Temperature Drift of PV Parameters in High-Power Laser Converters

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Abstract. At high laser radiation a PV converter output parameters are greatly influenced by its heating. Open circuit voltage could be an indicator of temperature drift. The dynamics of the heating process of GaAs PV cell was investigated for cases of sufficient and insufficient heat removal. The conditions of insufficient heat removal are discussed.

INTRODUCTION

Studies of the photovoltaic converters parameters at high-power laser radiation require control of the temperature regime, since a large amount of radiant energy is delivered to the sample under test. In open circuit mode light energy is predominantly converted into thermal energy. It increases the temperature of the phase transition and proportionally decreases the open circuit voltage [1, 2]. Temperature reduction is usually done with a heatsink. The quality of the heatsink depends on its material, shape, heat recovery efficiency. [3,4,5] In addition, thermal processes do not occur immediately. And characterizing a photovoltaic system cannot be done with too fast measurements even with sufficient heat removal. This paper is devoted to the study of the dynamics of heat removal process in the PV cell-heatsink-ambient air systems.

INFLUENCE OF TEMPERATURE ON PARAMETERS OF PV CELL UNDER HIGH-INTENSITY IRRADIATION

In the conditions of high-intensity irradiation, PV cell operation is accompanied by the heat release in proportion to the input power. The process of thermal energy accumulation leads to temperature increase, and therefore to the open circuit voltage decrease. In the first moments of irradiation, the accumulated heat energy is small and does not affect the photoelectric parameters of the sample under test [6].

For constant irradiation, heat flux stabilization is inherent. The temperature gradient between the p – n junction and its environment is constant in time. In such a case, intensity distribution on the PV cell surface is important. For local and uniform illumination, the temperature gradient is significantly different. In the present work, the photodetector surface is assumed uniformly illuminated. And its area is almost full PV cell area. In this situation, when considering the air as a heat isolator, the temperature gradient between the p-n junction and the back side of the heatsink can be described using the one-dimension Fourier thermal conductivity law [7] being applied to the “PV cell – heatsink – ambient air” system (1):

$$grad(T) = -\frac{\vec{q}}{\chi_{cell}} - \frac{\vec{q}}{\chi_{heat\sin k}} \tag{1}$$

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where $\mathbf{q}$ is the heat flux density vector, χ_{cell} is the thermal conductivity of the PV cell structure, $\chi_{heatsink}$ is the thermal conductivity of the heat sink.

So, for example, for GaAs cell ($\chi_{cell} = 55 \frac{\mathrm{W}}{\mathrm{m*K}}$ [8]) of 1 mm^2 photo-receiving surface area and of 450 μm thickness with the aluminum-based heatsink ($\chi_{heatsink} = 120 \frac{\mathrm{W}}{\mathrm{m*K}}$ according to the specification) under continuous irradiation of 0.1 W (it corresponds to 10 W/cm^2), the calculated difference between the temperature of the back side of the sufficient heatsink and the temperature of the p-n junction is about 1 ° C in open circuit mode. If the irradiation power density increases to 2 kW/cm^2, this difference will be 8 ° C. The increasing value of the temperature gradient cannot be reduced even in the case of an ideal heatsink. It is the inherent property of the PV cell.

TEMPERATURE DYNAMICS IN P-N JUNCTION

The above values of the p – n junction overheating are valid for the continuous irradiation mode after all transients. The dynamics of temperature rise in p-n junction region can be described by heat equation. [9] The exponential function is the solution for it. Heat flow stabilization time depends on PV cell and heatsink heat capacity and thermal resistance. It is 3τ, where τ = C * R.The number of exponential terms depends on the number of links in the chain “PV cell"-"ambient air”. So for the case of the “PV cell"-"heatsink"-"ambient air”, the p-n junction temperature is described by a function with two exponential terms (2):

$$T(t) = T_0 + \Delta T_{cell}(1 - Exp(-\frac{t}{\tau_{cell}})) + \Delta T_{heat\sin k}(1 - Exp(-\frac{t}{\tau_{heat\sin k}})) \quad (2)$$

where T_0 is the ambient air temperature (the temperature of the sample under test is equal to it before the the illumination), τ_{cell} and τ_{heatsink} are time constants for stabilization of heat flux through the PV cell and heatsink, $\Delta \mathrm{T}_{cell}$ and $\Delta T_{\mathrm{heatsink}}$ are temperature gradients in the PV cell and heatsink. It is easy to verify that the temperature expression is a solution to the heat balance equation for the system "PV cell"-"heatsink"-"ambient air". And according to the uniqueness theorem there are no more solutions [9].

