_m/R_{sh}\}[1 - \exp\{(q/AkT)(I_{sc}R_s - V_{oc})\}]}\right]. \quad (8)$$

The L.S. minimization technique is not applied here to find out simultaneously the best fit values of A and R_s since these values might not satisfy the exact analytical relation between A and R_s given by eqn (8) and may lead to unrealistic values of A and R_s[6].

On the other hand, the solution procedure is started here in the short-circuit-current region

($I_{sc} > I > 0.85I_{sc}$) to obtain the first estimate of R_{sh} taking $A = 1$ and $R_s = 0$ in eqn (5). The initial values of A along with the first estimate of R_{sh} determine the first estimate of R_s through the guiding relation given by eqn (8). The least-squares minimization procedure according to eqn (7) then evaluates the first estimate of A by utilizing the first estimate values of R_s and R_{sh}. The first estimate values of A and R_s are then fed back to the analysis of R_{sh} in the short circuit current region again to obtain the second estimate of R_{sh} and the whole sequence of operation is repeated to find out the second estimate of A and R_s. This iteration procedure through the parameter space of A, R_s and R_{sh} is continued until the relative current deviations in the short circuit region given by $\Sigma_i \sqrt{(I_{cal} - I_i)^2}/\Sigma_i I_i$ in the short circuit region and the relative voltage deviation given by $\Sigma_i \sqrt{(V_{cal} - V_i)^2}/\Sigma_i V_i$ in the open-circuit to maximum power point region become less than 0.1%, sufficient to give a good fit of the theoretical curve with the measured one. It is found in general that about 100 iteration steps are sufficient for a fairly accurate determination of the parameters A, R_s and R_{sh}. Knowing these values, the other parameters I_o and I_{ph} are also calculated directly by utilizing eqns (2) and (3).

4. RESULTS AND DISCUSSION

The measured and computed I–V characteristics of (i) the texturised 75 mm diameter single crystal silicon solar cells fabricated in the laboratory and (ii) a 4 cm^2, 16.5% efficiency reference cell[13] are shown in Figs 2 and 3. The figures also indicate the extracted best fit values of the parameters $I_o, I_{ph}, A, R_s, R_{sh}$. Table 1 shows the relevant measured and computed data for the various cases. It can be observed that there is an excellent fitting between the calculated curves and the experimental ones for various illumination intensities ranging from 20 to 100 mW/cm^2 under illumination from a tungsten halogen lamp (Sylvania, ELH 300 W) and even for different qualities of cells having fill factors in the range of 0.4–0.78 and efficiencies in the range of 6–16.5%. The present method is therefore applicable to a different range of intensities and different qualities of cells. This is in contrast with the I–V area method[10] which gives even negative R_s values in some cases[9] and maximum power point method[4] which is usable as long as $R_s < 1\ \Omega$ and $R_{sh} > 1000\ \Omega$. It is interesting to note that in the case of comparatively large R_{sh} ($> 100\ \Omega$) and low series resistance ($< 0.1\ \Omega$) the shunt resistance determined accurately by eqn (5) is very close to the approximate value determined by others[3] assuming a first order polynomial. However, the assumption of first order polynomial[3] for low R_{sh} values leads to a large relative error in R_{sh} giving unrealistic best fit values of A and R_s.

To test the validity and utility of the present method, the fill factors have been calculated using the empirical formulation by Green[11] and compared with the experimentally determined ones. In the empirical method, the ideal fill factor of a solar cell is expressed as

$$FF_o = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1}$$

where $v_{oc} = qV_{oc}/AkT$ and the magnitude of the effect of R_s and R_{sh} on the fill factor can be found by introducing a characteristic resistance $R_{ch} = V_{oc}/I_{sc}$. An approximate expression for the fill factor in the presence of series and shunt resistance is then given by

$$FF = FF_o(1 - r_s)\{1 - [(v_{oc} + 0.7)/v_{oc}] \cdot [FF_o/r_{sh}]\} \quad (9)$$

