AIP | Review of Scientific Instruments

Manual/automated I–V system for analyzing solar cells

R. D. Turner, C. J. L. Moore, and D. E. Brodie

Citation: Review of Scientific Instruments **55**, 1797 (1984); doi: 10.1063/1.1137662
View online: http://dx.doi.org/10.1063/1.1137662
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/55/11?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in

A non-iterative technique for determination of solar cell parameters from the light generated I-V characteristic
J. Appl. Phys. **114**, 084904 (2013); 10.1063/1.4819961

Evaluation of the solar cell internal resistance in I-V measurements under flash illumination
AIP Conf. Proc. **1477**, 152 (2012); 10.1063/1.4753856

Teaching solar cell I-V characteristics using SPICE
Am. J. Phys. **79**, 1232 (2011); 10.1119/1.3636525

Subcell I-V characteristic analysis of GaInP/GaInAs/Ge solar cells using electroluminescence measurements
Appl. Phys. Lett. **98**, 251113 (2011); 10.1063/1.3601472

Inexpensive microcomputer-based system for solar cell I-V characterization
Comput. Phys. **3**, 46 (1989); 10.1063/1.168343

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 35.8.11.3 On: Wed, 27 Jan 2016 12:48:46

Manual/automated I–V system for analyzing solar cells

R. D. Turner, C. J. L. Moore, and D. E. Brodie

Guelph-Waterloo Program for Graduate Work in Physics, Waterloo Campus, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1

(Received 7 March 1984; accepted for publication 19 July 1984)

A measurement system for the current–voltage characterization of solar cells has been developed. The instrument is based on an Intel 8088 microprocessor, which allows for enhanced data collection and storage, as well as automated measurement control. A high-power analog supply makes measurements in the range of -10 to $+10$ V and -0.75 to 0.75 A possible, and provides the capability for sinking currents up to 1 A at $+10$-V output. Measured data may be transferred to an IBM personal computer for immediate display, and for consequent analysis (to obtain the characteristic parameters). The system provides a rapid, effective I–V curve measurement and analysis method for many devices, and experimental solar cells in particular.

INTRODUCTION

In recent years, the high level of research activity taking place in the field of photovoltaic cells has inspired interest in the measurement of current–voltage characteristics for these devices. Useful information is obtained from a study of the illuminated and dark I–V curves of a solar cell. However, due to the nature of the solar cell as an active electronic device, such I–V measurements have not proven to be altogether straightforward.

Since the solar cell acts as a source of current while under illumination, any instrument designed to supply power to a cell must be capable of "sinking" such a reverse current at a positive output voltage. In order to accurately determine open circuit, short circuit, and maximum power conditions, measurement of discrete data values at a high density along the I–V curve is desirable. Finally, a standard AM1 (100 mW cm^{-2}) illumination delivers a large amount of energy to a test device, much of which is dissipated as heat. In order to maintain a sample at a stable temperature during such a measurement, some method of cooling must be available, unless measurements can be done extremely rapidly.

From a consideration of some of the above ideas, it becomes readily apparent that an instrument designed specifically for solar cell I–V measurements would be useful. Several such instruments[1–3] concentrating on the measurement of the "performance" parameters V_{oc} (open circuit voltage), I_{sc} (short circuit current), FF (fill factor), and efficiency η, have been recently reported. However, these systems have limited applicability. Thus, it would be highly desirable to expand the capabilities of such I–V systems for applications in active device research. The research instrument of Schultz *et al.*[4] demonstrates one important aspect of this needed versatility, as it makes use of microprocessor control to improve measurement and data handling. More recently, Warner and Cox[5] and Cardinali and Faldella[6] have reported microprocessor-controlled solar cell I–V measurement systems, designed for more research-oriented applications.

Absent from all of these systems is the capability for theoretical modeling of the data, which could allow the determination of the internal cell parameters such as the series (R_s) and shunt (R_{sh}) resistances and the diode parameters I_0 (reverse saturation current) and n (diode quality factor). The instruments described by Castaner *et al.*[7] and Emery and Dubow[8] further expand the capabilities of a microprocessor-based measurement apparatus by adding I–V curve modeling. A variety of new parameters are made available by such adaptation, and complete I–V measurement and analysis systems result.

The measurement and analysis system reported in this paper has been designed, developed, and tested successfully in the areas of measurement and analysis for "performance" and the determination of the internal and diode parameters outlined above. Its capabilities in temperature and intensity monitoring, performance parameter access, and theoretical modeling make it unique among such systems.