An important property of the temperature expression is its dynamics at various values of the input heat flux. Indeed, with the input power, the rate of relative change of heat fluxes remains equal, since it depends only on such structural parameters as the heat capacity and thermal resistance.

OPEN CIRCUIT VOLTAGE STUDY

During the operation of a PV cell, part of the energy goes to an external circuit, while the other part is released as heat in the cell itself. In high irradiation mode heating process becomes especially noticeable. The open circuit voltage can be used as an indicator of temperature processes in the PV cell, since it depends linearly on the temperature of the p – n junction ΔU = α ΔT. For the sample under test α = 1.36 mV/°C.The dynamics of the open circuit voltage was studied at pulsed laser illumination (λ = 850 nm, pulse duration 0.5 ms, duty cycle 0.5) GaAs PV laser power converter. Cells with 1 mm^2 illumination area and 450 μm structure thickness were selected as test samples. Samples with the aluminum-based heatsink and without a heat sink were investigated. Irradiation was delivered to a sample by an optical fiber of 200 μm in diameter. The distance between a sample and the fiber was 1.7 mm. It excludes the extremely high local radiation on the illumination area. For the selected source-sample pair operation at the selected wavelength in a wide temperature range is stable.

The selected pulsed irradiation mode does not deform the dynamics of the open circuit voltage. The duty cycle, however, proportionally changes the effective irradiance of the sample. Simulation of the open circuit voltage dynamics due to heating show the equivalence of 2 W pulsed irradiation with 0.5 duty cycle and the constant 1 W irradiation. The calculated dynamics of the open circuit voltage for GaAs laser power converter with aluminum-based heatsink is shown in Figure 1. Laser radiation is supposed to be here a heat flux through the photodetector window of the PV cell.

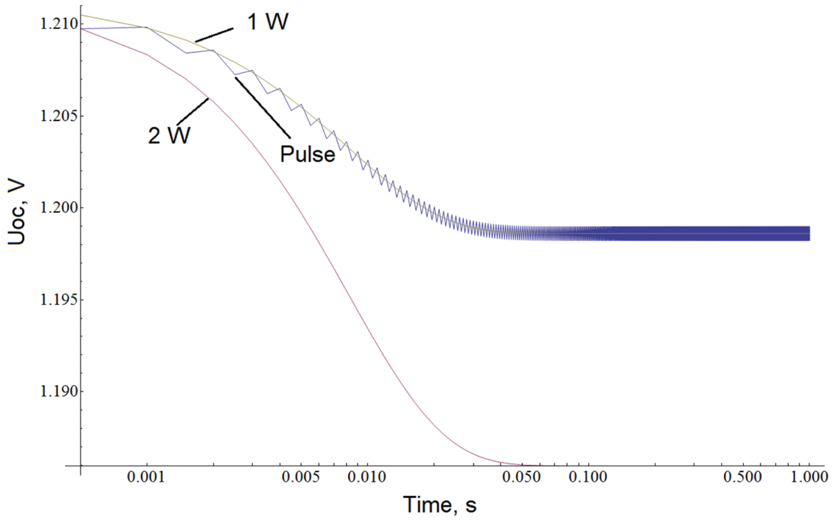

FIGURE 1. Calculated open circuit voltage at constant and pulsed illumination. In the pulsed irradiation mode, the irradiation power was 2 W, and the duty cycle was assumed to be 0.5.

In the pulsed irradiation mode the structure is heated and cooled. It corresponds to moments of illumination and pauses between pulses. During several initial cycles heating prevails over cooling. The temperature rise rate slows down over time and the cooling passes more intensively. When both of these processes compensate each other, some kind of equilibrium is established. In practice temperature stabilization for the heat-cool cycle occurs. The time constant for this quasi-equilibrium state match up with the time constant for continuous irradiation.

Practical studies were carried out at 2 W pulsed laser output power, which at 0.5 duty cycle corresponds to 1 W effective irradiance. Samples with aluminum-based heatsinks were mounted on Peltier thermoelectric cooler with stable temperature 25° C. The measurements were carried out in two series. In the first series, the thermal grease was between heatsinks and Peltier cooler (sufficient heat removal). In the second series paper was placed between the heatsinks and the Peltier cooler (insufficient heat removal). Thus, in the first series, sufficient heat dissipation was ensured (a temperature of 25 ° C at the heat sink). In the second measurements series because of paper the heat removal was disturbed, however, at the same time, the heat capacity of the heatsink remains unchanged. The results of the open circuit voltage study with sufficient and insufficient heat removal are presented in Fig. 2.

