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Cell Chip Temperature Measurements In Different Operation Regimes Of HCPV Modules

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Abstract: A new method has been developed for accurate measurements of the solar cell temperature in maximum power point (MPP) operation regime in comparison with that in open circuit (OC) regime (T_{MPP} and T_{OC}). For this, an electronic circuit has been elaborated for fast variation of the cell load conditions and for voltage measurements, so that V_{OC} values could serve as an indicator of T_{MPP} at the first moment after the load disconnection. The method was verified in indoor investigations of the single -junction AlGaAs/GaAs cells under CW laser irradiation, where different modifications of the heat spreaders were involved. PV modules of the "SMALFOC" design (Small-size concentrators; Multijunction cells; "All-glass" structure; Lamination technology; Fresnel Optics for Concentration) with triple-junction InGaP/GaAs/Ge cells were examined outdoors to evaluate temperature regimes of their operation.

Keywords: Solar III-V cells, Concentrator modules, Temperature measurements.
PACS: 88.40.F-88.40.ff, 88.40.H-88.40.hj, 88.40.jp

INTRODUCTION

In high concentration photovoltaic modules (HCPV modules), the solar cell holder must dissipate heat efficiently to keep the cell cool. The issue is to remove this heat from the cell in the cheapest and most reliable way. Proper thermal managements are of great importance in the module design. An indicator for success in the managements is a low over-temperature of the cells relating to ambient temperature in operational conditions, that is the electrical loading in the maximum power point (MPP) of the I-V curve.

There exist three methods to compute indirectly the semiconductor chip temperature. A "standard" approach is to measure the temperature dependent voltage drop across the chip p-n junction at a definite current (in the dark). Another "standard" approach related to the direct bandgap materials, is to measure the temperature dependent peak wavelength of the electro- or photo-luminescence emission spectrum. The third method is the most popular one in investigating solar cells: measurements of the temperature dependent open circuit voltage (V_{OC}) under illumination bearing in mind the preliminary determined temperature coefficient. The latter "illumination" method has such drawbacks as the V_{OC} and temperature coefficient both are functions of the incident irradiation level (photocurrent density) and depend on other factors (material quality differences and others). Furthermore, the V_{OC} value as a temperature indicator gives very rough information about MPP operational conditions of a highly efficient cell, when a considerable part of power is dissipated in the external load.

In the present work, a number of steps have been realized for accurate cell temperature measurements in both OC and MPP operation regimes (T_{OC} and T_{MPP}). For this, an electronic circuit has been developed for fast variation of the cell load conditions and for voltage measurements, so that V_{OC} values could serve as an indicator of T_{MPP} at the first moment after load disconnection. The method was verified in indoor investigations of the single-junction AlGaAs/GaAs cells under CW laser irradiation, where different modifications of the heat spreaders were involved as well for comparison. After this, the PV modules of the "SMALFOC" [1] design (Small-size concentrators; Multijunction cells; "All-glass" structure; Lamination technology; Fresnel Optics for Concentration) with triple-junction InGaP/GaAs/Ge cells were examined outdoors to evaluate temperature regimes of their operation.

DETERMINATION OF THE V_{OC} TEMPERATURE COEFFICIENTS

First of all, involved in the experiments 1-j AlGaAs/GaAs and 3-j InGaP/GaAs/Ge cells (4x4 and 2.3x2.3 mm^2, respectively) have been examined

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indoors for obtaining their V_{OC} temperature coefficients. The measurements were performed at photocurrent levels similar to those at generation under laser or concentrated sunlight illumination. For this, a "one sun" flash tester with a light collimating system developed earlier [2] has been applied together with a cooling/heating cell holder (–10/+80°C). The cell heating effect in flash measurements during about 1÷2 milliseconds was considered to be an inessential one [3, 4]. Using Fresnel lenses similar to those in the concentrator modules, it was possible to simulate correctly cell illumination conditions (except heating) relating to those under laser and sun illumination. In general, obtained by us V_{OC} temperature coefficients were in a good agreement with the values reported by many authors [5, 6]. These coefficients were practically constant in the temperature range typical for the subsequent experiments.

