Електронні системи

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The laboratory tester of solar cells with dynamic reconfigutration of measuring system

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***Abstract*—An express meter of photovoltaic solar cells based on the programmable system on a chip PSoC5 and a personal computer is proposed. This tester is best suited for research on experimental samples of solar cells with non-standard dimensions and parameters, but can also be used as a standard tester for standard samples to control their characteristics with high precision. For the implementation a minimum of discrete elements — a PSoC5 chip, a transistor and a couple of resistors and diodes are required. And such devices as voltage supplies and a computer are available in each laboratory. The standard test conditions (irradiance 1 kW per sq.meter; spectral distribution AM 1.5; sample temperature 25ºC) are conditions that obtainable in a laboratory by using a xenon single flash tube or by an incandescent lamp with filter to reduce the red part of spectra. Despite of the simplicity of the implementation the tester performs measurements of the basic parameters of solar cells (open-circuit voltage, short-circuit current, internal serial resistance and shunt resistance, maximum power, voltage and current at maximum power, efficiency, fill factor, short circuit current density) with high precision and charting current-voltage characteristic of solar cell during less than a second. All the parameters and the current-voltage characteristic are automatically saved to a file and can be examined later. Advantages of the tester are a low cost and highly flexible implementation of the measuring system that allows you to explore experimental samples of solar cells with different characteristics. This was implemented through the use of dynamic reconfiguration of system on a chip that adapts to the conditions of measurement. Depending on the photoelectric current, the algorithm, written in the memory of the programmable system on a chip, selects the appropriate configuration of the measuring system and adjusts the bit resolution (up to 20 bit) and type of the analog-to-digital converter, and gain of the built-in amplifier to provide a minimum time of measurement and maximum of accuracy at given conditions. This allows researchers to reduce the time for investigation of objects with unknown characteristics at a given measurement accuracy. In addition, a sufficient number of additional hardware resources of the programmable system on a chip (digital blocks for logic, timers, counters, analog blocks for operational amplifiers, a programmable gain amplifier, comparators, mixer sample and hold circuit, etc.) with the possibility of their easy configuration into the electronic circuit in the graphic mode of the PSoC Creator allows to researchers easily and quickly to fill up / adjust the electrical scheme to their needs without the need to change the circuit board of the device. The presence on the PSoC of the ARM Cortex-M3 32-bit CPU and the 24-bit fixed-point digital filter processor allows the researcher to supplement the measurement circuitry with digital signal processing, which is especially relevant for small-scale research samples with weak signals in the presence of noises.**

Ref. 10, fig. 7.

Keywords* — *solar cell; measurement; express tester; system on a chip

I. Introduction

A wide range of research of new materials and different designs for solar energy conversion requires operational measurement the basic characteristics of non-standard photoelectric converters designs. The existing equipment with high measuring characteristics is suitable mainly for standard solar cells and often is too expensive for small laboratories [1]–[3]. Simplified measurement designs [4] do not always meet specifications of researchers.

Usually small samples are used for research of new materials and structures. These designs may give small currents and have low heat capacity of the solar cell samples. It defines specific requirements for measuring equipment. Weak current must be measured against the backdrop of external noise and the measurement must be short in time so as not to cause the sample heating.

Proposed rapid automated tester aimed to satisfy the requirements. It is assembled with a minimum number of components, which together with a personal computer is a handy laboratory device with high performance for fast (less than a second) and precise identification of the main cell's characteristics of non-standard photoelectric converters: the open-circuit voltage (Voc), the short-circuit current (Isc), the internal resistances (the serial resistance Rser and the shunt resistance Rsht), the maximum power (MPP), the efficiency (Eff%), the fill factor (FF%), the voltage (Vmpp) and the current (Impp) at maximum power, the short circuit current density (Jsc). Also it plots the current-voltage characteristic (CVC) of the sample. Also the measured parameters can be calculated to standard temperature conditions. All measured data with addition information about the sample (name, size, date of measuring etc.) are automatically saved to a file for their future studies. Based on the programmable system on a chip PSoC5 the flexible measuring circuit allows adapting the system to test characteristics of the solar cells with new design or based on new materials due to make use of dynamic reconfiguration of the system on a chip [5].

