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Static and Dynamic Characterization of P-N Junction Solar Cells

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Abstract. This work presents an accurate, fast and automated technique for characterizing p-n junction single crystal solar cells. A PC-based system was constructed to measure the static conditions — current-voltage characteristics, and dynamic characteristics — capacitance-voltage characteristics in the reverse bias region and impedance-frequency-voltage characteristics in the forward region.

Different techniques were used to extract the model parameters as well as the most important physical and technological parameters. The five parameters single diode lumped model was used to fit the measured I-V data under AM1 illumination. The extracted parameters of the lumped model were used as an input for the PSPICE program to simulate the solar cell characteristic.

Both measurement and extraction of parameters were carried out on-line under the direct control of a personal computer. The developed system exhibits reliable performance and its use can be extended for characterizing other semiconductor devices.

Nomenclature

A cross-sectional area (cm^2)
C total capacitance (F)
C_j junction (depletion-layer) capacitance (F)
C_s minority carrier storage capacitance (F)

FF solar cell fil factor (%)
G_{sh} small signal shunt conductance (υ)
I_L photogenerated current (A)
I_{max} current at maximum power (A)
I_s diode saturation current (A)
I_{sc} short-circuit current (A)
n ideality factor
n^+ heavily-doped n-type material
N_A acceptor concentration (cm^{-3})
Q quality of fit factor (%)
q electronic charge (C)
R_s series resistance (Ω)
R_{sh} shunt resistance (Ω)
R_{sho} shunt resistance (Ω) near $V_A = 0$
r_j small-signal junction shunt resistance (Ω)
r_s small-signal series resistance (Ω)
V_A applied voltage (V)
V_{bi} junction built-in voltage (V)
V_{max} voltage at maximum power (V)
V_{oc} open circuit voltage (V)
V_R reverse bias voltage (V)
V_T thermal equivalent voltage (V)
ω angular frequency (rad/s)
Z impedance (Ω)
η conversion efficiency (%)
ε_o permitivity of free space
ε_r relative dielectric constant of semiconductor
τ the time constant (s)
τ_n electron minority carrier lifetime (s)

Introduction

Personal computer aided characterization (PCAC) has become a necessity in research and development because of its potential in regards to accuracy, speed, reliability and computational capabilities.

Fast and accurate determination of solar cell parameters from experimental data is very important in the design, evaluation and quality control of solar cells. Therefore the use of PCAC will be effective and powerful in that area.

PCAC used in this paper includes two main processes: (a) PC-aided data acquisition process in which both static and dynamic characteristics are measured, and (b) PC-aided data analysis process in which the measured data are used to extract the different models and physical parameters.

The static conduction characterization includes the measurement of the I-V characteristic under dark and different illumination conditions and the measurement of I_{sc}-V_{oc} under very low illumination conditions. Assuming the single diode lumped model, these measured characteristics are used to extract the five model parameters (n, I_s, R_s, R_{sh} and I_L) and the output parameters (FF and η).

The dynamic characterization includes the measurement of the C-V characteristics in the reverse bias region needed to extract the doping concentration level in the p-region and the barrier height of the device under test (DUT). Also it includes the measurement of the (Z - V - ω) characteristics in the forward bias region to extract the value of the minority carriers lifetime (τ_n) in the p-region.

Experimental Work

Measurement of the static conduction characteristics

The setup used for the measurement of the I-V characteristics is shown in Fig. 1.

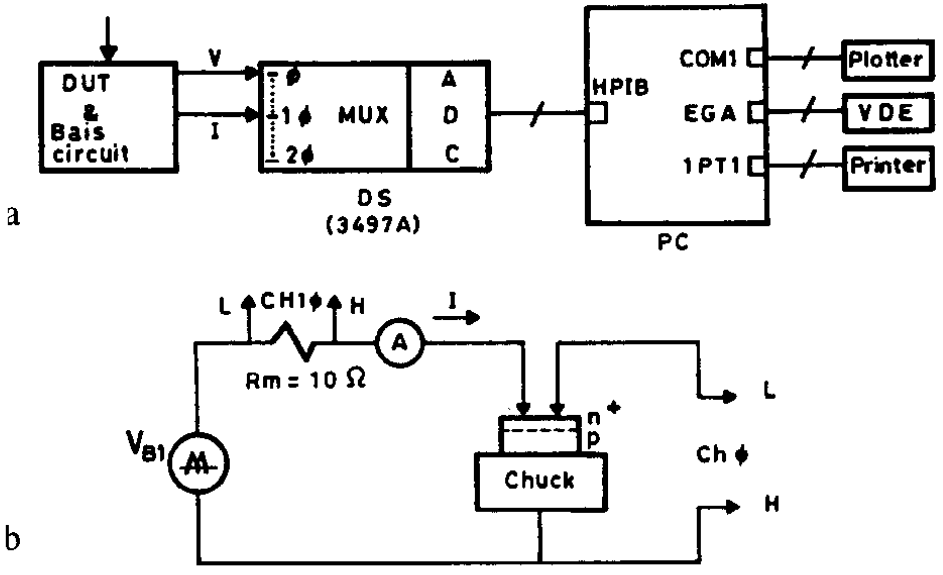

Fig. 1. (a) Block diagram for I-VA measurement setup (b) The DUT in the bigs circuit using three-point probe technique.