ELECTRONIC BOARD AND MEASUREMENT METHODOLOGY

A two-functional electronic board has been developed. It measured voltage magnitudes with an accuracy of around 1 mV. In accordance with the program for the measurement cycle, it was possible to manage an operation of a field-effect transistor for fast arrangement of the required regime of cell operation. A diagram of the time-dependent measurement cycle and the sketch of a cell-to-load connection are shown in Fig.1.

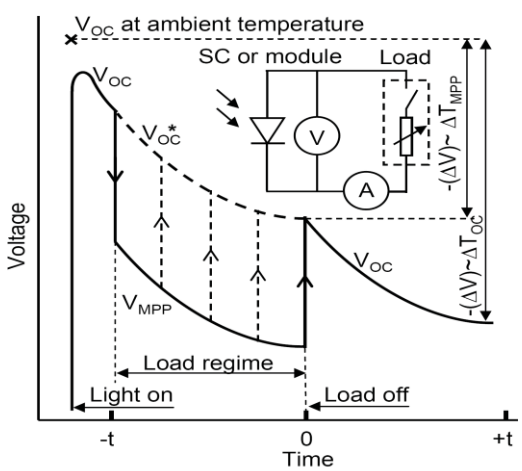

FIGURE 1. Diagram of the time-dependent measurement cycle and sketch of the cell-to-load connection.

The measurement procedure consisted of three parts. In the beginning, illumination is turned on and V_{OC} is measured instantly. If light is "on" faster than in 1÷2 milliseconds, the initial V_{OC} magnitude of the cell or module is equal to that at ambient temperature. Due to a gradual cell heating, the V_{OC} drops. The cell is connected to the optimum load in during the first second (at "-t" moment). For this purpose the transistor serves, which sets the necessary resistance as a result of a fast I-V measurement and MPP conditions determination. All second period of "t" duration, the cell is kept in MPP conditions for temperature T_{MPP} stabilization. During this period transistor repeats fast I-V measurements many times, and the obtained V_{OC} magnitudes continue to be indicated in the graph representing the cell temperature in MPP conditions (dashed line in Fig. 1). At the moment "0", the electrical load is off and the "normal" V_{OC} magnitudes are measured up to "+t" moment, when the cell temperature T_{OC} is stabilized.

Under moderate steady-state illumination conditions in OC regime, the over-temperature of a PV device relating to the ambient temperature ΔT_{OC} is proportional to the absorbed light power. In Fig.1 ΔT_{OC} may be calculated as proportional to ($-\Delta V$) in the OC regime. In the MPP regime a part of the absorbed light power is converted into electricity and transferred into the external load, so that the corresponding over-temperature ΔT_{MPP} is definitely lower.

Information on the cell chip ΔT_{MPP} allows predicting more correctly the temperature behavior of the PV module efficiency, avoiding uncertainties arising at direct temperature measurements on different structural elements in a module housing. In an ideal case, one can estimate the PV conversion efficiency (η) from a simple ratio: $\eta = (\Delta T_{OC} - \Delta T_{MPP}) / \Delta T_{OC}$, where the numerator is proportional to extracted from chip electric power and denominator – to incident light power. Also, observation of V_{OC} dynamics after the fast load regime changes gives a possibility to estimate how hard is transition regime for a cell mounted on the carrier made of the different materials.

EXPERIMENTS AT LASER IRRADIATION

The nearest approach to an ideal case for the considering subject consists in investigations of the 1-j cell samples under laser irradiation. These indoor experiments were conducted by us with AlGaAs/GaAs cells soldered to the heat spreaders made of copper 0.5 or 3 mm thick and steel 1 mm thick (all of them were 30x30 mm^2 in area). Thin copper and steel of the above dimensions are the materials involved in fabrication of the "SMALFOC" modules, when individual Fresnel lenses in a concentrator parquet are 40x40 mm^2 in area. A λ=808 nm CW diode laser with the output power of up to 3.5 W was used as an illumination source.