II. *Measuring Scheme*

A. *Measuring circuit*

For accurate determination such characteristics as Voc, Isc, Rser, Rsht, it is desirable to measure the CVC in a wide range, which goes beyond the positive values of current and voltage as it is shown on fig. 1. Measuring begins from the point "a" to the point "b", so that the points of intersection of the CVC with the axes (Voc and Isc) and Rser, Rsht could be precisely calculated by mathematical processing by a sufficient number of points on both sides of the axes.

Based on these requirements the scheme shown on Fig.2 was used for measurements. The scheme provides the definition of currents and voltages of photovoltaic cell at positive and also at negative values.

The powerful channel field effect transistor T1 is used to control the load of photovoltaic cell and obtaining the CVC. Changing the cannel resistance of the transistor T1 from high to low by control the gate voltage of the T1 we go through the CVC from point "a" to point "b" (see fig. 1).

The voltage source E2 (fig. 2) is included into the load circuit for measuring the CVC in negative voltage region. It is need for precise determination of short-circuit current and the internal resistance of the cell. The voltage source E2 also compensates for voltage drop in the channel of the transistor T1 and on the resistance R1, which is used to measure current. Thus the value of minimum resistance of open channel does not affect the measurement as opposed to the scheme in [4]. The maximum negative voltage on photovoltaic cell Vr is determined by the voltage of the source E2 minus the voltage drop on the open channel of the transistor T1 and on the resistance R1 at the current through the cell is near the Isc when the transistor T1 is full opened (point "b" on fig. 1).

The voltage source E1 is included into the load circuit to supply negative current through the photovoltaic cell. The negative current reaches a maximum value -Ir when the transistor T1 is fully closed (point "a" on fig. 1). The current Ir is determined by voltage source E1, along with the resistor R1, given the voltage drop across the sample on the measuring resistor R2 and the internal serial resistance Rser of the sample:

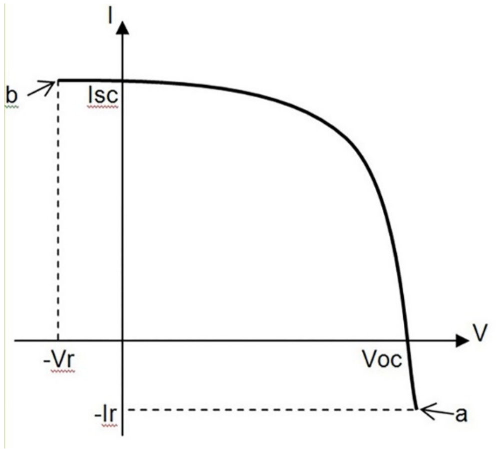

Fig. 1 Current-voltage characteristic of photovoltaic cell (-Vr — maximum negative voltage on photocell, -Ir — maximum negative current through photocell, Voc — open-circuit voltage, Isc — short-circuit current).

$$Ir = (E1 - Voc)/(R1 + R2 + Rser)$$

Taking into account that R1>>(R2+Rser) and E1>Voc for the estimation of the Ir we can use the expression:

$$Ir \approx E1/R1$$

These formulas are presented to assess the maximum voltages and currents in the sample that may arise in the measuring system.

To implement this measuring scheme the programmable system on a chip PSoC5 was chosen because it has enough hardware resources for analog and digital signal processing (digital blocks for logic, timers, counters, analog blocks for operational amplifiers, a programmable gain amplifier, comparators, mixer sample and hold circuit, etc.) and allows the flexibility to use them by configuration (and reconfiguration in run time) of the hardware inside the chip [6]. Also a powerful 32-bit core ARM Cortex-M3, 24-bit fixed-point digital filter processor and 24Kb of RAM allows fast control, process and store operational data.