The hardware support around the host IBM compatible PC (HP Vectra) consists of an IEEE-488 interface card (HPIB), connected to a Data Acquisition System (DAS)/Control Unit (HP 3497 A) with a built-in digital voltmeter (HP 44420 A) and a 20-Relay Multiplexer Assembly (HP 44421 A). The bias sweep voltage is obtained via a function generator (Tektronix FG-504). The maximum and minimum values of the input sweep voltage must be chosen such that it biases the cell from reverse to forward in a suitable range. The sample is connected so that the two measured quantities are fed to the DAS via two separate channels.

The contact to the cell must be implemented carefully in order to eliminate the effect of contact resistance, between the cell and the measuring probe, on the I-V characteristics. The three-point probe technique is used here, where the contact resistance effect will be decreased assuming sufficiently large back surface area.

A program was written in Basic to control the setup via the PC and to measure the I-V characteristics either under dark or under different illumination conditions.

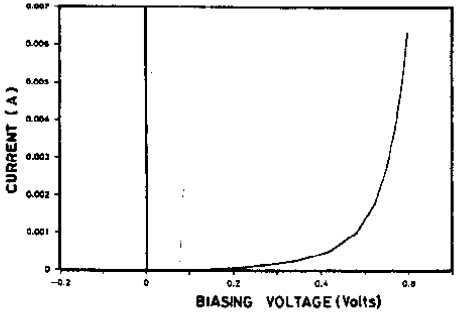

Fig. 2a. Measured I-V_A characteristics of the solar cell in dark

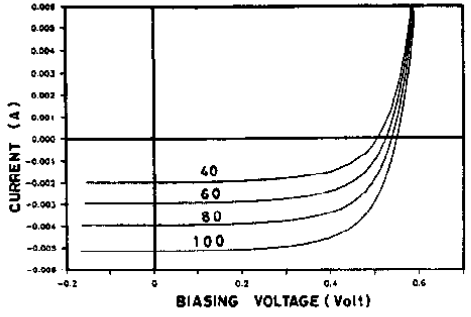

Fig. 2b. Measured I-V_A characteristics of the solar cell under illuminations

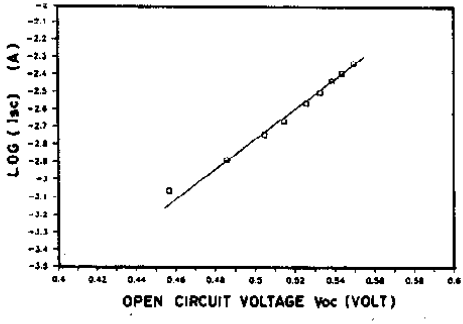

Fig. 2c. Log (I_{sc}) vs. V_{oc} at different illuminations

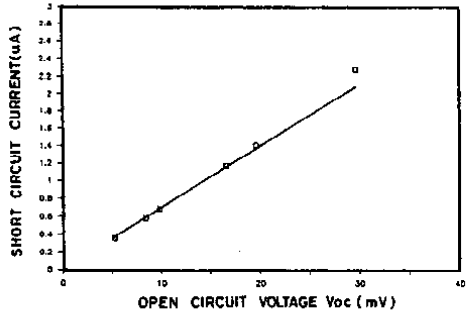

Fig. 2d. Log (I_{sc}) vs. V_{oc} at very low illumination conditions

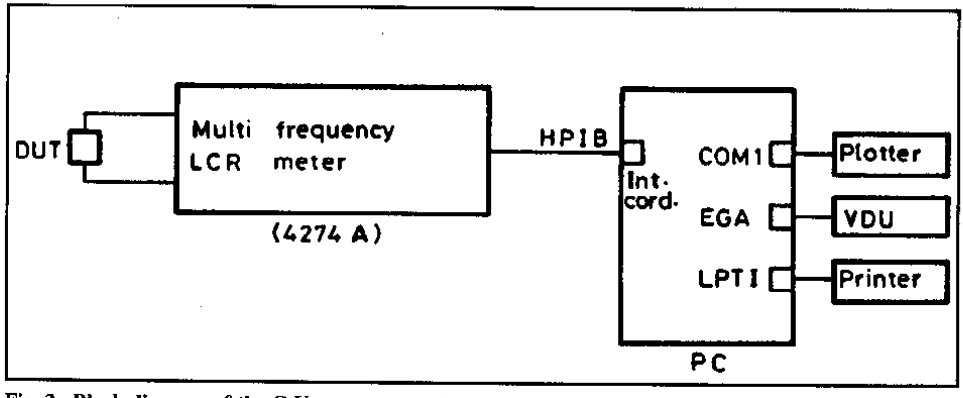

Fig. 3. Block diagram of the C-V_A measurement setup.

A 0.18 cm^2 single crystal n^+-p solar cell specimen has been characterized, using the setup of Fig. 1 and the Basic program. Typical results are shown in Fig. 2.

