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RESEARCH ARTICLE

"In-field" cell temperature evaluation in solar modules through time-dependent open circuit voltage measurements

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ABSTRACT

A method for the evaluation of p–n junction cell temperature in PV modules operating in the maximum power point (MPP) mode has been proposed. The method does not require specialized equipment and (for the concentrator modules) the data on the open circuit (OC) voltage temperature coefficients measured under pulse illumination. It consists of measuring several open circuit voltage magnitudes together with temperature measurements on the external module surface near one of the cells. In this procedure, a fast transition from MPP to OC operational mode is carried out, during which a time-dependent voltage measurement is carried out with the help of a memory oscilloscope. A "reference" OC voltage magnitude in a "cold" module (a condition, as if the cells are kept at ambient temperature) is obtained by calculations, so that there is no necessity in a fast mechanical shuttering of the module aperture area. In the case of the concentrator modules, the module OC voltage temperature coefficient can be measured, if heat sinking process is artificially modified during outdoor measurements. Copyright © 2015 John Wiley & Sons, Ltd.

KEYWORDS

III–V solar cells; concentrator modules; temperature measurements

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1. INTRODUCTION

The performance of photovoltaic (PV) modules is greatly affected by the temperature at the p–n junction(s) $T_{p\text{–}n}$ of each individual cell [1–4]. Electrical loading the module at the maximum power point (MPP) of the I–V curve reduces cell temperature, because a part of incident solar energy is transferred to the load by the current. The cell open circuit (OC) voltage (V_{OC}) is the most reliable and easily measured parameter, which can characterize the p–n junction temperature. But knowing the V_{OC} value gives very imprecise information on the temperature in the MPP operational mode in the case of the highly efficient multijunction cells in the flat and concentrator modules, because a considerable part of the absorbed power is dissipated in an external load [5].

The problem of p–n junction temperature evaluation in MPP mode may be regarded as consisting of three parts:

(i) to "adjust" OC voltage measurement to MPP conditions at the thermal balance of the module with the environment;
(ii) to compare obtained result with the OC voltage magnitude corresponding to a temperature equal to the ambient one;
(iii) to translate the difference in voltages into the difference in temperatures.

A simple procedure for making V_{OC} an indicator of operational temperature in MPP mode of concentrator modules has been proposed in [6]. The procedure consists of measuring the magnitude of the V_{OC} just after the moment of a fast switching from the MPP mode to that of the OC (denoted as V_{OC}^{MPP}). The V_{OC}^{MPP} value measured in such a way should now be compared with that corresponding to the case of cells kept at an ambient temperature (denoted as V_{OC}^{amb} in a "cold" module) for calculating an increase in p–n junction temperature.

Determination of the V_{OC}^{amb} value is certainly a specific problem which has been under discussion for a long time. In particular, a procedure for direct measurement has been suggested in [7], and which was also used in [6]. It supposes a fast mechanical shuttering of the module aperture while measuring: meteorological conditions, OC module voltage, and heat sink temperature (temperature on an external side of the module T_{ext}). In [7], the shutter time necessary to reach the maximum V_{OC} was from about 5 to 150 ms depending on the module aperture area: the shortest time corresponds to the mechanical shuttering of an individual small-area cell; the longest one is implemented when a piece of heavy black cloth is initially placed over the face of the meter-sized module and then removed manually. It should be noted that, in [7], the procedure for the determination of the V_{OC}^{amb} was developed only with the aim of the cell p–n junction temperature evaluation in the OC mode, not in MPP.

Meanwhile, extensive experience in characterizing concentrator PV cells under pulse illumination has shown that the rise in temperature in cell chips soldered to a heat sink could roughly be estimated as about 1 °C per 1 ms at concentration ratio of 1000× [8,9]. This coefficient is valid for the initial period of measurements after the step-like beginning of cell illumination. Cell heating process in corresponding period is controlled by the heat capacity of chip material. It means that correct (with an accuracy of about 1 °C) measurement of cell temperature in high-concentration PV modules through the translation of OC voltage may be carried out, if a "cold" module is opened to illumination for a period of time of less than 1 ms.