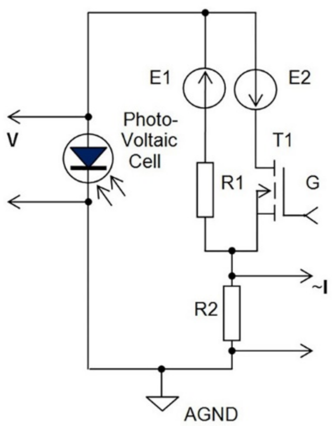

Fig. 2 Scheme for measuring current-voltage characteristics of photovoltaic cell.v

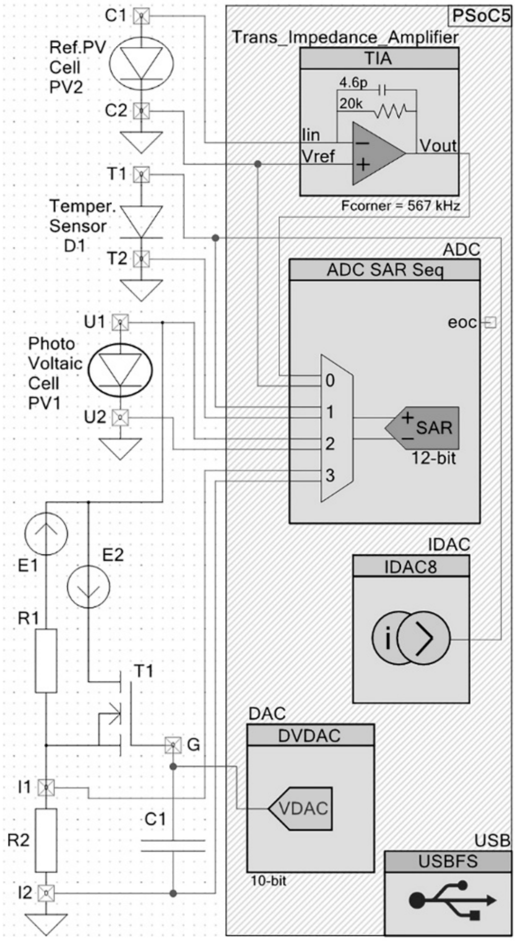

Fig. 3 Measuring circuit with the base configuration of the programmable system on a chip PSoC5.

Measuring circuit with base configuration of PSoC5 is shown on fig. 3. This configuration inside of PSoC5 may be changed in dependence of requirement conditions [7]. It can be done or by the reprogramming the chip or by the reconfiguration without reprogramming if alternative configuration was predefined in the design. The basic configuration of PSoC5 includes an analog-to-digital converter with differential input and with a built-in multiplexer for 4 differential channels (ADC SAR Seq), a digital-to-analog converter (DVDAC), a current digital-to-analog converter (IDAC8), a current-to-voltage conversion amplifier (trance impedance amplifier TIA) and a full speed USB (USBFS). This configuration ensures the minimum time of measurement cycle.

The digital-to-analog converter (DVDAC) is used to control the voltage on the gate of the transistor T1 (and the resistance of its channel and finally the current load of the solar cell). The resolution of the DAC can be set from 9 to 12 bits, depending on the needs of details of the CVC and speed of measurement (higher resolution gives more measuring points but requires longer time).

Temperature of the measured photovoltaic cell PV1 is controlled by a temperature sensor, which uses the p-n junction of the diode D1 as a sensor of temperature [8]. The diode is powered by current about 1-2 mA from the current digital-to-analog converter (IDAC8), which is used as a current source.

Irradiance is controlled by the reference photovoltaic cell PV2, which operates at a short circuit regime. A current of PV2 is proportional to irradiance. The current is converted into a voltage by means of the trans-impedance amplifier TIA.