Measurement of the capacitance-voltage characteristic

The C-V measuring setup is shown in Fig. 3. The multi-frequency LCR meter (HP 4274A) can be programmed via the PC using the HPIB interface bus to measure the C-V characteristics of the sample in the reverse bias region at different frequencies. It can provide the small signal as well as the dc bias internally. Figure 4 shows measured C-V characteristics using the setup of Fig. 3. It is important to mention here, that the measured capacitance almost represents the depletion capacitance because the diffusion capacitance under reverse biasing is very small and the frequency of measurement is low.

Measurement of the impedance-voltage-frequency characteristics

The measurement set up is shown in Fig. 5. The lock-in amplifier (LIA) (ITHACO 362 A) is used because of its ability to measure very small signals (amplitude and phase) with respect to a reference signal. It is controlled through the PC using the HPIB interface bus. The LCR meter is used to provide both the programmed small signal and the forward dc bias voltage to the sample. The small signal is also used as a reference signal for the LIA.

Through the LIA, the PC can measure two signals that are proportional to the voltage across the sample and the current through it. By this measurement the forward impedance is calculated easily using Ohm's law. Typical results are given in Fig. (6).

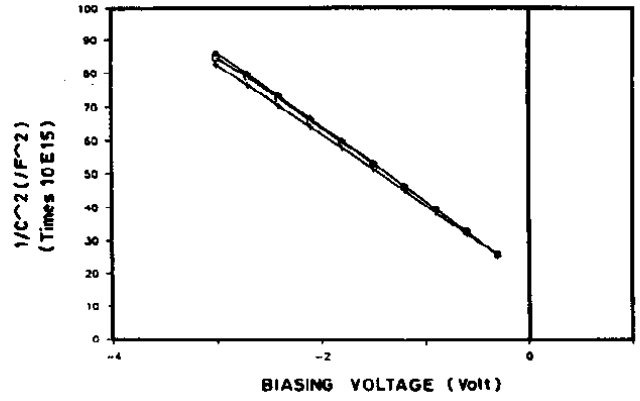

Fig. 4a. The measured $(1/C^2)$-V at different frequencies

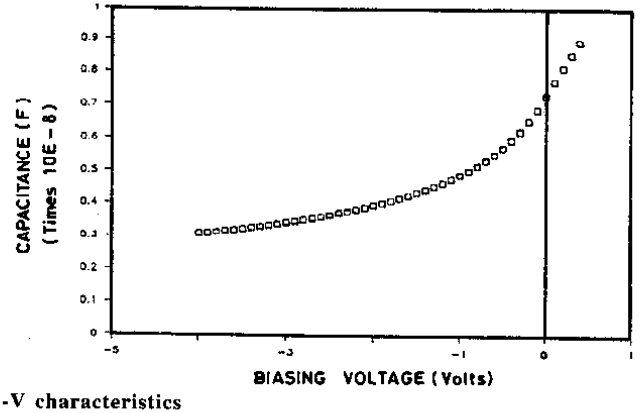

Fig. 4b. C-V characteristics

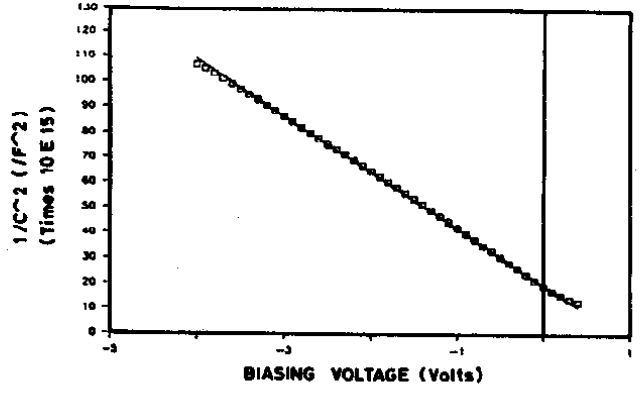

Fig. 4c. $(1/C^2)$ vs V characteristics.

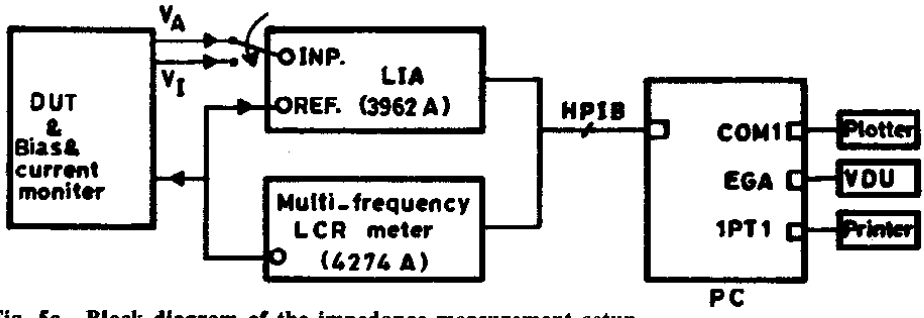

Fig. 5a. Block diagram of the impedance measurement setup.

