A Fast Low-Cost Solar Cell Spectral Response Measurement System with Accuracy Indicator

S. Silvestre, L. Sentís, and L. Castañer

Abstract—**A novel automated spectral measurement system is presented. Special attention has been focused on the design in order to obtain rapid measurement facilities, minimize hardware and simplify serial communications between the different subsystems involved, resulting in a low-cost measurement system. It is controlled by an HP-9000 computer, through a fully menu-driven interface, and the primary measurement instrument is a HP-4142B modular source-monitor. A new indicator of measurement accuracy is defined, implemented and displayed in real time. This automated system has been employed intensively to study characteristics of different solar cell types in order to optimize their fabrication process. Such this automated measurement system is clearly useful for both the research and fabrication.**

Index Terms—**Automatic test software, measurement, photovoltaic cells, spectral analysis.**

I. INTRODUCTION

THE spectral response (SR) measurement of a solar cell is one of the richest in information tests currently performed in design and fabrication processes. The spectral response at a given wavelength λ is defined as

$$\mathrm{SR}(\lambda) = \frac{J_{\mathrm{ph}}(\lambda)}{I(\lambda)} \tag{1}$$

where $J_{\mathrm{ph}}(\lambda)$ is the total photogenerated short circuit current density at a given wavelength λ and $I(\lambda)$ is the spectral irradiance of the incident light. In state of the art solar cells, the photogenerated current can be approximated by the short-circuit current, which is then measured at several wavelengths using monochromatic light from a filtered light source.

The spectral response of a test cell can be measured by direct comparison with the output of a cell with calibrated spectral response. One of the most extended techniques is to use a white light source (approximating sunlight spectrum) to bias the cells, and measure the incremental spectral response to a small superimposed alternating component of monochromatic light [1], a quartz prism monochromator or a filter wheel are used as monochromatic source, and the exit beam is chopped at low frequency. The test and reference cells are mounted on a slide with suitable positioning stops and are alternately illuminated and measured, the system includes an amplifier and a rectifier.

A simplest technique consists in using a steady-state source of monochromatic light from a monochromator or that obtained by passing white light through narrow-band optical filters and without chopper. This second technique is used in our system with the modifications described below. Although this technique may appear less accurate, in fact the final accuracy is evaluated by a comparison with short circuit-current measured with white light illumination as it is described below.

A set of 15 interferencial filters have been used in a manner similar to the broadband-filter method for spectral responsivity measurements [2]. A reference calibrated solar cell of known spectral response is measured under identical conditions of temperature and irradiance than the test sample. Measuring the reference cell short circuit current, and using the values of the spectral response, the irradiance of the incident light exciting the cell under examination at each wavelength is found immediately. This procedure is recommended as an international standard [3], [4].

The internal quantum efficiency (IQE) of the solar cell is also derived from the measurement of the spectral response by using

$$\mathrm{IQE}(\lambda) = \frac{\mathrm{SR}\left(\frac{hc}{q\lambda}\right)}{(1 - r(\lambda))} \tag{2}$$

where $r(\lambda)$ is the reflectance, h is the Planck's constant, q is the electronic charge and c is the velocity of light in free space.

The spectral response and the internal quantum efficiency of the solar cell are currently used to extract information about important material parameters of the cell: Front and rear surface recombination velocity, diffusion length at the emitter and at the base, width of the depletion region, length of the emitter and light trapping properties among the most important [5], [6]. The determination of the electrical parameters of solar cells is of crucial importance to optimize photovoltaic devices. For the device engineer, accurate knowledge of the spectral response is indispensable for optimization of the cell efficiency. This work describes a fast, automatic, and low-cost measurement system controlled by an HP-9000 (series 300) to measure with accuracy and reliability the spectral response of a solar cell. Such an automated system is useful for both the research and fabrication process of solar cells.

II. SYSTEM DESCRIPTION

Fig. 1 shows a pictorial representation of the main components of the automated spectral response measurement system. The system is composed of an HP4142-B DC source-monitor, an Oriel 68 820 sun simulator, an AM1.5 calibrated solar cell, a set of interferencial filters, a filter array holder and control

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The authors are with the Semiconductor Devices Group, Electronics Engineering Department, Universitat Politècnica de Catalunya, Barcelona, Spain.