The results of V_{OC} measurements at laser power of 0.36 W are shown in Fig.2. It should be noted that voltage data in electronic board were measured during one microsecond, and each point in a data acquisition system included 50 initial measurements after statistical treatment. Quantity of points indicated in graphs of Fig. 2 is sufficiently less than that collected in the data system. The branches of the curves on the left from “0-time” correspond to the V_{OC} values representing cell temperature in the MPP regime, and ones on the right– to the “normal” voltages in the OC regime. The left and right voltage axes are slightly moved one with respect to another due to a small difference in “ambient” V_{OC} magnitudes for different cell samples. It was done for better demonstration of the differences in thermal behavior of the samples depending on heat spreader modification. There are two inserting graphs in Fig. 2. They show the voltage decrease in time (in relative units) during the initial periods after the “light-on” and “load-off” events.

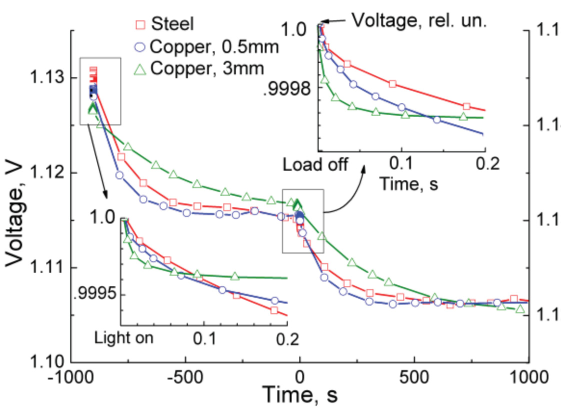

FIGURE 2. Time-dependent V_{OC} measurements at 0.36 W laser photoexcitation of the 1-j AlGaAs/GaAs cells soldered on the different heat spreaders (see text).

In the considered case, the “light-on” process was faster than 2 ms due to the small laser beam aperture, so that the first V_{OC} magnitudes could be regarded as the “ambient” ones. For both thicker and thinner copper carriers, decrease in V_{OC} (that means increase in temperature of a cell chip) was faster than for steel one. It is seen from Fig. 2 that thicker cell holders, both copper and steel ones, require a longer time for heating. Also, it is seen that in the steady-state conditions before “0-time” the cell on a thick copper has higher V_{OC} being colder in comparison with the cells on thinner holders, whereas in the OC regime at the end of measurements the voltages and temperatures were closer to one another. Independent measurements of the PV conversion efficiency (η) have shown that the reason for such a behavior was just difference in η values: η=51.8, 46.5 and 46.4%, respectively.

Measurements of the PV conversion efficiency in two ways – by “temperature” method described in the previous paragraph using ΔT_{OC} and ΔT_{MPP}, and by a “standard” method using laser and I*V power meters, may be regarded as an experiment for methodology verification of the “temperature” method. In Fig. 3, the dependences of ΔT_{OC} and ΔT_{MPP}, as well as one of η, on the laser power are shown for the cell on copper holder 3 mm thick. In both OC and MPP regimes cell temperature was computed from graphs similar to one presented in Fig.2. Obviously, temperatures increased together with laser power. It was found from the I-V curve measurements that at the same time the curve’s fill factor decreased. Therefore, a decrease in PV conversion efficiency took place. There existed a good agreement between two methods of the η computation. In general, a reason for possible disagreement could lay in uncertainty due to partial screening of a cell photosensitive area by contact fingers and partial light reflection from them, but contribution of such effects was very low.

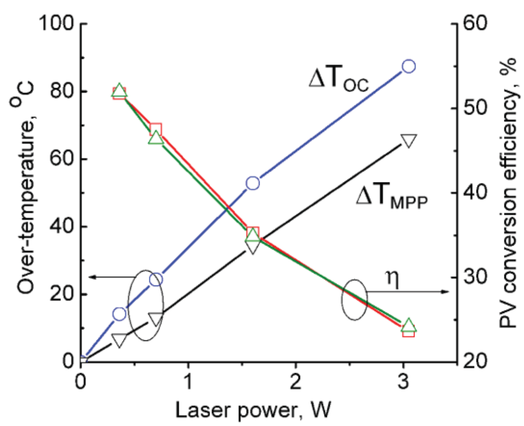

FIGURE 3. Dependences of ΔT_{OC} and ΔT_{MPP} (left axis), as well as one of η (right axis) on laser power for a 1-j AlGaAs/GaAs cell mounted on a copper holder 3 mm thick. ΔT_{OC} and ΔT_{MPP} have been computed from graphs similar to one presented in Fig.2. Laser power meter LM2 “Karl Zeiss” and I-V meter were used at “standard” PV conversion efficiency measurements.