It became obvious that a different way would be required for V_{OC}^{amb} determination. It should exclude fast mechanical module shuttering procedure, because necessary shutter speed of 1 ms cannot be realized. This way has been proposed in our previous work [10]. According to [10], the V_{OC}^{amb} evaluation is carried out through calculations. Initial data for the calculations are the following parameters, which have to be measured: two open-circuit voltage magnitudes; two temperatures on an external side of the cell heat sink; ambient temperature. In the procedure, the first OC magnitude, V_{OC}^{MPP}, is measured at a fast transition from MPP (after achieving thermal balance with environment) to the OC operational mode, as proposed also in [6]. The second voltage magnitude is simply the V_{OC} of an investigated cell, or module, in OC mode, again after achieving thermal balance with environment. In experiments with laser beam illumination of the small single-junction cells [10], it was possible to verify corresponding approach at measuring V_{OC}^{amb} directly and accurately using a mechanical shutter with response time as short as 0.3 ms and an electronic switcher (from MPP to OC) with response time about 0.01 ms. This gave the possibility to compare the calculated V_{OC}^{amb} value with the directly measured one.

Let us consider translating the OC voltage of a PV module into the p–n junction cell temperature. The corresponding procedure is carried out by using the V_{OC} temperature coefficients for individual cells and a module as a whole. As regards the cells, this coefficient depends on the cell material and structure, as well as the photocurrent density. As a rule, the coefficient is determined from pulse measurements under variable temperature conditions. The current stage of multijunction cell development is characterized by a variety of cell designs. Hence, a concentrator module based on the cells of a certain design and subjected to temperature research should be supplied with results of pulse measurements. Individual cells in one and the same module may have slightly different PV parameters. An "ideal" situation occurs, if the V_{OC} temperature coefficient is known as relating to the assembled module. But, pulse V_{OC} measurements are not easy to take for high-concentration PV modules as they require a temperature controlled chamber and a specialized flash solar simulator with a light collimating system.

In this paper, a quite simple temperature evaluation procedure for solar modules (flat and concentrator ones) is described in detail (it was briefly presented in [11]), which may be applied even "in-field" practice outdoors. There are V_{OC} values to be measured, one of which is time dependent and measured by a standard memory oscilloscope at MPP-to-OC switching. Stationary ones are measured under conditions of thermal balance. In the concentrator modules, it is proposed to determine the V_{OC} temperature coefficient using two stationary V_{OC} values, when module heat sinking properties and, consequently, temperature on an external part of a module are varied by means of a "heat variator". After that, the difference in OC voltages in "cold" and "MPP" conditions is converted into the rise in the p–n junction temperature $\Delta T_{p\text{–}n}$ comparing it to the ambient temperature.

The developed method has been applied at the outdoor research of the high-concentration PV modules of SMALFOC-design [4] based on Fresnel silicone-on-glass lenses and triple-junction GaInP/GaInAs/Ge cells.

2. BASIC PRINCIPLES OF THE METHOD

The theoretical consideration of the thermal processes in a continuously illuminated solar module (at a moderate rise in temperature compared with the ambient one) is based on two commonly applied principles of thermal balance with environment:

- linear dependence of temperature of any part of the module on the power dissipated in this module; as a consequence—a proportional relationship between the p–n junction cell temperature $T_{p\text{–}n}$ and the temperature of any external module element T_{ext};

- linear dependence of the OC voltage on cell p–n junction temperature.

The first principle can be expressed by the plots presented in the graphs in Figure 1. It is obvious that the most heated elements in a solar module are the solar cells being at the temperature $T_{p\text{–}n}$. Any element on an external part of the body of the module is characterized by a lower temperature T_{ext}. The upper part of Figure 1 illustrates the rise in $T_{p\text{–}n}$ and T_{ext} at a variation of solar incident power P_{inc}, when the cells are in OC mode of operation. The external module element should be located near one of the cells. Temperature of this element has to be directly measured in the experiment. At zero incident power, the aforementioned temperatures are equal both to each other and the ambient temperature. At increased incident power, which is then dissipated, there is a difference between these temperatures, but the corresponding translation coefficient is unknown.

The lower part of Figure 1 shows a change in the temperatures considered if the power dissipated in the cell chip is varied through the extraction of photogenerated electric power at P_{inc} = const. An amount of extracted electric power P_{El} is determined by the photovoltaic conversion efficiency of the cells in a module and is placed within an interval corresponding to the OC and MPP operational modes. A situation in which both temperatures in thermal balance with environment are equal to T_{amb} could be implemented hypothetically under the conditions of 100% PV conversion efficiency.