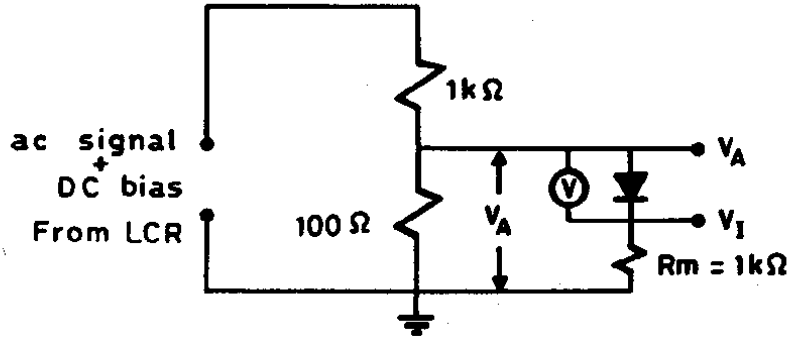

Fig. 5b. Connection of the DUT and the bias circuit.

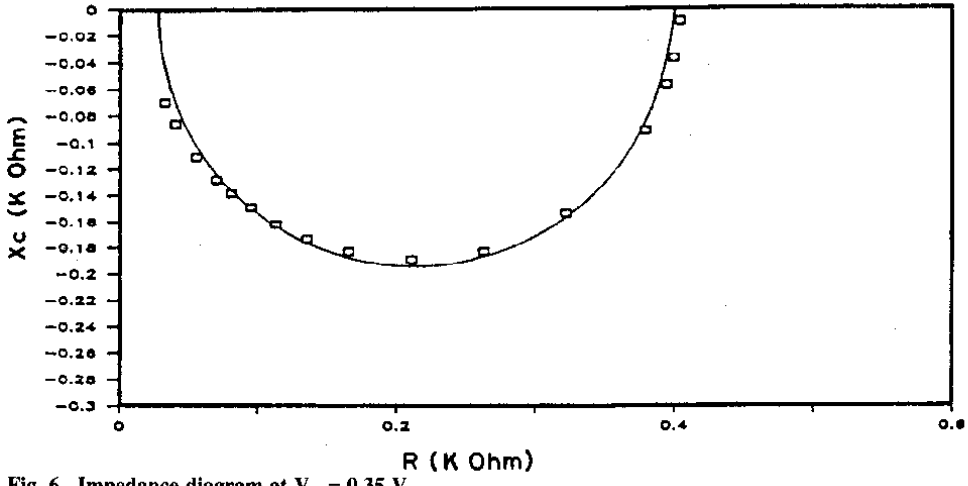

Fig. 6. Impedance diagram at V_A = 0.35 V.

Parameter Extraction and Discussion

I-V Characteristic under dark condition

The measured I-V characteristics shown in Fig. 2a can be used to extract the parameters of the single diode model of the solar cell shown in Fig. 7 [1,2]. The general relation between the current and voltage of the solar cell can be written in the following form [1]

$$I = I_s \left[e^{(V_A - IR_s)/nV_T} - 1\right] + \frac{(V_A - IR_s)}{R_{sh}} \qquad (1)$$

where $V_T = \frac{kT}{q} = \frac{T}{11600}$

In most solar cells $R_s/R_{sh} << 1$, so Eq. 1 takes the form

$$I = I_s \left[e^{(V_A - IR_s)/nV_T} - 1\right] + \frac{V_A}{R_{sh}} \qquad (2)$$

Equation (2) can be used at different regions of current values to extract certain parameters in the regions where these parameters are dominant.

The experimental I-V characteristic of Fig. 2a can be approximated near the origin by a straight line to extract R_{sho}. The Log (I)-V plot shown in Fig. 8 can be approximated by a straight line in the medium current region to extract I_s and n. R_{sh} and R_s can then be found at each bias voltage in both low and high current regions respectively.

It was found that R_s and R_{sh} values vary with bias as shown in Fig. 9, so their average values are calculated. Table 1 summarizes the results of the analysis described above.

The extracted parameters of the lumped model are used as an input for the PSPICE program to simulate the solar cell characteristics. Figure 10 shows good matching between the simulated and measured characteristics. The increase in the R_s lumped value could be explained by the distributed nature of the cell equivalent circuit. The bias voltage distribution is not uniform over the cell surface (current crowding effect) [3]. On the other hand, the decrease of R_{sh} with bias has also been reported in the literature [4]. It might be caused by metal spikes penetrating the top layer causing Schottky-like barriers.

The I-V Characteristics Under Illumination Conditions

Two methods for extracting the solar cell parameters under illumination are presented in this section [5].

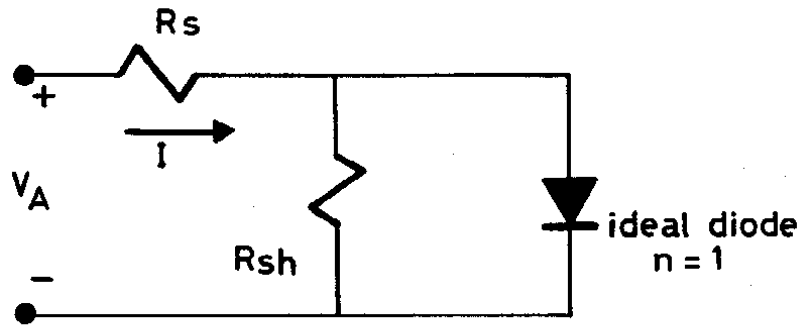

Fig. 7. Static condition model.