I. THE MEASUREMENT SYSTEM

A. The instrument

An overall layout of the primary elements of the I–V measurement system appears in Fig. 1. This system was developed as a more cost effective (about 1/4 the cost) solution than using a dedicated personal computer. Several of these component units were chosen specifically for use in this instrument, and a brief comment on each of these important elements should be made.

1. The 8088 processor board

A functional block diagram of the 8088 processor board and its important peripherals are shown in Fig. 2. The position of the 8088 as the central controlling feature of this system is made clear in this diagram. The final operating system uses a clock frequency of about 2 MHz, with two clock cycles of "wait" in all memory access operations. In addition, the 32-kbyte of EPROM/RAM memory was organized according to function as 8K of monitor system (and library functions) EPROM, 18K of "*C*" control software EPROM, and 6K RAM (up to 200 I–V points may be stored). The system was provided with a simple restart capability via a manual reset contact switch. Two RS232 serial

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 35.8.11.3 On: Wed, 27 Jan 2016 12:48:46

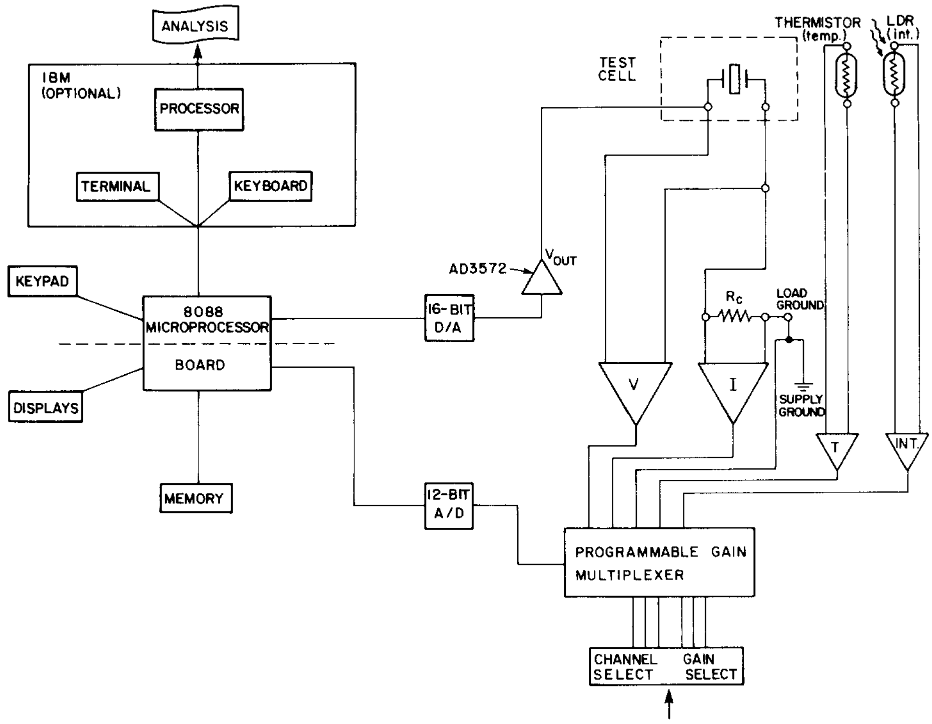

FIG. 1. A schematic of the complete I–V measurement system including the external link to the IBM personal computer used for data reduction and analysis.

channels were implemented. During the software development stage, one serial port was connected to a video display terminal and the other was connected to a host computer where the software was originally written and compiled.

2. The 3572 operational amplifier

The device power supply used in the system was a Burr Brown 3572 AM Power operational amplifier. It was chosen due to its special capabilities, which are particularly suited to the driving of an active load such as a solar cell.

(a) It is capable of a high output power (up to 2 A at 10 V output may be easily achieved) far in excess of any likely to be requested of it in the present application (at the maximum our system might require 2 A at 4 V).

(b) The device can sink a current of up to 1 A safely at an ouput voltage of 10 V. This resolved the problem of a solar cell acting as a source of current (under illumination) and potentially damaging the driving device if it could not accept significant reverse current at positive output voltages.

(c) The current supplied from any device used to drive the 3572 need never exceed 10 mA (in an optical wiring configuration, the actual current is much smaller due to the high input impedance of the device) in the circuit used. This allows the user to drive a solar cell easily with a very-low-power supply signal generator as a "manual" signal source.