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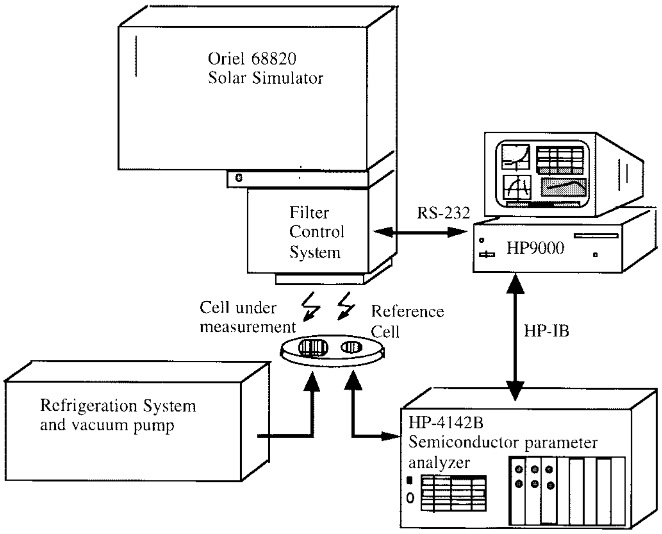


Fig. 1. Major components of the automated spectral response measurement system.

system, a refrigeration system and an HP-9000 computer. The system is controlled by the computer with a custom designed menu-driven user interface in the HP-9000 environment. It is capable of synchronizing HP4142-B measurements and filter set control functioning, collect and further processing measurement results. The main menu appears on the screen as shown in Fig. 2.

A menu-driven HPBasic-6.2 program is developed to conduct the HP4142-B measurement operation through the HP-IB bus, and the filter set control operation through the RS-232 serial port. The filter set control system selects the correct filter and places it in the correct position between the light source and the cells at each short circuit current measurement. A commercial slide projector (Reflecta AF–1800) has been used to drive the set of filters. Filter and slide sizes are the same (5 cm × 5 cm), most of the filters are thicker than the slides and the slide projector platform has been conditioned in order to fit in the filters. The internal optics of the slide projector is not necessary, this part has been eliminated, and the control hardware described in Section II-A as been included.

The built-in software package allows the user to perform different analysis, including control of the measurement accuracy, and some graphic display options to print out or to compare results obtained in several solar cells under test. Fig. 3 shows the different menu options implemented.

The HP4142-B modular DC source-monitor is the primary measurement instrument. This is a high speed, highly accurate controlled DC parametric measurement instrument to characterize semiconductor devices. The HP4142-B allows easy programming controlled by HP-IB commands, and their source-measurement units are capable of supplying or monitoring a voltage or current.

In order to measure the solar cells at standard AM1.5, 1000 W/m^2, 25 °C test conditions, we use a refrigeration system controlled by a temperature sensor placed in the wafers holder. The short circuit currents were measured with a four point arrangement using this instrument.

A. Filter Set Control System

The monochromatic light is obtained with a set of narrow band interference filters with a half power bandwidth around 8 nm. The spectral range of interest λa–λb is 300 nm–1200 nm. This window is covered by a set of 15 filters starting at a central wavelength of 399 nm and ending at a central wavelength of 1152 nm. The rest of filter central wavelengths are equispaced 50 nm over the total interval. The filters are mounted on a platform, which is driven by a stepper motor, and computer controlled positioning. An infrared sensor (CNY70) is used to detect the reference position. Fig. 4 shows the circuit controlled by the infrared sensor, the infrared light emitted by the led is detected by the phototransistor when this infrared beam is reflected by a white surface painted on the filter platform near the first filter. At this moment a low pulse is sent to the HP-9000 via TD line, and the measurement process is started by the computer.

Special attention was focused on the design of our control system in order to simplify hardware and serial communications reducing the total cost of the measurement system. The stepper motor is controlled by a relay (BD137).

The filter platform movement is accomplished applying a pulse of appropriate duration at the relay via the RD serial transmission line. The pulse duration determines the moving direction.