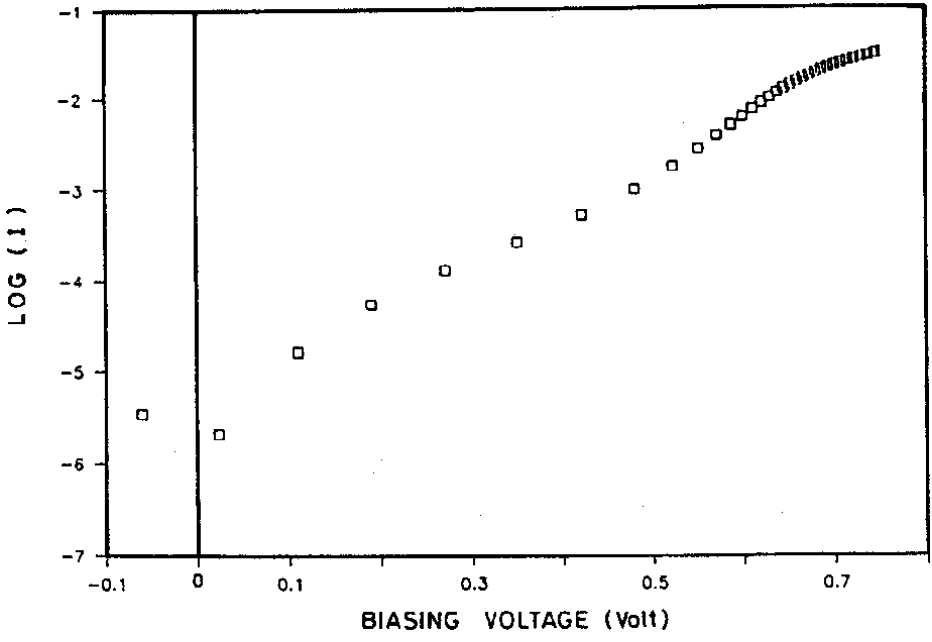

Fig. 8. Log (I) vs bias voltage at dark condition.

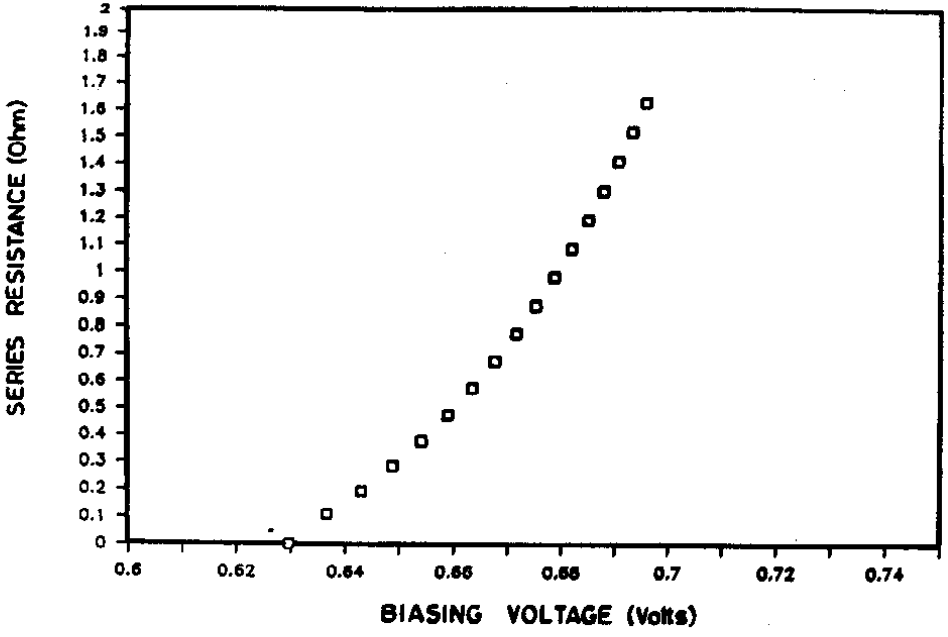

Fig. 9a. Equivalent lumped series resistance vs bias voltage.