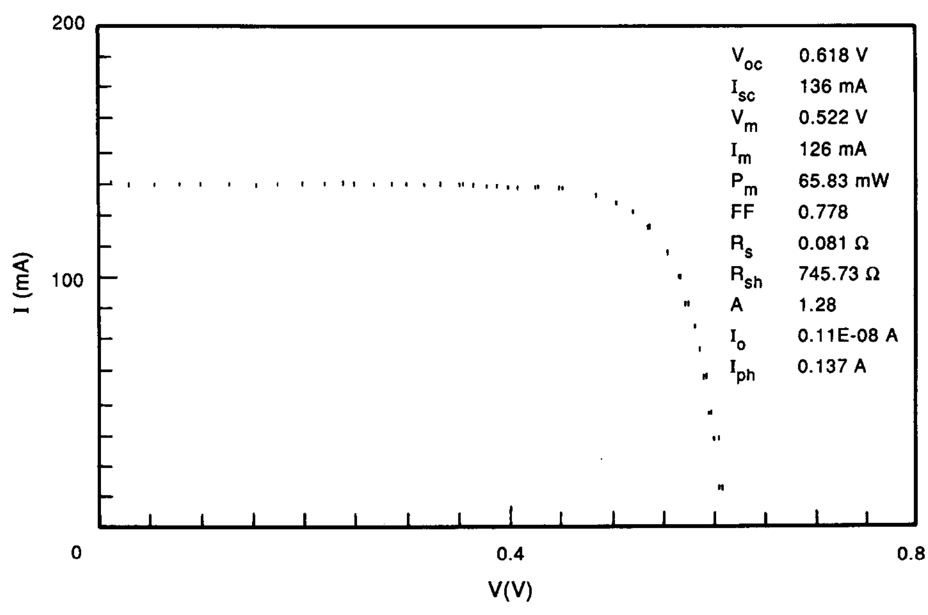


Fig. 3. Actual and fitted I–V characteristics and different solar cell parameters of the reference solar cell.

Table 1. Experimental values of different parameters of solar cells and experimental and computed values of fill-factors for different cases

Cell No.	Illumination intensity (mW/cm^2)	V_{oc} (V)	I_{sc} (A)	Parameters determined by the present curve fitting method: I_{ph}(A)	I_0(A)	A	R_s (Ω)	R_{sh} (Ω)	Measured fill-factor	Calculated fill-factor	Measured efficiency (%)
1(a)	23.5	0.549	0.352	0.353	7.5×10^{-8}	1.37	0.054	29.9	0.709	0.717	12.9
1(b)	57	0.579	0.844	0.849	7.6×10^{-8}	1.39	0.060	14.01	0.679	0.685	12.9
1(c)	90	0.593	1.32	1.33	6.6×10^{-7}	1.59	0.037	8.90	0.663	0.672	12.8
2	90	0.538	1.11	1.21	1.3×10^{-8}	1.01	0.194	2.39	0.459	—	6.8
3	40	0.518	0.569	0.598	1.8×10^{-8}	1.17	0.327	6.44	0.475	0.450	7.8
4	100	0.618	0.136	0.137	1.1×10^{-9}	1.28	0.081	745.7	0.778	0.785	16.5

Cell Nos 1, 2 and 3 have an area of 45.15 cm^2; cell No. 4 has an area of 4 cm^2.

where

$$v_{oc} > 10, \quad r_s\ [= (R_s/R_{ch})] < 0.4$$

and

$$r_{sh}\ [= R_{sh}/R_{ch})] > 2.5.$$

Table 1 shows the experimental and computed values of fill factors for different cases. It has been found that the agreement between the fill factors calculated from eqn (9) using the determined values of A, R_s and R_{sh} and the experimentally obtained values of the fill