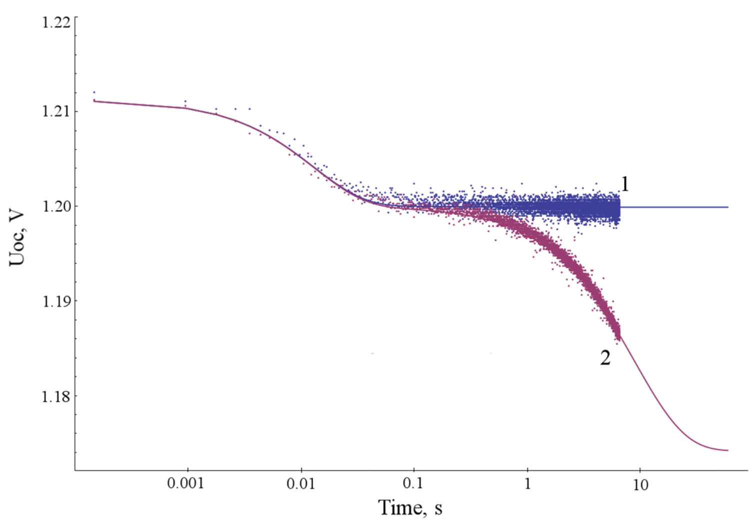

FIGURE 2. Open circuit voltage at laser (λ = 850 nm) pulse irradiation of GaAs PV laser converters with sufficient (1) and insufficient (2) heat sink. Pulse power is 2W, pulse duration is 0.5 ms, duty cycle is 0.5 Points are measured data, lines are calculated data.

At irradiation up to 0.1 s the open circuit voltage for both cases of heat removal is the same. This part of the curve is mainly determined by the process of heating the PV cell crystal. The time constant for the process is ~0.015 s (the heat capacity is $8 * 10^{-3}$J/K, and thermal resistance is 10 K/W). It agrees with the measured time of temperature stabilization in the crystal and corresponds to $3\tau_{cell}$= 0.05 s. At irradiation more than 0.1 s the open circuit voltage curve for the case of sufficient heat dissipation clearly does not present the second exponential component since the temperature gradient depending on the heat sink is about 0.5 ° C. It is comparable with the measurement error. In case of insufficient heat dissipation, the temperature gradient was about 20 ° C, and the time constant of the process of thermal stabilization was 8 s. So the heat capacity of aluminum-based heatsink is 0.5J/K, but thermal resistance 17 K/W corresponds to the system "heatsink-paper"

Voltage stabilization for insufficient heat removal in 0.05–0.1 s interval is possible due to the ratio of its temperature gradient to the time constant. In this period, it is possible to measure the parameters of the PV cell even in the absence of a sufficient heat sink. To enable such an interpretation of measurements, the necessary condition is:

$$U_{error} \geq grad(T)_{heat\sin k} * Exp(-\frac{t}{\tau_{heat\sin k}}) \quad (3)$$

where U_{error} is the measurement error, $\tau_{heatsink}$ is the time constant of the “bad” heat sink, t is the maximum illumination time without significant overheating because of insufficient heatsink. Thus, in the first moments the influence of the heat sink conditions on the open circuit voltage is insignificant. If this influence is less than a measurement error, it can be neglected. And an exact time estimate of this process can be obtained from equality (3).

The reasoning is applicable for any PV cell and heat sink pair. It is important to note that the conditions for insufficient heat dissipation, however, should not also mean an insufficient heat capacity of the heat sink. Since insufficient heat capacity leads to a time constant decrease.

CONCLUSION

This work is devoted to the study of the heat dissipation dynamics in systems "PV cell"-"heatsink"-"ambient air" and its effect on the open circuit voltage of the sample under test. Studies of the open circuit voltage in condition of high-power pulsed illumination (100 W / cm^2) for GaAs PV cell were carried out. It has been shown that the pulsed nature of the irradiation does not affect the temporal parameters of the temperature drift dynamics. It affects only the magnitude. For the sample with the illumination area of 1 mm^2 and thickness of 450 µm, the time constant of heating the structure is about 0.015 s. Temperature of PV cell with a sufficient heatsink stabilizes in 0.05 s. In case of insufficient heat removal, the second exponential component of the thermal stabilization process is clearly present with the time constant 8 s. In the general case, insufficient heat removal does not impede the obtaining of true data at the initial moments of measurement. The time constant together with the temperature gradient determine the rate of the heating process in case of insufficient heatsink. So for the considered case when the illumination pulse is less than 0.1 s, there is no additional heating effect on the p-n transition of the sample under test. Therefore, it is possible to neglect the additional heating within the 0.05–0.1 s time interval and to guess that experimental data recorded at sufficient heat removal conditions.

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