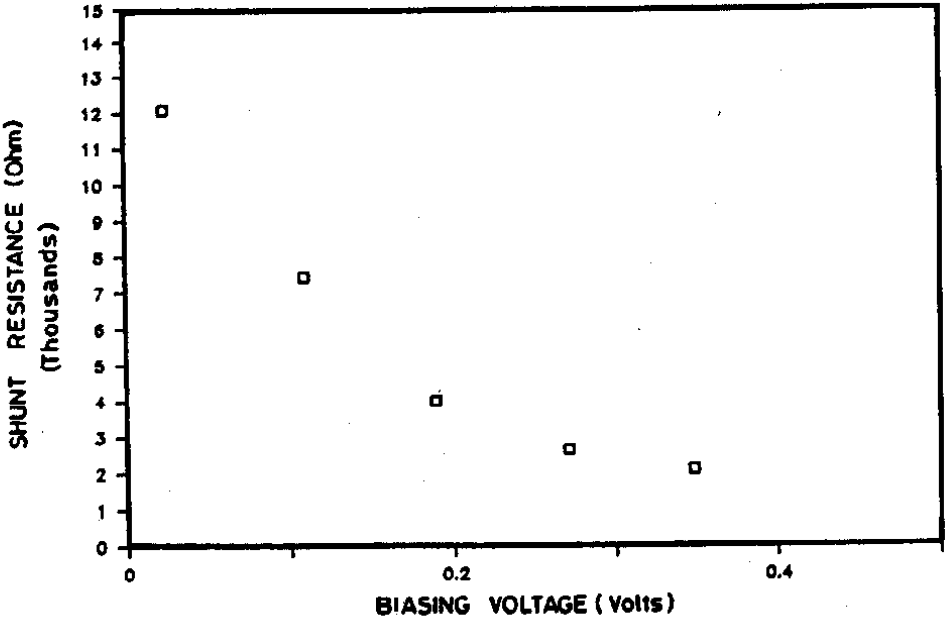

Fig. 9b. Equivalent lumped shunt resistance vs bias voltage.

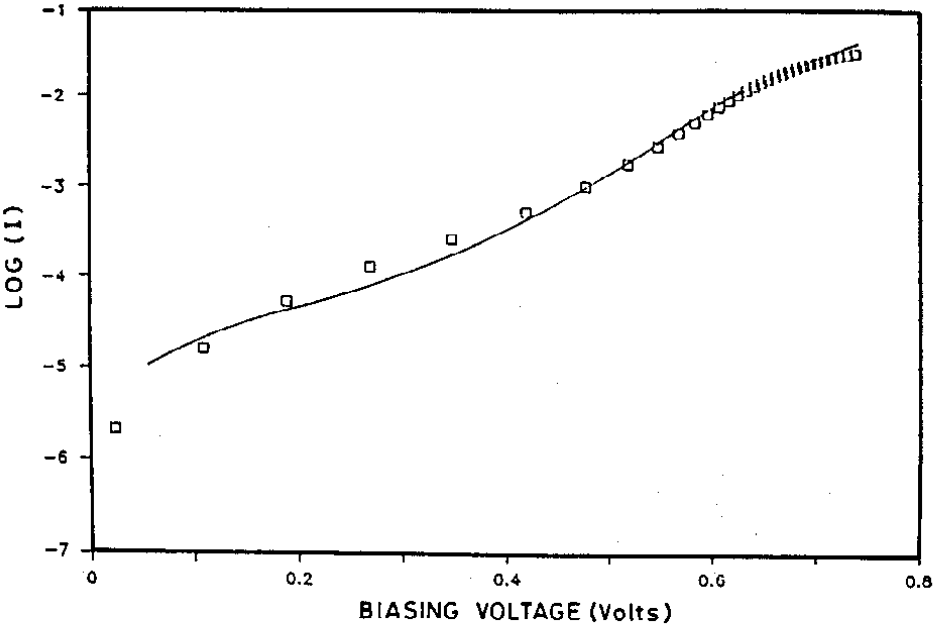

Fig. 10. PSPICE simulation of the extracted lumped model

A) Analytical method

The mathematical relation between the I_{sc} and V_{oc} under high illumination conditions can be shown to have the following form,

$$I_{sc} \cong I_s \, e^{V_{oc}/nV_T} \tag{3}$$

Table 1. Single-diode model extracted parameters under dark condition

I_s (A)	n	R_{sho} (kW)	R_{sh} (av.) (W)	R_s (av.) (kW)
3.12E-7 ± 4.2E-9	2.333 ± 0.017	13.34 ± 2.5	1.3	5.65

Table 2. Single-diode model extracted parameters under illumination using analytical method

I_s (A)	n	R_{sh0} (av.) (kW)
2.03E-7 ± 1.15E-8	2.12 ± 0.08	13.77 ± 0.0

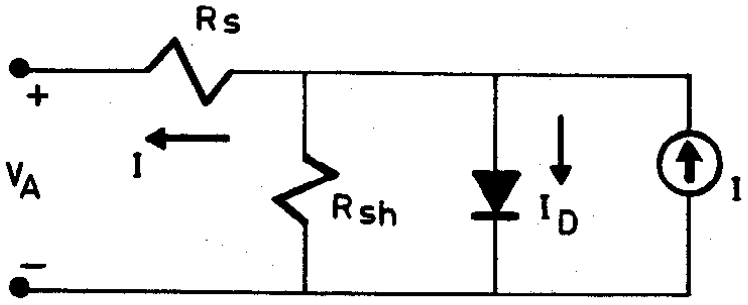

Fig. 11. Solar cell five parameters single diode lumped model.

Thus if the log (I_{sc}) - V_{oc} characteristic shown in Fig. 2c is approximated by a straight line, I_s and n can then be extracted directly. But the mathematical relation between I_{sc} and V_{oc} under very low illumination conditions can be written in the following form,

$$I_{sc} \cong \frac{V_{oc}}{R_{sho}} \tag{4}$$

which means that if the I_{sc} - V_{oc} characteristics shown in Fig. 2d is approximated by a straight line, R_{sho} can be easily extracted. The analysis results are summarized in Table 2.

B) Curve fitting techniques

Another approach is followed here to extract all the parameters of the solar cell model from the whole set of measured I-V characteristics using fitting techniques. The five parameters single diode lumped model shown in Fig. 11 is used to fit the measured I-V data under AM1 illumination (100 mW/cm^2).