The condition of P_{inc} = const (lower graph in Figure 1) gives a possibility to consider an approach at which OC voltage could be used as an indicator of $T_{p\text{–}n}$ along the corresponding graph. After switching from loaded cell mode to OC mode, a rapid rise in cell voltage is accompanied by a delay in temperature rise because of a finite heat capacity of the cell material. A procedure of OC voltage measurement with the aim of evaluating the operational temperature in MPP mode is illustrated in Figure 2. Here Figure 2a shows the transition from MPP mode, at which V_{MPP} is measured under the condition of balance with environment, to OC mode, at which the OC voltage is measured under the non-stationary condition of fast disconnection of external load (it is denoted as V_{OC}^{MPP}). Figure 2b shows time-dependent change in voltage at corresponding measurements. Measurement of V_{MPP} and V_{OC} in both the stationary MPP and stationary OC modes is taken using a standard DC voltmeter. At V_{OC}^{MPP} evaluation, amplitude of voltage pulse, arising at load disconnection, can be measured using a standard memory oscilloscope with AC input (Figure 2b). The accuracy of the V_{OC}^{MPP} measurement is ensured by rather high

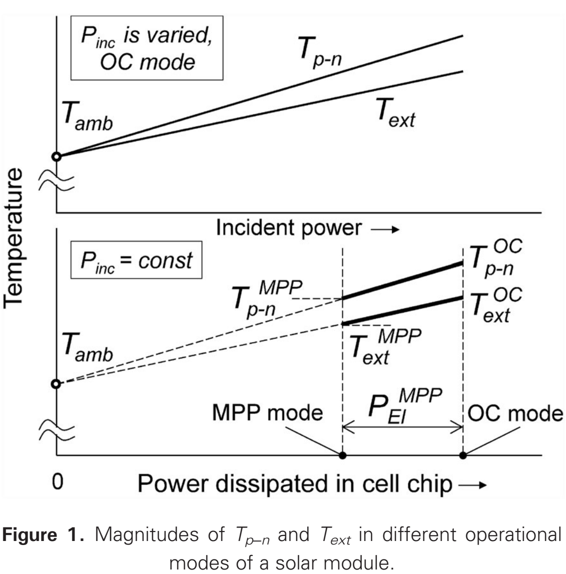

Figure 1. Magnitudes of $T_{p\text{–}n}$ and T_{ext} in different operational modes of a solar module.

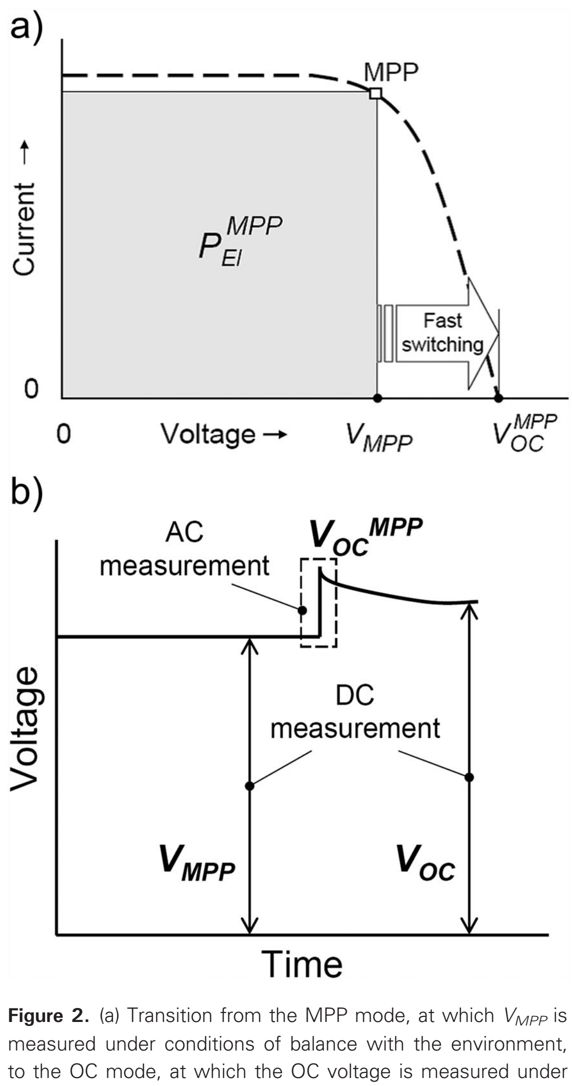

Figure 2. (a) Transition from the MPP mode, at which V_{MPP} is measured under conditions of balance with the environment, to the OC mode, at which the OC voltage is measured under non-stationary conditions of fast disconnection from the external load; (b) time-dependent change in voltage at the corresponding measurements in DC and AC configurations of the measuring instruments.

accuracy of the V_{MPP} DC measurement and proper accuracy at AC measurement of a relatively small difference between the V_{MPP} and $V_{OC}{}^{MPP}$ magnitudes.