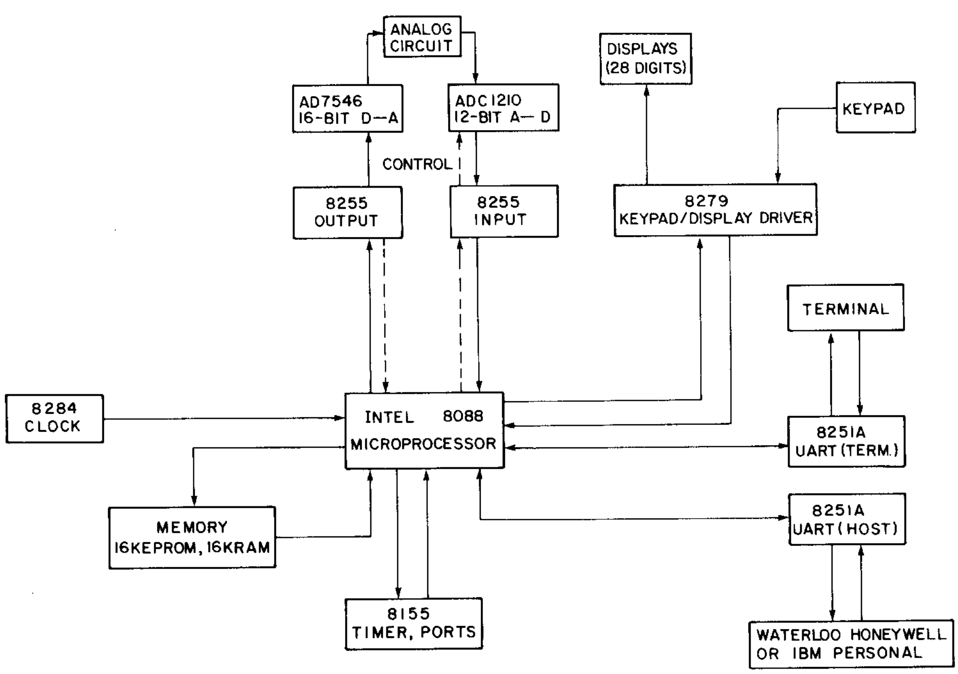

FIG. 2. An expanded block diagram of the measurement system. An Intel 8088 microprocessor controls this section of the system. Parameter information may be passed to the system from the keypad of the remote control unit, from a standard RS232 interfaced video display terminal (optional), or from an IBM personal computer (optional) via an RS232 link. The system is designed to run as a stand-alone system or in conjunction with the IBM PC which is used for the data analysis and modeling.

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 35.8.11.3 On: Wed, 27 Jan 2016 12:48:46

The device itself required relatively simple wiring, although decoupling of the power supplies, and a well chosen current-limiting resistor ($R_{+sc} = 2.7$, $R_{-sc} = 3.3\ \Omega$) were essential to the desired operation.

3. The LH0036 differential operational amplifiers

Cell voltage and current values were measured differentially using National Semiconductor LH0036 instrumentation operational amplifiers. These devices were configured to allow for both offset and CMRR (common mode rejection ratio) adjustments.

The high differential input impedance (about 300 $M\Omega$) of these operational amplifiers makes them ideal for monitoring the required voltage-difference signals without drawing significant current from the circuit. For measuring current (I), the voltage across a known, selectable resistor R_c is measured, and the result divided by the calibrated value of R_c in the software to yield current.

4. Analog–digital interfacing

A precisely selectable voltage output to the test sample was desired, and the chosen digital-to-analog converter was the 16-bit Analog Devices AD7546 (Fig. 3). This device was found capable of converting and supplying a selected voltage to 0.1 mV over the range -4 to 4 V (which represents the operational range of the system at present).

Due to the number of signals requiring analog-to-digital conversion prior to analysis and/or storage on the 8088 board (voltage, current, temperature, and intensity primarily), a multiplexer A-to-D converter combination was used. The Burr Brown PGA100 programmable gain eight-channel multiplexer was selected for this purpose, as it allows complete digital control of its operation, and provides selectable gains from 1 to 128 on each of eight input channels. The output from this device was fed into a National Semiconductor ADC1210 12-bit analog-to-digital converter (Fig. 4) prior to its transfer to the 8088 processor board. The wiring of the 4093 was arranged to provide a start signal latch prohibiting overlap of conversions. CMOS-to-TTL voltage level conversion was required at the ADC1210 output to generate voltage levels acceptable to the TTL digital circuitry.