The numerical algorithm used in the proposed fitting technique is given in literature [1]. The fill factor and efficiency can also be calculated. Table 3 represents the output list of the fitting program while Fig. 12 shows the experimental points over the generated fitting curve.

C-V Characteristics

It is clear from Fig. 4a, that the measured capacitance under reverse bias voltage is independent of the small signal frequency and represents the junction (depletion-layer) capacitance directly.

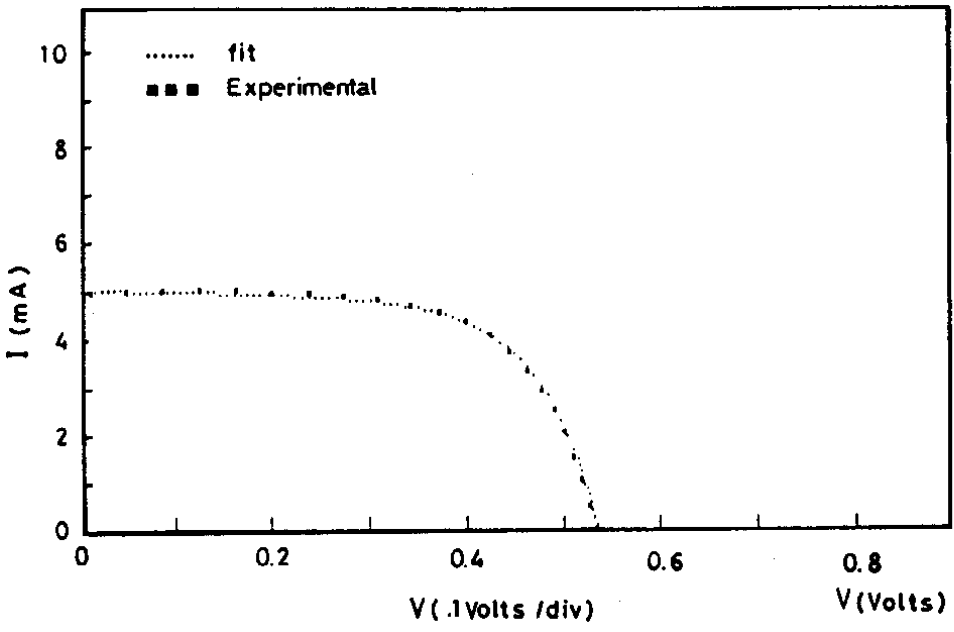

Fig. 12. Plot of the best fit over the measured data points.

Table 3. Solar cell extracted parameters using fitting techniques

I_L (A)	5.00E-03
I_S (A)	5.20E-07
B	16.97
n	2.27
R_S (W)	0.21
G_{sh} (u)	0.00063
N	65
N_1	55
Fit factor (%)	88.13
I_{SC} (A)	4.97E-03
V_{OC} (V)	0.536
I_{max} (A)	4.16E-03
V_{max} (A)	0.411
FF (%)	64.1
h (%)	14.9 (active area)

The general relation between the capacitance and the bias voltage for any p-n junction is,

$$\frac{1}{C_j^2} = -\frac{2}{q\varepsilon_r\varepsilon_o A^2 N_A}(V_R - V_{bi}) \tag{5}$$

or

$$\frac{1}{C_j^2} = \frac{1}{BN_A}(V_R - V_{bi}) \tag{6}$$

where

$$B = -\frac{q\,\varepsilon_r\,\varepsilon_o\,A^2}{2}$$

If the measured points of Fig. 4c are approximated by a straight line to represent the relation (6), the doping concentration in the base (N_A) and the barrier height (V_{bi}) can be extracted. The following values are obtained respectively,

$$N_A = 1.68E16 \pm 4.3E12\ cm^{-3}$$
$$V_{bi} = 0.88 \pm 0.02\ V$$

We should point out here that the error $\pm$ 4.3E12 cm^{-3} in N_A is due to the fitting of the experimental data with a straight line. Other sources of errors, such as estimating the cell area are not considered.

The relatively high value of the barrier height voltage (V_{bi}) is due to the highly doped top layer of the (n^+- p) junction under test.

Z-V-ω Characteristics

The small signal model of the p-n junction solar cell at forward bias is shown in Fig. 13. The total impedance expression can be written at certain forward bias as follows:

$$Z = [r_s + \frac{r_j}{1+\omega^2 c^2 r_j^2}] - j\,[\frac{r_j^2 c\omega^2}{1+\omega^2 c^2 r_j^2}] \tag{7}$$