3. DETERMINATION OF $V_{OC}{}^{amb}$

The aim of this section is to determine the $V_{OC}{}^{amb}$ value by combining two basic principles:

(i) the proportional relationship between the p–n junction cell temperature $T_{p–n}$ and the temperature of any external module element T_{ext};
(ii) the linear dependence of the cell OC voltage on p–n junction temperature $T_{p–n}$.

Using the relationship between $T_{p–n}$ and T_{ext} from the lower graph in Figure 1, and replacing $T_{p–n}$ by the corresponding OC voltage values at different resistances of the external load (they could be measured in a similar way, as $V_{OC}{}^{MPP}$ was measured in Figure 2), one can obtain a straight line between $V_{OC}{}^{MPP}$ and V_{OC}, as shown in Figure 3. In this figure, the OC voltages are placed in a straight line as they depend on the temperature on the external part of the module. All temperatures should be measured under thermal balance conditions.

The geometric consideration of graph in Figure 3 leads to the following expression for $V_{OC}{}^{amb}$:

$$V_{OC}^{amb} = \frac{V_{OC}^{MPP}\left(T_{ext}^{OC} - T_{amb}\right) - V_{OC}\left(T_{ext}^{MPP} - T_{amb}\right)}{T_{ext}{}^{OC} - T_{ext}{}^{MPP}}. \quad (1)$$

Hence, in the proposed method, the fast manual shuttering of the module aperture for obtaining the OC voltage in "cold" conditions is replaced by the calculations of this value using data, obtained from fast electrical switching from the MPP to the OC operational modes. Knowledge of the $V_{OC}{}^{amb}$ value gives the possibility of evaluating the p–n junction temperatures in both OC and MPP modes of module operation.

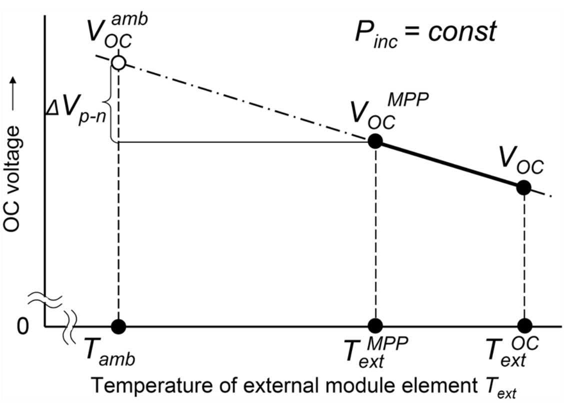

Figure 3. Reconstruction of Figure 1 into the dependence of V_{OC} magnitudes on T_{ext} at P_{inc} = const.

4. TRANSLATION OF THE DIFFERENCE IN VOLTAGES INTO THE DIFFERENCE IN TEMPERATURES

The aim of this section is to determine the OC voltage temperature coefficient α for an assembled concentrator module to avoid the procedure of pulse measurements in temperature-controlled conditions. The ideal situation would consist of the OC voltage measurements in the same module at the same intensity and same spectrum of sun illumination, but at two different ambient temperatures (let T_{amb2} be higher than T_{amb1}). In a thermal balance, an increase in ambient temperature gives rise to an equal increase in the temperature of the cells and that of any external module part:

$$T_{amb2} - T_{amb1} = T_{p-n2}^{OC} - T_{p-n1}^{OC} = T_{ext2}^{OC} - T_{ext1}^{OC}. \quad (2)$$