All voltages (including a voltages proportional to the irradiance, current and temperature) via a built-in multiplexor come to the SAR ADC for digitizing tasks with precision from 8 to 12 bits (sampling rate up to 1 Msps).

For very small samples of solar cells with very low currents the Delta Sigma ADC with up to 20 bits resolution and built in programmable gain amplifier can be used as alternative ADC (instead of ADC SAR Seq with built in multiplexer) by reconfiguring the PSoC5.

But the Delta Sigma ADC has lower sampling rate from 8sps to 384 kbps. In this case it should be configured with the differential analog multiplexor (AMux) as a separate component of PSoC5 (fig. 4).

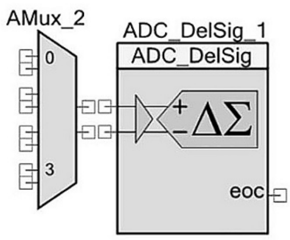

Fig. 4 Differential Analog Multiplexer (AMux) component and Delta Sigma Analog to Digital Converter (ADC_DelSig) component for alternative configuration of PSoC5.

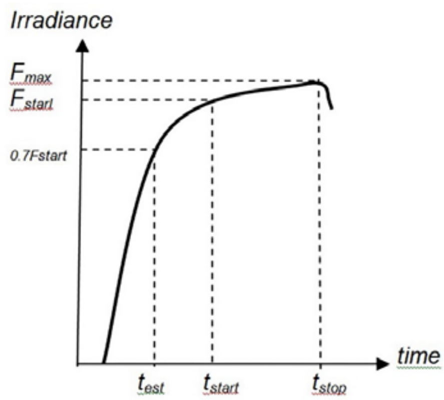

Fig. 5 Measuring Irradiance pulse vs time (test — point of estimation of solar cell current for configuration choice; tstart — beginning of CVC measurement (the first point of CVC); tstop — last point of CVC).