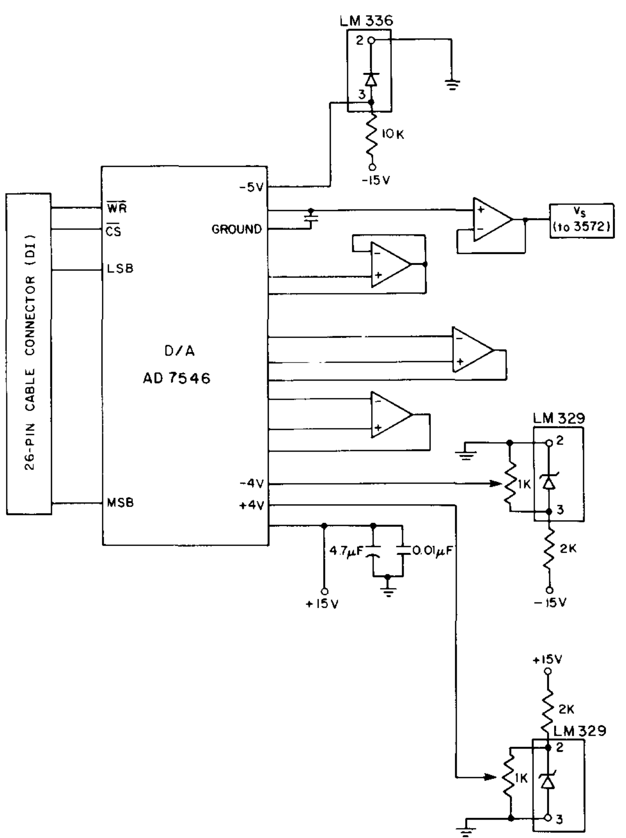

FIG. 3. The digital-to-analog interface. The 16-bit AD7546 provides a "glitch"-free voltage source used to supply the 3572 power amplifier circuitry.

5. Temperature and intensity monitoring

The purpose of including these monitoring circuits in the system was to provide a means of checking both absolute levels and fluctuations in these two important measurement parameters.

These circuits make use of FENWAL GB31M2 glass-encapsulated miniature thermistors, and a Phillips CdS photocell 600-950003 LDR, respectively, for temperature and intensity monitoring. The measuring circuits used on the interface board (see Fig. 5) and details of the calibration procedures used, as well as the calibration curves for both thermistors and the light-dependent resistor (LDR) may be found in Ref. 9. The thermistors have been arranged so that one (T1) could be placed in direct contact with the cell/sample surface using a pressure contact technique, and the other which was attached directly (using thermally conductive epoxy) to the sample stage provided a "reference" reading. The LDR is glued to a wooden holder and can be moved in or out of the illuminated area. Signals are brought into their appropriate conditioning circuits via small coaxial cable connectors.

B. Use of the system

1. "C" control software: measurement procedure

The flow chart in Fig. 6 outlines the operational process provided by the C control software package. Several of the routines which appear in the flow have a self-explanatory function [such as WAIT( )], but in order to clarify the system operation the flow will be briefly explained with reference to Fig. 6.

The flow diagram represents a sequence of steps and function calls contained in the MAIN( ) or MRCTL( ) routine, the overall control program. INIT( ) causes reinitialization of all memory, variables, and peripherals. This procedure is followed by CONN-CHK( ), which is responsible for checking the connection status of the IBM personal computer and the video display terminal (both are optional).

SCAN( ) simply scans the user keypad for key closures, and responds to these commands. At the start of a measurement run, the user may optionally set the desired values of such parameters as starting (VMIN) and finishing (VMAX) voltage, and voltage step size (voltage difference between measured points). To start a measurement run, the START

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 35.8.11.3 On: Wed, 27 Jan 2016 12:48:46