It should be noted that, in practice, a reasonably small change of cells temperature can be caused artificially, if the heat dissipation process in a concentrator module is modified in a certain way. For instance, under windless outdoor conditions, it is possible to use an external blower to slightly intensify heat removal, whereas at a temperate windy weather, a mesh-type woven blanket may be used to make a module hotter. Such a modification can be made during one outdoor experiment and, hence, under the same sun illumination conditions. The latter circumstance ensures certain constancy in the temperature drop along a path from the cells to the external module surface. Therefore, the directly measured change of temperature on an external module element after artificial change of heat dissipation process can be plainly attributed to that of the p–n junctions in the cells. Generally speaking, the latter assertion may have certain limitations. First, the heat dissipation should take place mainly from a single (rear) side of a module. This situation is typical for concentrator modules with passive air cooling. Second, it is supposed that distribution of temperature along the rear side of a module is rather uniform. A little artificial variation of heat sinking efficiency (increasing or decreasing) does not lead to redistribution of temperature along the heat sinking elements. The latter is equivalent simply to the change of temperature of these elements because of changing of ambient temperature. At P_{inc} = const the temperature difference between $T_{p–n}$ and T_{ext} remains constant. Therefore, difference in T_{ext} in a "normal" OC mode and in a "modified" one is equal to difference in $T_{p–n}$. In this case the OC voltage temperature coefficient α of the module is calculated using the following formula:

$$\alpha = \frac{V_{OC(\mathrm{m})} - V_{OC}}{T_{ext(\mathrm{m})}^{OC} - T_{ext}^{OC}}. \quad (3)$$

In formula (3), the parameters with index (m) correspond to conditions of modified heat dissipation process, when a heat variator (blanket) is applied to the rear of the module. Using this coefficient α, one can calculate the increase in the p–n junction temperature of the cells in MPP operational mode as compared to the "initial" ambient temperature T_{amb}:

$$\Delta T_{p-n}^{MPP} = \frac{V_{OC}^{MPP} - V_{OC}^{amb}}{\alpha}. \qquad (4)$$

Finally, the required temperature of the cells in MPP mode is calculated as a sum of T_{amb} and $\Delta T_{p-n}{}^{MPP}$:

$$T_{p-n}^{MPP} = T_{amb} + \Delta T_{p-n}^{MPP}. \qquad (5)$$

5. SETUP FOR OUTDOOR PROBING

Outdoor temperature evaluation experiments were carried out on high-concentration PV modules of the so-called SMALFOC-design [4]. The corresponding module structure has been recently developed at the Ioffe Institute. The aforementioned abbreviation highlights the specific features of such a design: Small lenses, Multijunction cells, All made of glass, Lamination, and Fresnel Optical Concentration. A fragment of the solar concentrator PV module of the SMALFOC-design is schematically shown in Figure 4. Full-size modules with a designated illumination area of 480 mm × 960 mm consisted of 128 (60 × 60 mm^2 each) lenses in a silicone-on-glass panel and a rear receiver panel with triple-junction metamorphic GaInP/GaInAs/Ge cells. Each group of 8 cells was parallel connected being soldered on a common heat spreader (Figure 4). These groups (16 pieces in each module) were series connected ensuring open circuit voltage of around 45 V at a PV conversion efficiency near to 23%. The averaged sun concentration ratio was about 300×. Before assembly in the module, some of the cells were used for the "T *vs* V_{OC}" measurements by means of a flash solar simulator at various photocurrent densities j_{ph}. Obtained in such a way data on the temperature coefficient α were used for further comparison with that obtained from outdoor experiments and calculation by formula (3). A Pt100 thermo-resistor was fixed on the rear of the tested module for T_{ext} measurements.

The investigated module was mounted on a sun-tracker. The rear side of a module could be shielded by means of a mesh-type woven blanket for varying the receiver panel temperature. Before the experiments, the front side of the module was shielded by a reflective cover sheet to prevent an initial heating of the module and to ensure the recording of the T_{amb}. A picture of the module on a sun-tracker is shown in Figure 5. Also demonstrated is a mesh-type woven blanket used in experiments.

The module was electrically connected with a variable resistive load to arrange the MPP operational mode (Figure 6). Under thermal balance conditions, the DC voltage and current magnitudes were recorded using Fluke multimeters. At the MPP-to-OC transition, a standard tumbler switch was used for a fast disconnection of the electrical load. At switching, a time-dependent voltage record was made by means of a Tektronix memory oscilloscope with an AC input.