The serial transmitted characters have a length of 10 bits: the start bit (high-level), eight data bits, and the stop bit (low-level). Data is transmitted in this serial format at 1200 bps. It is possible to generate a high level pulse of the appropriate duration if all characters transmitted have high level data bits. The idea is similar to a pulse width modulation (PWM). The duration of the low levels, associate to the stop bits of the characters, is too short to excite the relay. The transmission of n consecutive characters has the same effect that a high level pulse of duration nT_i, being T_i the duration of one pulse. Transmitting 20 consecutive characters the relay is switched on during 166 ms, and the steeper motor forces the filters to advance one position forward. On the contrary, if 80 consecutive, characters are transmitted, the relay is switched on during 666 ms and filters are shifted back one position.

When the system is initialized and made ready for operation the filters are moved until the first filter is placed between the light source and the solar cells, the HP-9000 sends a train of pulses, via RD line, forcing the filters to advance until the first filter is detected by the infrared sensor, this allows to detect the reference position. At this moment a pulse is received by the computer via TD line and a new train of pulses is sent to the slide projector control forcing the filters shift back until the first filter is placed and the first short-circuit current measurement can be made. Fig. 5 shows the RD and TD signal description along this process.

At the beginning of the process, sequences of pulses are transmitted forcing the filter platform to advance until the first position is detected by the infrared sensor and line TD is activated (low-level). The TD line, indicating the detection of the reference filters position, is the input RXD line of the serial port. When the RXD input detects the correct

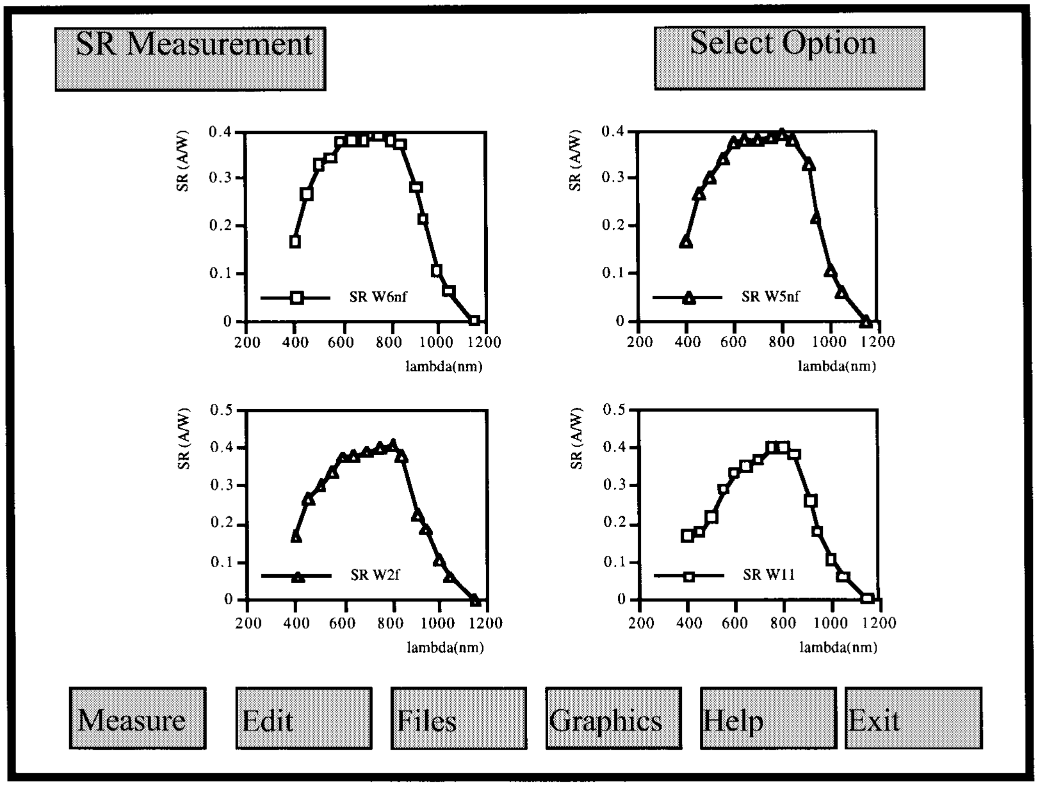


Fig. 2. Menu showing four different spectral response results.