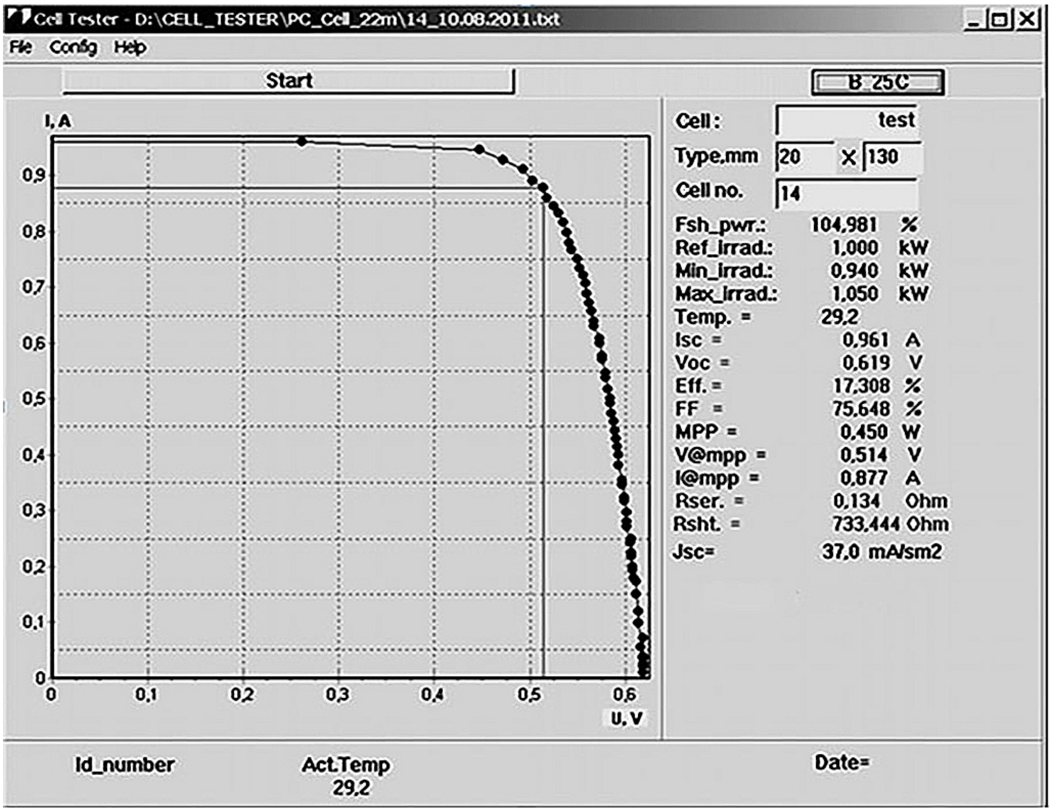

Fig. 6 The application window for control and representation of measurement results.

The array of the digitized values for each point of current-to-voltage characteristic (current, voltage, irradiance, temperature) through the Universal serial bus interface full speed (USBFS) comes to a personal computer for saving the data on a hard drive and for further processing and presenting the CVC and solar cell's parameters (Voc, Isc, Rser, Rsht, MPP, Eff%, FF%, Vmpp, Impp, Jsc.) on the computer display. The USB of PSoC is configured as HID (Human Interface Device). This allows using the standard driver of operating system for devices.

B. Measurements at Standard Test Conditions (STC)

Standard Test Conditions (irradiance 1kW/m2; spectral distribution AM 1.5; sample temperature 25oC) are conditions that obtainable in a laboratory [9] according to "IEC 60904-3. Photovoltaic Devices: Part 3. Measurement Principles for Terrestrial Photovoltaic (PV) Solar Devices with Reference Spectral Irradiance Data". Some difficult task is to obtain a spectral irradiance distribution. With incandescent lamps the source temperature is approximately 3,200 K, while Sun surface temperature is about 5800K. For that reason the radiation in red part of spectra needs to be filtered.

The better way is to use a xenon single flash tube that has the spectral distribution very closely to AM0 spectral distribution. Simple filtering can drive to AM 1.5.

All measurements are performed during a single irradiance pulse with the shape shown on fig. 5. Starting of measurement occurs at a predetermined level Fstart as measured by the Reference Cell PV2. Stopping measurement occurs when the voltage at the sample PV1 drops to the predetermined negative value near – E2 (fig. 1, point "b"). Number of measurements and measurement duration depends of DAC step and are fixed by soft.

III. Function Principle of the Cell Tester

The PSoC5 is controlled by an application installed on a personal computer. The application has a main window with fields for inputting sample sizes, plotting CVC, displaying the main parameters, current temperature of the solar cell, and control buttons (fig. 6).

When the button "Start" has been pressed the signal from the personal computer is transmitted through USB to the PSoC5 to start the measurement. On the fig. 7 the block diagram of the algorithm and the distribution of functions between a personal computer (PC) and the PSoC5 are shown. The PSoC5 turns on the light source and begins to monitor irradiance level (fig. 5).

When the irradiance level reaches 70% of Fstart the tested solar cell is loaded by opening the transistor T1 on a short time and the current from the cell is estimated by PSoC5 in the base configuration (fig. 3). If the signal from the sample is less than the predetermined level, the PSoC5 reconfigures the measuring scheme to configuration with higher sensitivity (delta sigma ADC with preamplifier, as mentioned above) and then it evaluates the signal level in the new configuration. On the results of this evaluation the gain of the built-in amplifier and Delta Sigma ADC resolution are adjusted. If the signal from the sample is more or equal to the predetermined level, the PSoC5 remains in the base configuration. In this case the resolution of the SAR ADC is adjusted. At this point the adaptation of the measuring system ends and the system continues to monitor the level of irradiance of the sample until it reaches the start level F_{start}..When the irradiance level reaches start level Fstart (for instance 95% of nominal) a cycle of measuring current-voltage characteristics begins. Simultaneously irradiance, voltage, current and temperature are measured and saved in RAM of PSoC5. Voltage from DAC is applied to the transistor T1 gate (Fig.3), which opens on the steps, increasing load current from negative values near –Ir (from point a) step by step through the CVC to maximum values of the current until voltage on the cell reaches the negative value –Vr (point "b"). Then PSoC5 switches off the light source and transmits the data from RAM of PSoC5 to the computer through USB for further processing, calculation of main parameters of photovoltaic cell [10] and display the CVC and the main parameters on the window of application (fig. 6).