6. "IN-FIELD" OUTDOOR EXPERIMENT

Manual shuttering the 0.5 × 1.0 m^2 modules gave rise to a long delay of about 400 ms in the OC voltage change

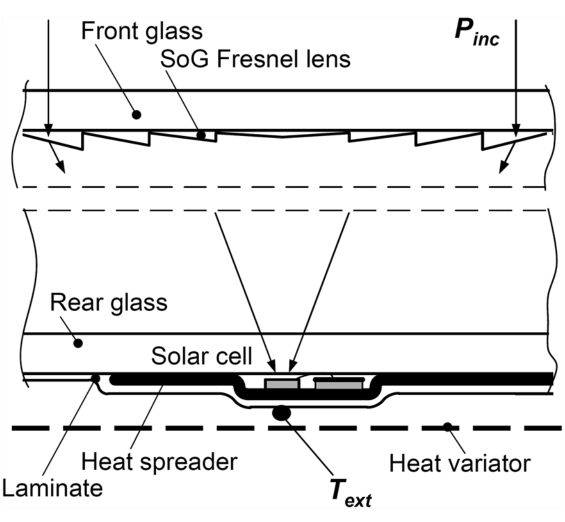

Figure 4. A fragment of the solar SMALFOC module developed at the Ioffe Institute [4]. A heat variator and point for the T_{ext} measurements on the external part of the module body are also shown.

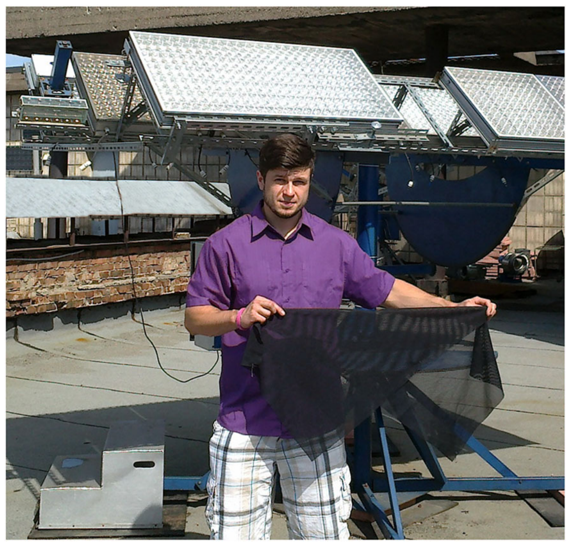

Figure 5. Picture of the tested SMALFOC module on a sun-tracker. Also, the mesh-type woven blanket used in the experiments is demonstrated.

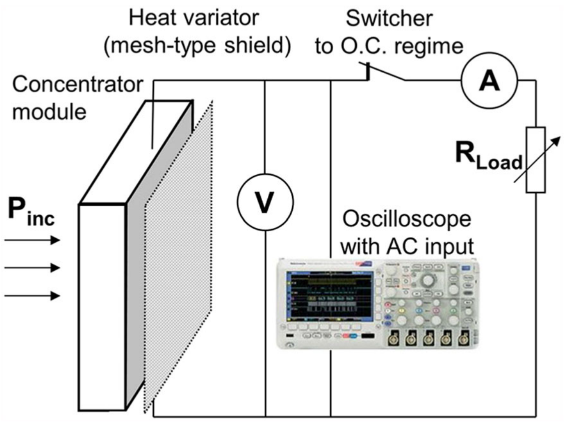

Figure 6. Electrical circuit used at "in-field" outdoor temperature evaluation experiments on concentrator PV modules.

(Figure 7a). Applying the developed in the present work procedure allowed the $V_{OC}{}^{amb}$ to be obtained by calculations with the help of formula (1). A very fast (less than 20 ms) transition from the MPP to the OC mode was easily realized using a tumbler switch (Figure 7b). The time-dependent voltage measurement was carried out using a rather sensitive AC input of the oscilloscope. The accuracy of the absolute $V_{OC}{}^{MPP}$ value was ensured by recording the steady state MPP base value with the help of an accurate DC voltmeter.

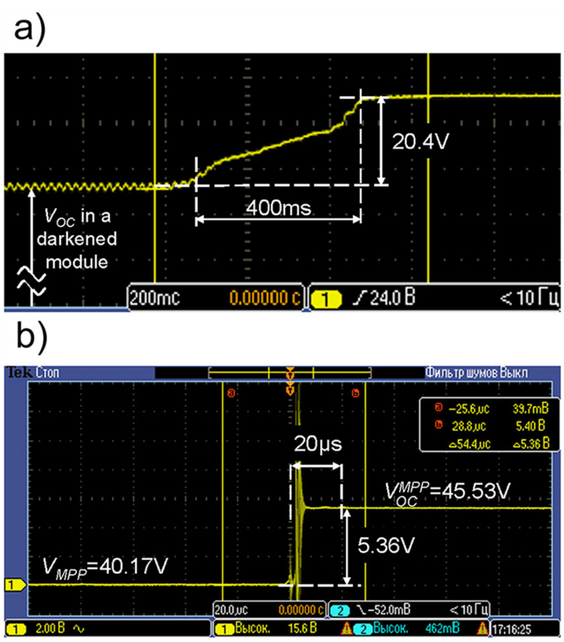

Figure 7. (a) The rise in the OC voltage during the manual shuttering of the module aperture area: presence of a "base" OC voltage in a darkened module is because of a low-level illumination of the cells through a partially transparent photoreceiver panel [4]; (b) the fast rise in voltage (less than 20 μs) during the transition from the MPP to the OC mode arranged by means of an electric switcher.