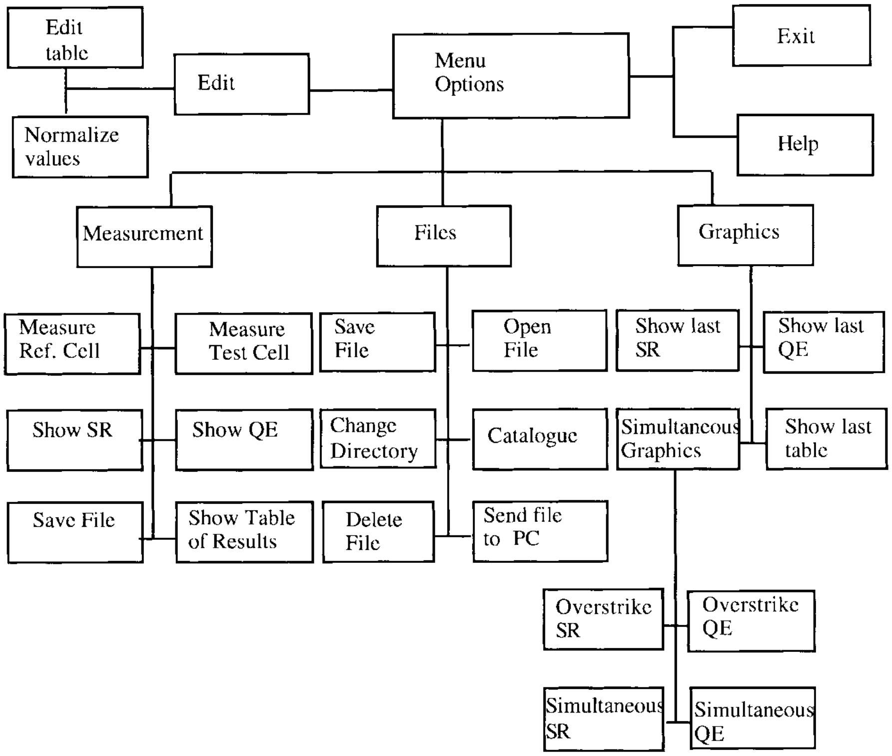


Fig. 3. Different menu options implemented.

position of the filters, the pulses are transmitted from the TXP output via the RD line, to the relay starting the measurement process. No handshake at all is necessary, hardware and serial communications have been minimized.

B. Determination of System Accuracy

In order to obtain a short circuit current value 1023 current measurements are made by the HP-4142B, at each wavelength of interest, and the average value is calculated.

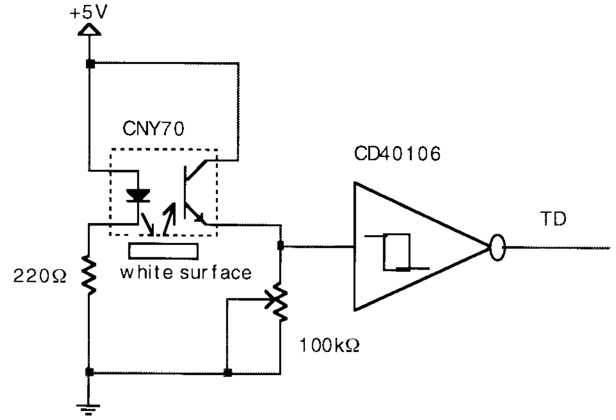


Fig. 4. Reference filter positioning detection unit.

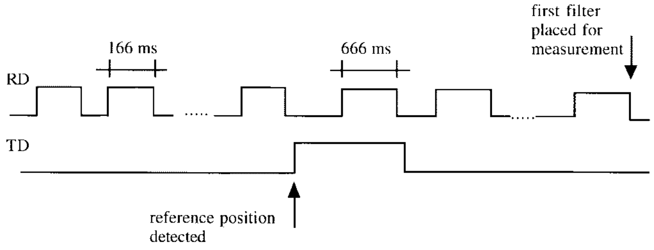
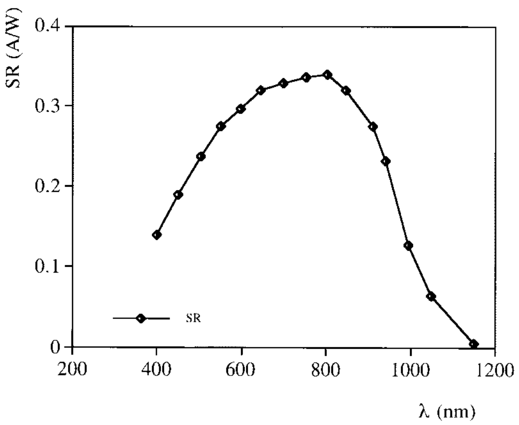


Fig. 5. RD and TD signal description along the initialization process positioning.