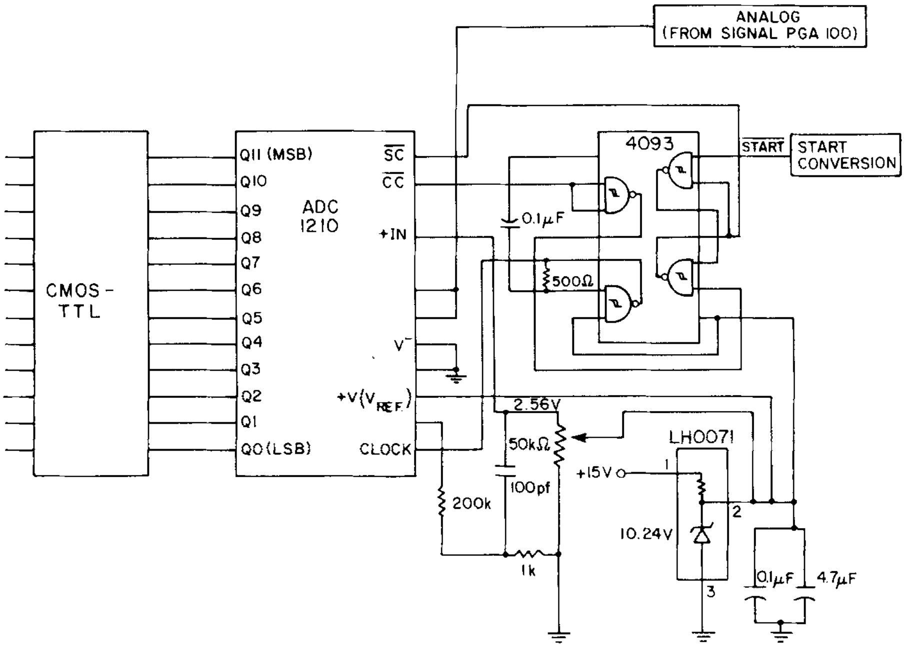

FIG. 4. The analog-to-digital interface. A 12-bit National ADC1210 was used to convert the analog signals supplied from a programmable gain PGA100 multiplexer. The converter converts voltages in the range −5.12 to 5.12 V and runs from a single 10.24-V supply. The level shifters convert from this level to standard TTL levels.

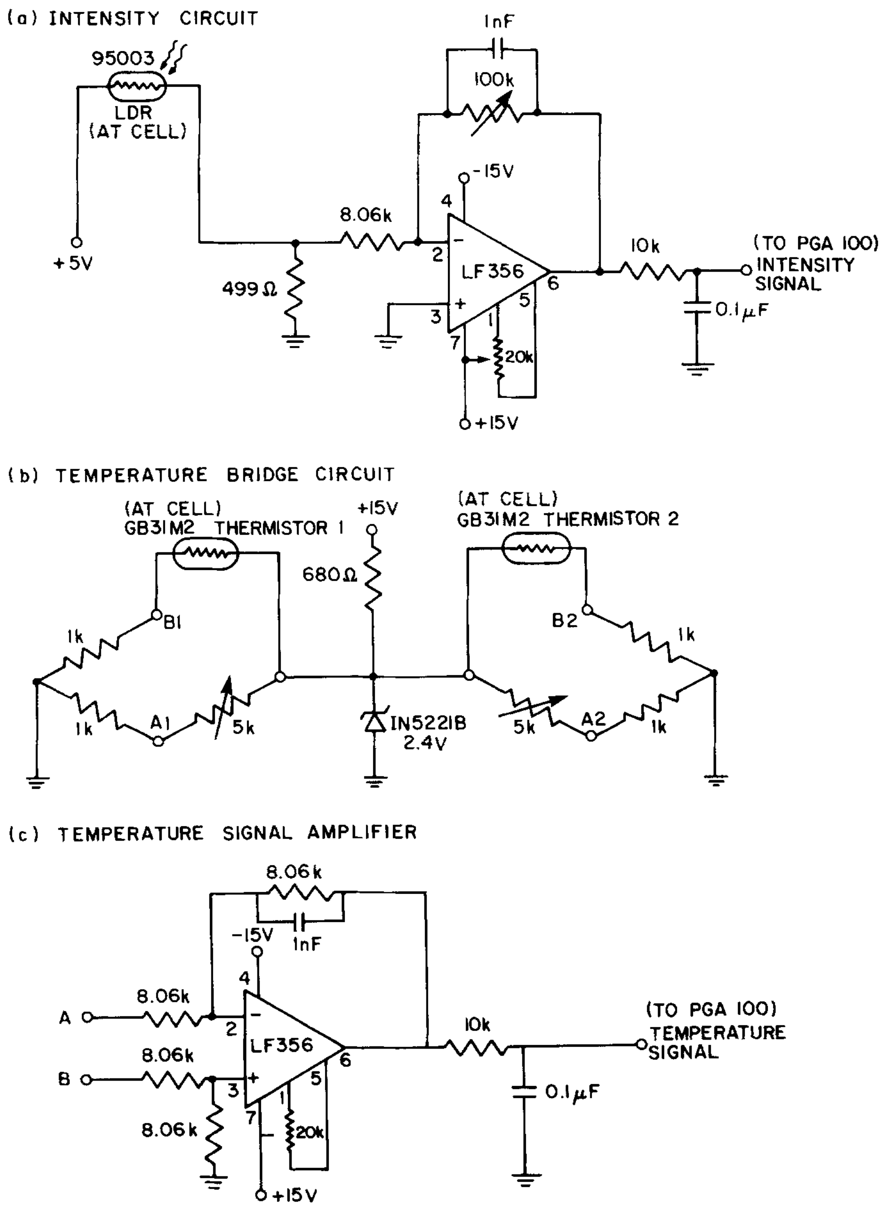

FIG. 5. Schematics of the intensity and temperature monitoring circuits. Two thermistors allow for a measurement of the spatial variation of temperature.