In Table I, the parameters measured in outdoor experiment and obtained from calculation are presented, as well as conditions significant for this procedure. The ambient temperature T_{amb}, being slightly unstable, was registered with precision to the first decimal place, and the other parameters—to the second decimal place. The parameters with index (m) correspond to conditions of a modified heat dissipation process, when the heat variator is applied to the rear of the module. The value of $V_{OC}{}^{amb}$ was calculated by formula (1). The $\Delta T_{p\text{–}n}{}^{MPP}$ and $\Delta T_{p\text{–}n}^{OC}$ values were calculated by formula (4). In the latter case, in the formula (4) the $V_{OC}{}^{MPP}$ value was replaced by V_{OC}.

7. RESULTS AND THEIR ACCURACY

One can see from Table I, the values of $T_{ext}{}^{MPP}$ and $T_{ext}{}^{OC}$, as well as $\Delta T_{p\text{–}n}{}^{MPP}$ and $\Delta T_{p\text{–}n}{}^{OC}$, differ substantially from each other. It occurs because of a partial transfer of the absorbed solar power into electric load in the MPP operational mode. In general, the greater the temperature difference (e.g. the higher PV conversion efficiency), the higher the accuracy of the $V_{OC}{}^{amb}$ evaluation (Figure 3). Consequently, the accuracy of the cell p–n junction temperature evaluation is higher as well. Tested in Section 4, the module was characterized by the PV conversion efficiency of around 23%, giving rise to the p–n junction overheating in the MPP mode to about 32 °C in almost windless environment. The temperature difference between the cell p–n junction and that point, where the thermo-resistor on the external module surface was placed (Figure 4), can be estimated as 27.2 + 32.31 – 57.51 = 2.0 °C. In the OC mode, this difference was about 2.8 °C. Such a small difference is explained by the following fact: temperature measurement was carried out immediately behind one of the cell in a "hot spot",

Table I. Parameters measured and obtained from calculations in the outdoor temperature experiments with a SMALFOC module. The conditions are as follows: Sun illumination intensity E=842±6 W/m^2; soft breeze; photocurrent density in each cell j_{ph}=2.63 A/cm^2. Temperature values are in °C; voltage values are in Volts.

Parameter	Magnitude
$T_{ext} = T_{amb}$	27.2
$T_{ext}{}^{MPP}$	57.51
$T_{ext}{}^{OC}$	69.81
$T_{ext(m)}{}^{OC}$	75.72
$V_{OC}{}^{MPP}$	45.53
V_{OC}	44.53
$V_{OC(m)}$	44.08
$V_{OC}{}^{amb}$ calculated	47.99
α [−mv/°C] calculated	4.76
$T_{p\text{–}n}{}^{MPP}$ calculated	32.31
$T_{p\text{–}n}{}^{OC}$ calculated	45.44

which is surrounded with heat spreader area, characterized by lower and almost uniformly distributed temperature.

Independent verification of the obtained results can be carried out only with respect to the temperature coefficient α. As was mentioned in Section 3, this coefficient could be measured using a flash solar simulator on several cells before their assembly in the tested module. The corresponding graph is shown in Figure 8. The coefficient $\alpha = -4.56$ mV/°C for the photocurrent density of $j_{ph} = 2.63$ A/cm^2, measured in the experiments with pulse illumination, differs from that of $\alpha = -4.76$ mV/°C calculated in Table I. It may lead to an uncertainty of about 1–1.5 °C in the results on ΔT_{p-n}.