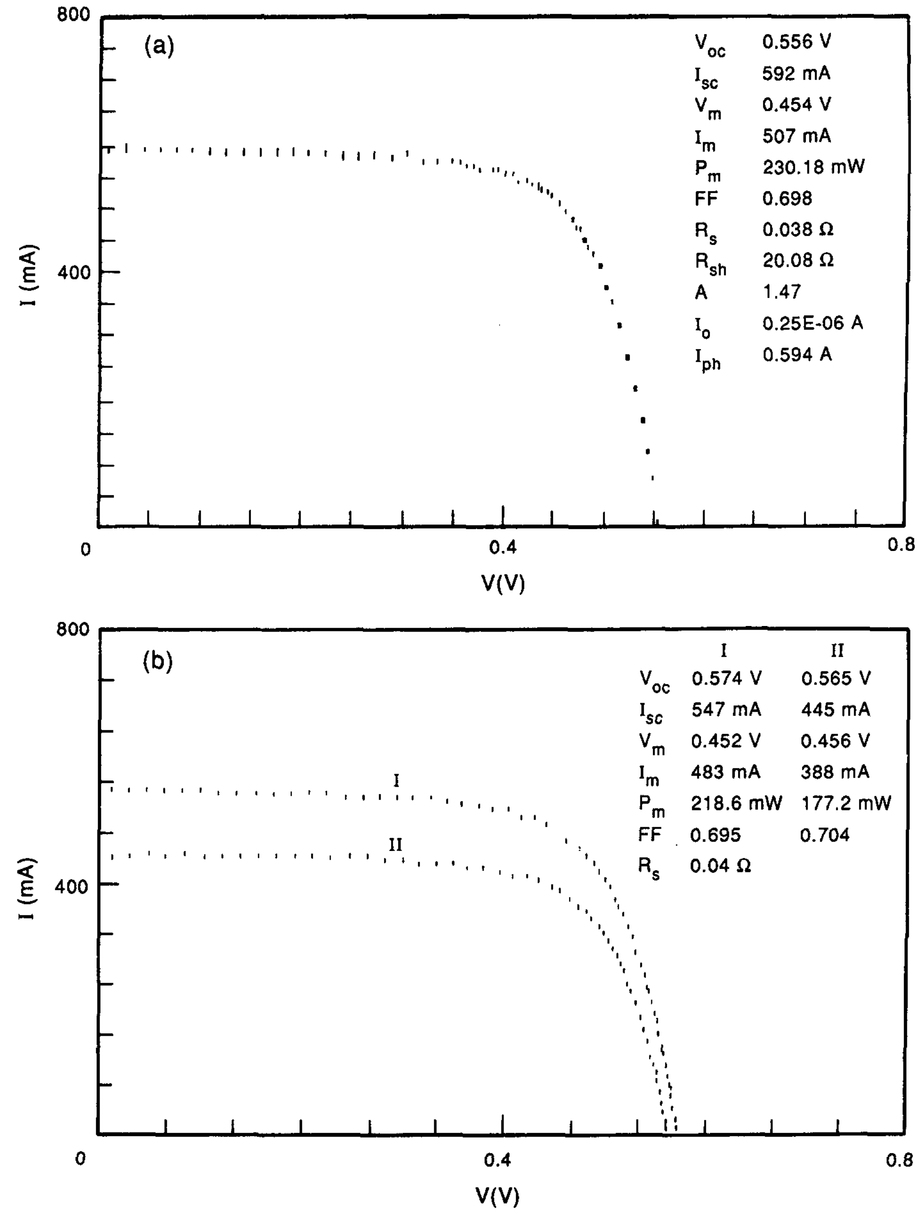


Fig. 4. Determination of series resistance by (a) the present method (b) by two intensity method.

factors is very good (better than 95%) in all cases satisfying the limiting conditions. It is also of particular interest to note that for a particular solar cell, R_{sh} does not appear to be constant and decreases with the increase in illumination intensity.

A further check on the realistic nature of the values of the parameters is carried out by determining directly the series resistances of the cell by the standard two intensity measurements[7]. Figure 4(a) and 4(b) shows the excellent agreement (better than 95%) in the values of R_s determined by our method and the two intensity method.

5. CONCLUSIONS

The method developed here for the determination of solar cell parameters in a single-diode model is very fast, precise and free from the usual approximations and applicable to various categories of solar cells. It gives realistic values of five solar cell parameters in one test as shown from an analysis of the I–V characteristics of silicon solar cells. The validity of the present method has been tested by comparing the theoretically obtained fill factor values with the experimentally determined one and also by direct measurement of R_s. The fast measurement and parameter evaluation technique can be suitably used to unravel the different physical processes occurring in a solar cell and is of particular interest when a feed back to the cell development is necessary.

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