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 35.8.11.3 On: Wed, 27 Jan 2016 12:48:46

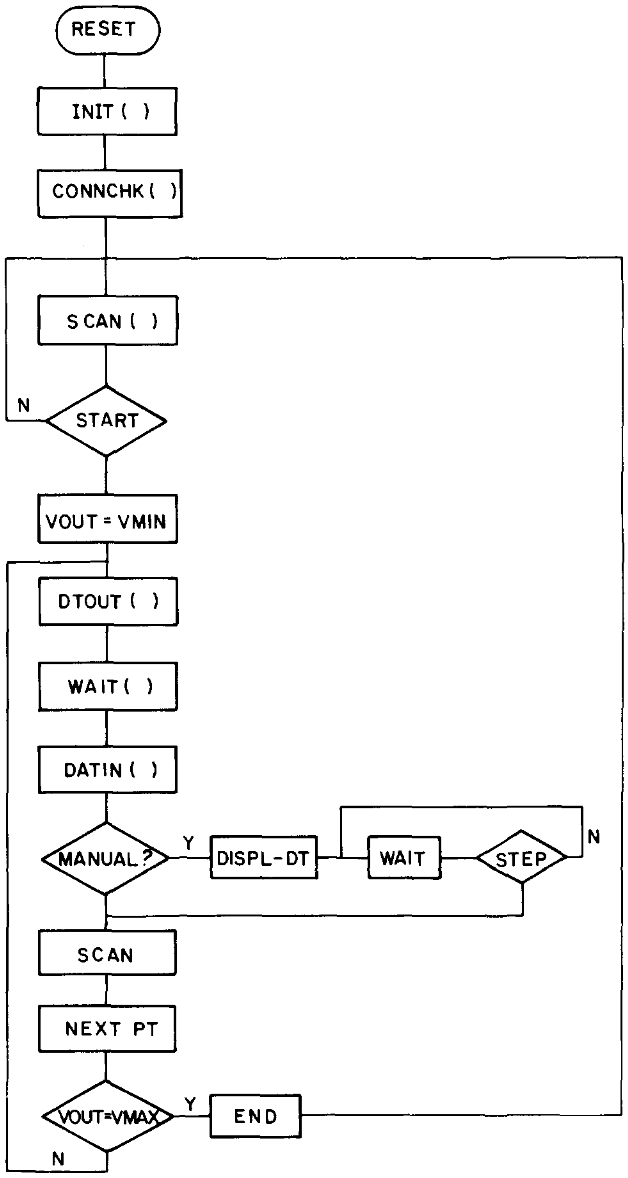

FIG. 6. A flowchart of the control software. This software was written in "C" on a host machine and downloaded into the system. The final version of this software resides in EPROM in the system.

key is pressed on the keypad (mode is set to "r").

The DTOUT( ) routine delivers the present value of VOUT to the analog circuit, and DATIN( ) performs the reading of all analog signals at this voltage point, and stores them. The IDSPL.DT( ) routine is responsible for displaying the current measured value of each parameter (voltage, current, intensity, temperature, "OLD," and "NEW"). SCAN( ) at position 52 provides a "pause" or "stop" option, as the user may break the run by pressing either of these keys which will be recognized at this point. A measurement may be carried out manually, in which case the program waits for the "STEP" key after each voltage step, or it may be done automatically (the run will continue to the end unless requested to stop or pause).

Voltage stepping occurs until the maximum voltage is reached, at which time the data set may be sent to an IBM personal computer [in the END( ) routine] if this is desired.

Complete measurements may be carried out manually using the analog measurement circuitry by supplying a manual input signal at the appropriate position on the front panel, and monitoring the analog output beside appropriate displays.

Should a user wish to operate the system without data transfer (for display and analysis) to the IBM personal computer, the maximum power point (voltage and current), open circuit voltage, and short circuit current values determined during each completed run may be displayed by pressing appropriate keypad keys.

2. IBM personal computer: display and analysis

Within approximately 1 min of completion of a measurement run (which will normally be completed within 1 min for 40 points) the plotting routines available on the IBM personal computer can provide a full color computer screen plot of the measured data. A chosen data set may then be fitted, using a single exponential model for the solar cell[10] of the form

$$I = -I_L + (V - IR_s)/R_{sh} + I_0\{\exp[q(V - IR_s)/(nkT)] - 1\}, \tag{1}$$

where the symbols have their usual meanings.