In our previous work [10], a good fit of the calculated V_{OC}^{amb} values (using the same approach as in the current work) to the directly measured ones has been demonstrated. It was done in the experiments on converting laser radiation into electricity in the single-junction AlGaAs/GaAs PV cells. It was possible to do so by using a high-speed mechanical shutter with a response time of about 0.3 ms. A quite small error in temperature evaluation of about 0.1–0.2 °C took place under variable, but rather stable, indoor conditions: (i) at a "normal" cooling (air convection) the cell holder; (ii) at an extra-heating of the cell holder; and (iii) at moderate cooling with the help of a blower. It should be noted that results in work [10] have been aimed at comparing the directly measured and calculated $V_{OC}{}^{amb}$ values under "ideal" (indoor) environmental conditions. An appeared discrepancy between results obtained there was connected with revealed actual instability of the ambient temperature during the long-term experiments, when thermal balance has to be achieved at several stages of measurements. Therefore, the accuracy of proposed method of cell p–n junction evaluation based

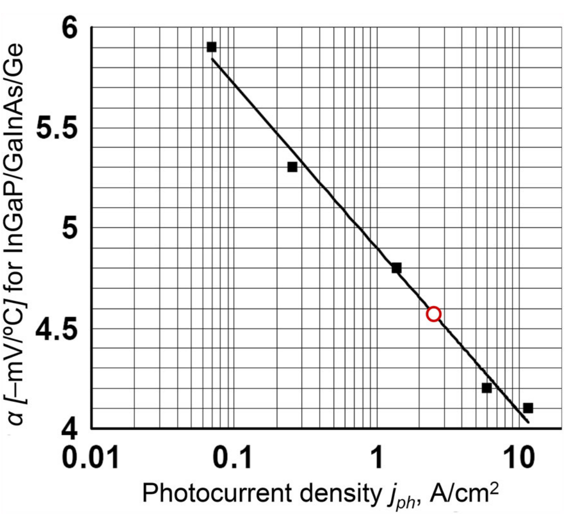

Figure 8. Temperature coefficients of V_{OC} at different photocurrent densities j_{ph} for GaInP/GaInAs/Ge cells assembled in the tested SMALFOC module (results obtained on individual cells under temperature-controlled conditions at measurements by means of a flash solar simulator).

on accuracy of the electronic measuring instruments is higher than possible instabilities in environmental conditions (indoor and, especially, outdoor ones).

If we continue the discussion on the accuracy of the results of ΔT_{p-n} in Table I, we should note their good agreement with analogous results recently published in our works [4,6]. In [4], smaller-in-size modules of similar (SMALFOC) design were tested under sun illumination, but indoors, through a window. Having a reduced aperture area (2 × 4 lens panels of 60 × 60 mm^2 lenses), the modules could be mechanically shuttered to sun illumination for about 20 ms. For evaluating the $V_{OC}{}^{amb}$ at a "zero" moment, a graph of V_{OC} *vs time* was corrected in a special way [6]. Overheating temperatures in the range of 33–35 °C in the MPP mode and 50–52 °C in the OC mode for cells on steel heat spreaders at illumination level of 850 W/m^2 were measured. In [6], corresponding results were 25–29 °C in the MPP mode and 37–41 °C in the OC mode for a full-size module, similar to that investigated in the present work, but with smaller individual lenses (40 × 40 mm^2 each) and at lower illumination level of 760–790 W/m^2. Differences of these temperatures from obtained data of Table I may be attributed to the influence of environmental conditions during the corresponding experiments.

It is obvious that meteorological conditions may cause considerable variations of the results at cell temperature evaluation. The reasons are instabilities in solar irradiation, air temperature, and wind speed during quite long outdoor experiments. It should be remembered that thermal balance conditions in a "module–environment" system should be fulfilled three times—in the MPP mode, in the OC mode, and, additionally, in the OC mode at modified heat dissipation. Stable meteorological conditions are desirable at any long-term outdoor experiments. Differences in results in cell temperature evaluation in different, but stable, environmental conditions cannot be attributed to errors in the measurement procedure. In each case these results simply characterize a tested solar module with respect to a present test conditions.

8. CONCLUSION

In the proposed method for finding out the p–n junction temperature in MPP mode of solar module operation, a fast transition from the MPP to the OC mode is carried out, during which a time-dependent voltage measurement is taken. A "reference" OC voltage magnitude in a "cold" module (a condition implemented at the moment after the step-like opening of the module to the sun's illumination), as well as the temperature coefficient of the module OC voltage (for the concentrator modules), are determined by calculations. Therefore, the mechanical shuttering of the module aperture area (a commonly used procedure, which, however, is characterized by not enough speed for correct measurements) is substituted for a fast electrical switching of an external load. Standard instruments and elements are used in the corresponding measurements, so that the method can be applied during "in-field" outdoor tests of the solar PV modules.

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