The obtained data can be recalculated to the standard reference temperature of 25C by pressing the button "25C". There is a configuration menu for settings the PSoC5 parameters according to the characteristics of the samples (step of the CVC points, start level of irradiance, etc.).

The firmware for PSoC5 was developed in the PSoC Creator IDE in C. The software for PC was developed in MS Visual Studio Community in C#. The both IDE (for firmware and software) are freely available on the websites of Cypress Semiconductors and Microsoft respectively.

This implementation requires a minimum of discrete elements — a PSoC5 chip, a transistor and a couple of resistors and diodes. Somewhat more special is the source of irradiance.

Conclusions

The proposed original solution of the express tester for scientific researches of photovoltaic cells with tiny design may be implemented with little cost meanwhile we obtained a complete device with accurate measurement of all main characteristics of a photovoltaic cell during a time less than one second. Using a programmable system on chip PSoC5 allows you to optimize the circuit for different minds and different very small samples of solar cells without redesign the hardware parts. It is shown that using of the dynamics reconfiguration of the programmable system on a chip allows adapting in run time a measuring system to the characteristics of the measured sample to ensure the required accuracy, measurement time and preventing of sample overheating. In addition, a sufficient number of additional hardware resources of the programmable system on a chip with the possibility of their easy configuration into the electronic circuit in the graphic mode of the PSoC Creator allows to researchers easily and quickly to fill up / adjust the electrical scheme to their needs without the need to change the circuit board of the device. The presence on the PSoC of the ARM Cortex-M3 32-bit CPU and the 24-bit fixed-point digital filter processor allows the researcher to supplement the measurement circuitry with digital signal processing, which is especially relevant for small-scale research samples with weak signals in the presence of noises.