$$Z = R(\omega) - jX_c(\omega) \tag{8}$$

where $C = C_j + C_s$ and $r_j = 1/G$

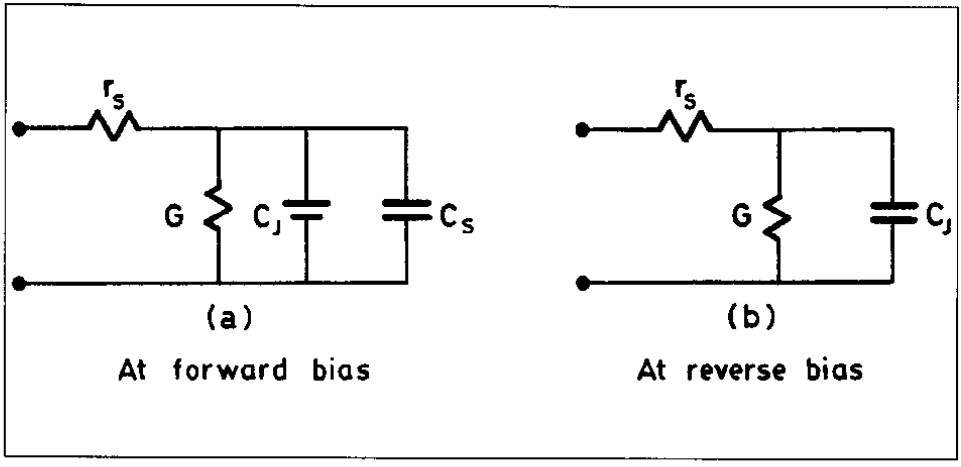

Fig. 13. Small signal model of a p-n junction

We should mention here that minority carriers storage capacitance includes the effect of the minority carriers in the neutral region (usually called diffusion capacitance) and the minority carriers in the depletion region (usually called space charge recombination capacitance). The expressions of these capacitances are given in [6] and [7].

The impedance locus in the R-X_c plan represents a semicircle as shown in Fig. 6. In this figure, the following relations apply

$$\tan f = r_j Cw \tag{9}$$

at $$f = 45° \quad r_j Cw = 1 \tag{10}$$

then $$t = r_j C = 1/w \qquad \text{at } f = 45° \tag{11}$$

The minority carriers lifetime is given by

$$t_n = r_j C_s \tag{12}$$

so $$t_n = t - r_j C_j \tag{13}$$

Using the impedance diagram in Fig. 6, the value of t can be calculated using equation (11) and the value of r_j can be estimated graphically. The value of the junction capacitance (C_j) at this bias can be found by extrapolating the straight line in Fig. 4c to the forward bias region. Equation (13) can then be used to calculate the value of the lifetime (t_n). Table 4 lists the calculated small signal parameters at a forward bias of 0.35V.

Table 4. Calcualted small signal parameters at 0.35 V forward bias

r_s (Ω)	$r_s + r_j$ (Ω)	r_j (Ω)	ω at ϕ=45 (kHz)	τ (μsec)	C_j (F)	τ_n (μsec)
30	400	370	38.2	4.166	0.91 E-8	0.799

Since the ideality factor obtained from the I-V characteristics is approximately 2, the recombination current component is the dominant one. Therefore we can speak about space charge capacitance rather than the diffusion capacitance. Also, the life time (τ_n) obtained from this measurement will represent mainly the life time of minority carriers in the space charge region.

The calculation of C_s has been made at relatively low frequency (less than 50 kHz), which satisfy the low frequency condition ($\omega \tau << 1$). Therefore C_s is considered independent of frequency.

Conclusions

A PC-based data acquisition system for characterizing a two-terminal solid state device is implemented. The system can be used to measure the current-voltage characteristics under both dark and illumination conditions, the capacitance-voltage characteristics and the impedance-frequency characteristics of p-n junction diode. The system has been used to measure with high speed and reliability the different characteristics for single crystal as well as polycrystalline silicon solar cells.

The measured data have been used to characterize the samples either by analysis or fitting techniques using a PC in order to extract the different solar cell parameters. The fitting program which was designed to extract the cell parameters from the illuminated I-V characteristics can be considered an accurate and fast approach for the characterization of the p-n junction solar cells.

It was found that recombination current component is dominant over diffusion component of current. Moreover, the device capacitances showed frequency independence up to 100 kHz.

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تمييز الخصائص المستقرة والحركية لخلايا شمسية ذات وصلة من نوع P - N

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(أستلم في ١٨/٥/١٩٩٦م؛ وقُبل للنشر في ٢/٧/١٩٩٧م)

ملخص البحث. يقدم هذا البحث أسلوبًا تقنيًا يتميز بالسرعة والدقة والتلقائية لتمييز الخصائص الكهربائية لخلايا شمسية ثنائية الوصلة. تم بناء نظام يعتمد على الحاسب الشخصي لقياس خصائص الحالة المستقرة (التيار - الفولتية)، والخصائص الحركية: السعة - الفولتية، في حال الانحياز العكسي، وخصائص المعاوقة الذبذبة - الفولتية، في حال الانحياز الأمامي.

استخدمت أساليب مختلفة لاستخلاص متغيرات الأنموذج بالإضافة إلى أهم المتغيرات الفيزيائية والتقنية. وتم استخدام نموذج مجمع للثنائي المفرد لاستخلاص الخصائص من بيانات التيار - الفولتية، المقاسة تحت إضاءة AM1. تلا ذلك استخدام هذه المتغيرات كمدخلات لبرنامج PSPICE لتمثيل خصائص الخلية الشمسية.

أجريت جميع القياسات واستخلصت جميع المتغيرات مباشرةً بواسطة الحاسب الشخصي. وقد أظهر النظام المطور أداءً موثوقًا يمكن توسيع استخدامه لتمييز خصائص نبائط أشباه موصلات أخرى.