The flowchart in Fig. 7 illustrates the software flow sequence developed to accomplish the data display and analysis for this system. Final version of any screen plots may be obtained in hard copy on a seven-pen HP plotter which is presently connected to this IBM personal computer.

Information from the illuminated and nonilluminated (dark) $I(V)$ curves is used to calculate the internal cell parameters. The user selects data ranges for which Eq. (1) can be simplified (for example, reverse bias). This data is fitted using a least-squares technique and analyzed for the appropriate parameters. After this analysis is complete the program plots the measured points and the calculated theoretical curve. This allows the user a second check on the validity of the parameters provided by the system.

A sample was measured on the current system and a previous system (the latter used a light source calibrated against a NASA standard cell) and the resultant data analyzed. The cell open circuit voltage changed from 0.516 to 0.528 V. A slight difference in the measurement temperature may account for this small change, otherwise the agreement is good. The theoretical analysis program discussed above calculated the internal cell parameters presented in Table I. This program follows the convention used by Braunstein *et al.*[11], where

$$\lambda = q/(nkT), \tag{2}$$

q = carrier charge, n = diode factor, k = Boltzmann factor, T = absolute cell temperature (K), and

$$\beta = 1 + R_s/R_{sh}. \tag{3}$$

This measurement was carried out at 290 K, so that according to Eq. (2) the effective value of n was closer to two than to one for this sample. A plot of the measured data and the fitted curve appears in Fig. 8, and this demonstrates the effectiveness of the simple modeling equation used in generating good theoretical curves. For this particular sample the

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 35.8.11.3 On: Wed, 27 Jan 2016 12:48:46

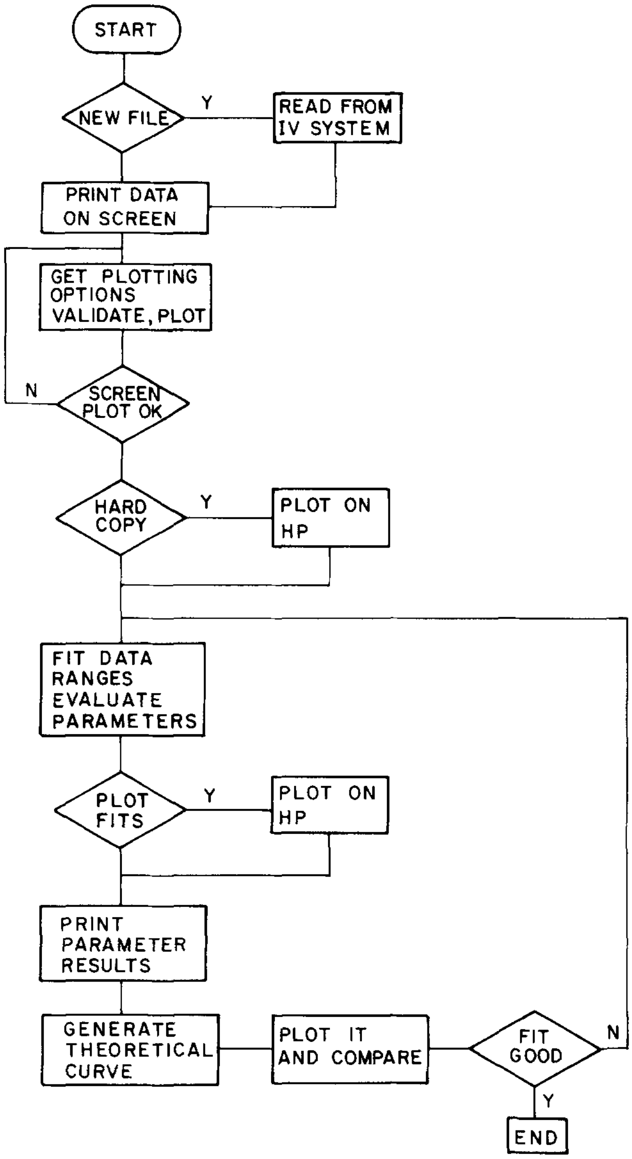

FIG. 7. A flowchart of the display and analysis system. This program runs on the IBM PC. Data is transferred from the I–V measurement system if further modeling and analysis is needed.

TABLE I. Theory 2 (curve-generating program) output for ITO cell.