OUTDOOR EXPERIMENTS WITH HCPV MODULES

If temperature measurements on the PV modules are conducted using temperature control of the external parts of the module housing, one should draw numerous statistical data to see a difference in the module temperature in the OC and MPP regimes

[7]. This is due to many uncertainties, which may arise in association with instabilities in sun illumination level, wind flow and ambient temperature.

In the described method, there exists a problem concerning uncertainty of the module V_{OC} value at ambient temperature. Indeed, in outdoor experiments with full-size concentrator modules of 0.5x1 m^2 it was not possible to arrange "light on" process to be faster than 20 ms. Time-dependent outdoor V_{OC} measurements under sun illumination of the module with 3-j InGaP/GaAs/Ge cells soldered to the steel heat spreaders [ ] are shown in Fig. 4. It is clear from analysis of the initial stages of the cell heating processes (see inserting graphs in Fig. 2 and Fig. 4) that 20 ms period is enough for a considerable drop in V_{OC}. The problem may be solved by using a flash solar simulator for the large-area concentrator modules (see [2]), but corresponding instruments are rather unique ones. On the other hand, in our method, there is a possibility for fast extraction and introduction of the definite portions of power (they correspond to the cell PV efficiency) from/into a cell chip by electrical commutation of the external MPP load. It means that the transition region curve in the vicinity of the "load off" point may be used for "correction" of the "light on" curve configuration (when a full portion of power is introduced into the cell chip) bearing in mind cell conversion efficiency as a fitting factor.

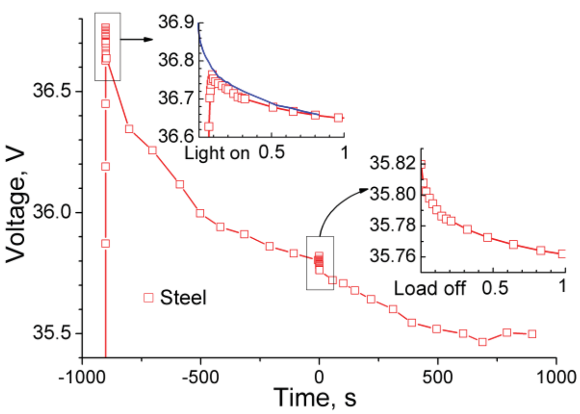

FIGURE 4. Time-dependent outdoor V_{OC} measurements under sun illumination of the full-size concentrator module of 0.5x1 m^2 in size with 3-j InGaP/GaAs/Ge cells soldered to the steel heat spreaders [1]. The lens parquet consisted of the 288 4x4 cm^2 SoG Fresnel lenses.

In the reality a set of the measurements similar to that shown in Fig. 4 have been conducted. They corresponded to the AM 2D sun illumination conditions at around 760÷790 W/m^2 of incident power and minus 2÷4ºC of ambient temperature. The modules were with copper and steel heat spreaders characterizing by the conversion efficiencies of about 22%. Corrections of the V_{OC}. values with respect to ambient temperature were done by a fitting procedure, as it is shown in inserting graph of Fig.4, as well as by independent V_{OC} measurements under flash illumination and subsequent correction on difference between outdoor and room temperature. The results of the experiments are as follows:

- cell chips on the 1 mm thick steel spreaders were characterized by over-temperatures of around 25÷29˚C in the MPP regime and 37÷41˚C in the OC regime;
- in the case of the 0.5 mm thick copper spreaders, these temperatures were by 2÷3ºC lower.

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