Jsc_c (Integral (mA/cm²))	Jsc_m (Measured (mA/cm²))	ε (%)
20.84	20.90	0.28

Fig. 6. Spectral response measured by the system.

During one full spectral response measurement 32 short circuit current values are measured: 16 from the test cell and 16 from the reference cell. In the measurement of the cell under test, 15 out of the 16 measurements are taken when the light is filtered and the sixteenth one is measured without interferencial filter. This last short circuit current measures the global AM1.5 short circuit current, Isc_m, and is useful to estimate the accuracy of the spectral response values obtained at the end of the measurement process, as described below.

The short-circuit current density (Jsc_c) for the cell under test can be estimated from integrated products of the spectral response, $\mathrm{SR}(\lambda)$, and the spectral irradiance of AM1.5 standard sunlight ($I(\lambda)$, 100 mWcm^{-2} [6]), as follows:

$$\mathrm{Jsc}_c = \int I(\lambda)\,\mathrm{SR}(\lambda)\,d\lambda. \tag{3}$$

The relative error introduced by the measurement process is defined as follows:

$$\varepsilon(\%) = 100\left(\frac{\mathrm{Jsc}_c}{\mathrm{Jsc}_m} - 1\right) \tag{4}$$

where Jsc_m is the Isc_m measured short-circuit current divided by the area of the cell under test.

The error in the spectral response measurement is calculated for the cell under characterization every time a spectral response measurement is done. The relative error value [$\varepsilon(\%)$] is shown when the spectral response is plotted. This means that if great differences are noticed between the AM1.5 short circuit current measurement and the estimated from (3), the SR measurement is invalidated and an error message is displayed showing the value of ε.

The main sources of errors are: The calibration of the lamp itself, the temperature variations ±0.25 °C, the AM1.5 simulator temporal intensity stability, typically ±0.5%, the spatial homogeneity in the test plane, about ±1.5%, and the accuracy of the calibrated reference cell ±1%.

The average relative error obtained in our measurements was of the order of $\varepsilon = 1.6\%$, this is a reasonable value taking into account the system limitations.

A set of spectral response measurements systematically made over one year on the same solar cell, has resulted an average deviation of 0.25%. This is the measured reproducibility of the measurement system. A good agreement is also obtained in spectral response measurements done on the same cells with two different systems, our system and the Solar Energy Institute, Polytechnic University of Madrid, spectral response measurement system.

Fig. 6 shows a spectral response measured by our system corresponding to a polysilicon emitter contacted solar cell, the area of the cell was 2 cm². Fig. 7 shows the external quantum efficiency of the same cell.

III. CONCLUSION

We have developed a rapid and low-cost automated spectral measurement system. It is controlled by an HP-9000 computer, through a fully menu-driven user interface. It is capable of performing an spectral response measurement in approximately one minute, giving to the user information about the measurement accuracy. During the measurement a table displays the temperature of the cells under test and the short circuit current values measured in real time.

Special attention has been focused on the design in order to minimize hardware and simplify serial communications, reducing the cost of the measurement system.

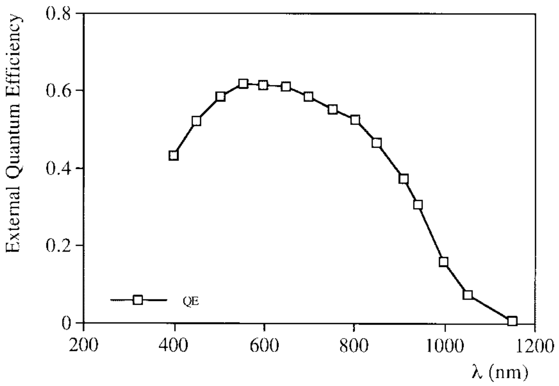


Fig. 7. External quantum efficiency measured for the same cell the spectral response of which is shown in Fig. 6.

This automated system has been employed intensively to study the characteristics of different types of solar cells in order to optimize their fabrication process. This automated system measurement is clearly useful for both the research and fabrication.

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