Theoretical trial results: parameters used:
R series = 1.75
$\lambda = 26$
I_0 (mA) = 4.212145E-05
Rshunt = 375
$\beta = 1.004667$

V(V)	I(mA)	I_{calc}(mA)
− 0.158	− 40.00	− 40.00
− 0.082	− 39.80	− 39.80
− 0.003	− 39.60	− 39.60
0.072	− 39.30	− 39.30
0.147	− 38.90	− 39.04
0.222	− 38.90	− 38.90
0.296	− 38.40	− 38.40
0.370	− 36.70	− 35.96
0.435	− 28.30	− 27.19
0.492	− 12.50	− 12.33
0.545	+ 6.40	+ 6.31
0.597	+ 26.70	+ 27.45

Deviation percent = 0.464967

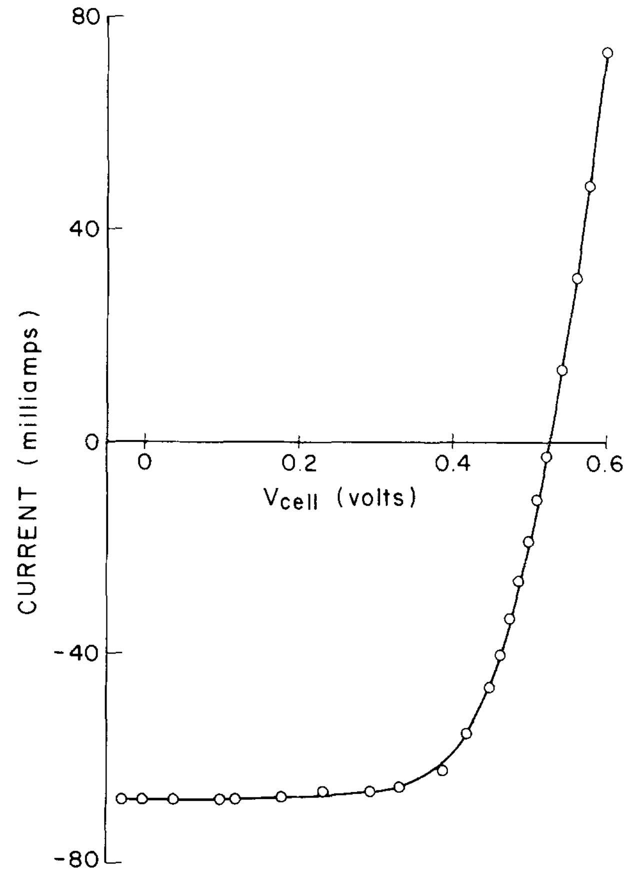

FIG. 8. A comparison of the calculated and measured data (O) for an indium tin oxide on silicon solar cell is given. The calculated fit (solid line) uses parameters obtained from the light and dark curves to model the cell behavior.

fill factor was calculated to be 0.63 and the maximum power point was $V = 0.382$ V and $I = -34.9$ mA. These results along with the values for R_s, R_{sh}, I_0, and n are calculated by the analysis software as requested by the user.

This system is unique among systems of this type[4–8] in that it provides temperature and intensity data as well as an effective automated $I(V)$ measurement. This system has a broad range of capabilities not previously available, even on expensive commercial systems which concentrate on a well-controlled measurement (with little analysis) or on the analysis of data obtained elsewhere.

ACKNOWLEDGMENTS

This work was supported in part by the National Research Council through a DSS contract No. 01SX-31155-2-2718 and NSERC of Canada.

[1]K. Murty and C. P. Schneider, IBM Tech. Discl. Bull. **23**, 3208 (1980).
[2]G. Popkirov, J. Phys. E **13**, 496 (1980).
[3]A. Nedungadi and R. Sharan, IEEE Trans. Instrum. **IM-31**, 206 (1982).
[4]R. Schultz, A. A. Meilus, S. C. Hu, and C. Goradia, IEEE Trans. Instrum. Meas. **IM-26**, 295 (1977).
[5]T. H. Warner and C. H. Cox, III, Solar Cells **7**, 175 (1982).

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 35.8.11.3 On: Wed, 27 Jan 2016 12:48:46

[6]G. C. Cardinali and E. Fladella, Commision of European Communities (CEC) IV Photovoltaic Solar Energy Conference (IV PSEC), 1982, p. 232.
[7]L. Castaner, A. Alabau, M. Sanchez-Nonell, J. Cabestany, and J. Ventosa, IEEE Trans Instrum. Meas. **IM-27**, 152 (1978).
[8]K. Emery and J. DuBow, Proceedings of the XIV IEEE Photovoltaic Specialists Conference (PSC), 1980, p. 506.
[9]R. D. Turner, M. Sc. thesis, University of Waterloo, 1983.
[10]M. B. Prince, J. Appl. Phys. **26**, 534 (1955).
[11]A. Braunstein, J. Bany, and J. Appelbaum, Energy Convers. **17**, 1 (1977).

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 35.8.11.3 On: Wed, 27 Jan 2016 12:48:46