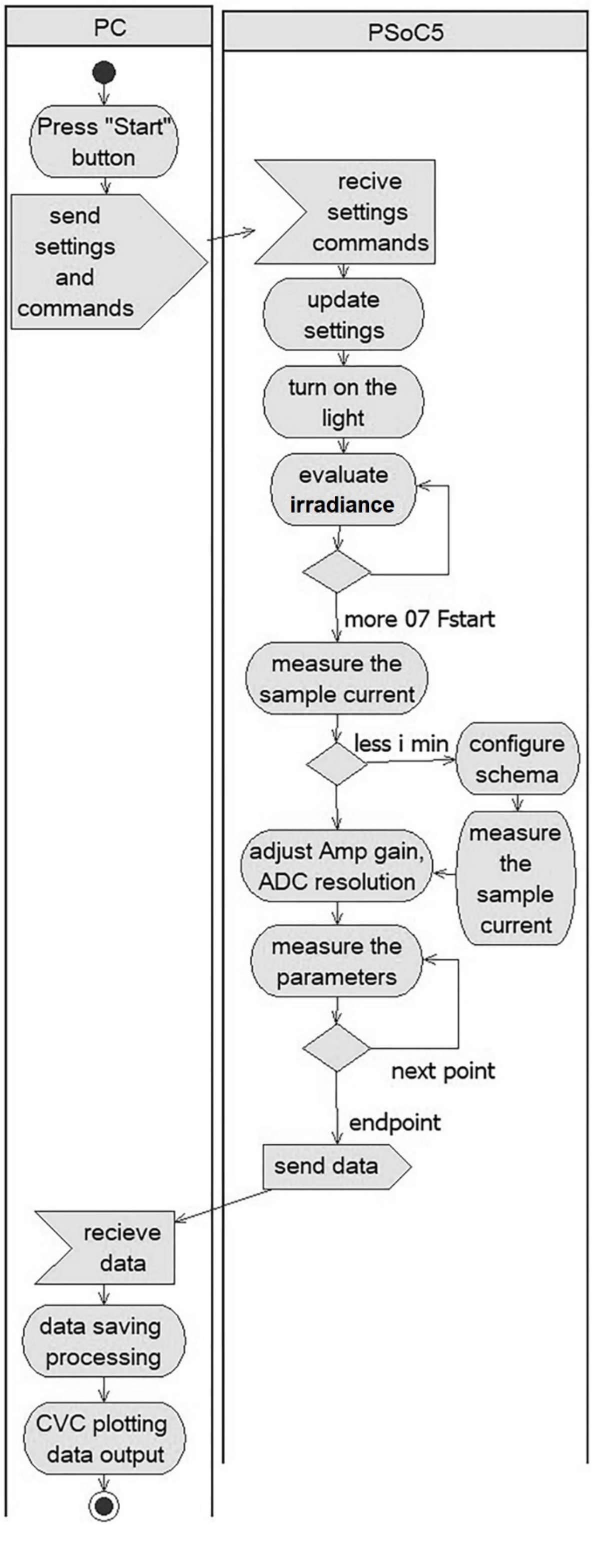

Fig. 7 Activity diagram of the tester. Distribution of functions between a computer (PC) and the programmable system on a chip (PSoC5).

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Лабораторний тестер сонячних елементів з динамічною реконфігурацією вимірювальної схеми

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***Реферат*—Пропонується експрес-тестер характеристик фотоелектричних сонячних елементів на основі програмованої системи на кристалі PSoC5 і персонального комп'ютера. Не зважаючи на простоту реалізації тестер виконує вимірювання основних параметрів сонячних елементів (напруги розімкнутого ланцюга, струм короткого замикання, внутрішній опір, максимальна потужність, ефективність та інші) з високою точністю і виводить графік вольт-амперної характеристики сонячного елемента менш ніж за секунду. Всі виміряні параметри та вольт-амперна характеристики автоматично зберігаються в файли та можуть бути розглянуті пізніше. Перевагами тестера є низька ціна і дуже гнучка реалізація вимірювальної схеми, що дозволяє досліджувати експериментальні зразки сонячних елементів з різними характеристиками. Це вдалося реалізувати завдяки використанню динамічної ре конфігурації системи на кристалі, яка адаптується до умов вимірювання.**

Бібл. 10, рис. 7.

Ключові слова* — *сонячний елемент; вимірювання; експрес-тестер; система на кристалі

УДК 621.383

Лабораторный тестер солнечных элементов с динамической реконфигурацией измерительной схемы

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***Реферат*—Предлагается экспресс тестер характеристик фотоэлектрических солнечных элементов на основе программируемой системы на кристалле PsoC5 и персонального компьютера. Несмотря на простоту реализации тестер выполняет измерения основных параметров солнечных элементов (напряжения разомкнутой цепи, ток короткого замыкания, внутреннее сопротивление, максимальная мощность, эффективность и другие) с высокой точностью и выводит график вольт-амперной характеристики солнечного элемента менее чем за секунду. Все измеренные параметры и вольт-амперная характеристики автоматически сохраняются в файлы и могут быть рассмотрены позже. Преимуществами тестера является низкая цена и очень гибкая реализация измерительной схемы, позволяющей исследовать экспериментальные образцы солнечных элементов с различными характеристиками. Это удалось реализовать благодаря использованию динамической реконфигурации системы на кристалле, которая адаптируется к условиям измерения.**

Библ. 10, рис. 7.

Ключевые слова — солнечный элемент; измерения; экспресс тестер; система на кристалле