Photoconverter Heating by Incident Radiation: Overheat Temperature and IV-curve Correction

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Abstract. The paper completes the study of the photoconverter overheating during IV-curve recording on the pulse simulator of solar radiation. It is experimentally found that after switching on the pulse of light photoconverter voltage decreases linearly with time. The voltage decrease rate proportionally depends on photogenerated current.It has been theoretically shown that such a proportionally is associated with the fact that temperature coefficient $\alpha = \Delta V/\Delta T$ (V – voltage, T - temperature) depends weakly on the photogenerated current. In using this fact, a method for obtaining isothermal IV-curves was developed. The method is applied to triple-junction GainP/GaAs/Ge solar cell IV-curves. It is shown that the overheating effect can be neglected at the sun concentration ratio less 500 suns (photogenerated current less than $6.5\ A/cm^2$). The p-n junction overheating temperature was also determined.

INTRODUCTION. MEASUREMENT OF V_{OC} AT HIGH SUNLIGHT CONCENTRATION RATIO

The heating of a solar cell (SC) by concentrated radiation is a well-known effect in concentrator photovoltaics. It is known that a cell is heated inside a concentrator installation because of constant irradiation with high-power radiation. However, as was found in [1], heating also occurs when IV-curve is recorded on a pulsed sunlight simulators. This effect was experimentally investigated on the V_{oc} (open circuit voltage) - J_g (photogenerated current) dependence. It has been shown that this dependence is not isothermal one: the voltage V_{oc} is less than in the isothermal case [1]. The following experiment was performed: in using a pulsed solar radiation simulator, the triple-junction GaInP/GaAs/Ge SC was illuminated by a short light pulse. During the whole pulse, the open circuit voltage (V_{oc}) was recorded. It was found that for relatively large solar radiation values (from ~ 1000 suns), the V_{oc} is linearly decreasing (see the dependence of V_{oc} on time in Fig. 1 and Fig. 2 in [1]). One can find that the higher photogenerated current (or sun concentration ratio) the faster the V_{oc} decrease rate. This is associated with the fact that heating of a solar cell increases with incident power.

In this paper, determination of the V_{oc} linear drop rate was performed. The result of the determination is shown in Figure 1. It is seen that the observed dependence is linear and starts from zero, what indicates the proportional growth of the dV_{oc}/dt rate with the photogenerated current. It should be noted that the value of dV_{oc}/dt is determined by the temperature coefficient α [2]. To ensure that dV_{oc}/dt is proportional to J_g, this coefficient should be a constant. However, theoretically, this coefficient depends on the photocurrent logarithmically. This was investigated theoretically and the coefficient α was obtained. It was shown that α is weakly depend at usually used range of J_g therefore, it can be considered as a constant.

The magnitude of the V_{oc} drop was used to determine the overheat temperature ΔT (difference between the SC temperature and the ambient one). Also new experimental data on IV-curve measuring at a high radiation concentration ratio are presented. It has been found that voltage in every IV-curve point decreases with the same rate as it happened with V_{oc}. In using that fact, a new method for IV-curve correction was developed and experimentally tested.

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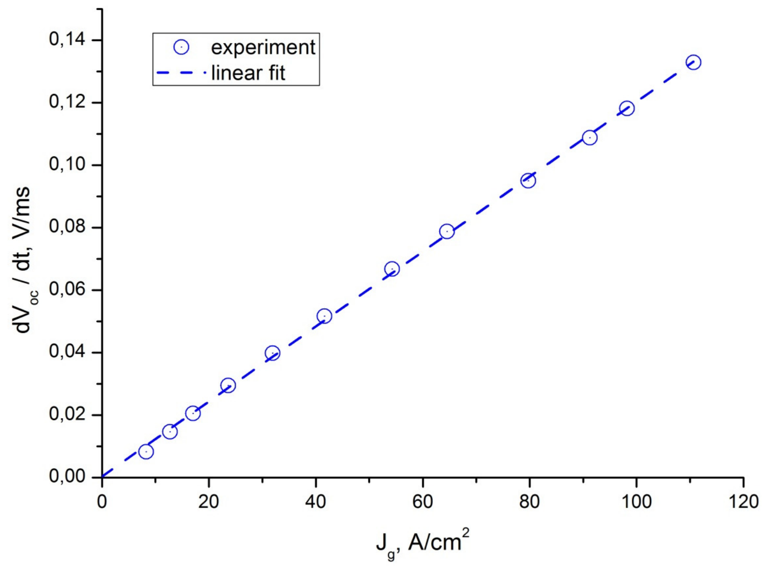


FIGURE 1. Experimentally measured dependence of the open circuit voltage decrease rate (immediately after pulse beginning) on the photogenerated current (light intensity).

TEMPERATURE COEFFICIENT OF V_{OC} AND P-N JUNCTION OVERHEATING TEMPERATURE

Theoretical calculation of the ΔV_{oc}-J_g dependence, which was also obtained experimentally for a multi-junction GaInP/GaAs/Ge SC was carried out. The same sample as in [1] was used in all experiments. The values of ΔV_{oc} were obtained by the difference between the reference isothermal and "heated" V_{oc}-J_g characteristics. The reference characteristic was experimentally obtained by the method described in [1]. Both characteristics are shown in figure 2a. The calculation allows for every characteristic point to determine the coefficient α and p-n junction overheating temperature ΔT. The calculation was based on the following. At room temperature and higher ΔV_{oc} is proportional to the overheating temperature: $\Delta V_{oc} = -\alpha\,\Delta T$ $(\alpha>0)$. The temperature coefficient α is given by the formula (1) deduced from the expression $V_{OC} = A\frac{kT}{q}\ln(\frac{J_g}{J_0})$.

$$\alpha = \frac{1}{q}\left(\beta + A\cdot k\cdot ln\left(\frac{J_0^*}{J_g}\right)\right) \tag{1}$$

where $\beta = |(\Delta E_g)/\Delta T|$ - the temperature coefficient of the forbidden bandgap, q is the electron charge, k is the Boltzmann constant, A is the p-n junction ideality factor, J_0^* is the multiplier of the expression for the "saturation" current $J_0 = J_0^* \exp\left(-\frac{E_g}{AkT}\right)$, (we assume J_0^* as constant, because in the above mentioned temperatures it depends on temperature in accordance with the power law, which is weaker in comparison with exponential multiplier [2]), J_g - photogenerated current, E_g - forbidden bandgap. In a multi-junction SC, the formula (1) has the following parameters:

$$\beta = \sum \beta_i \quad A = \sum A_i \qquad J_0^* = \sqrt[A]{(J_{01}^*)^{A1}(J_{02}^*)^{A2}\ \dots\ (J_{0n}^*)^{An}} \qquad J_g = \kappa\cdot J_{g,min}$$

$$\kappa = \sqrt[A]{{\kappa_1}^{A1}{\kappa_2}^{A2}\ \dots\ {\kappa_n}^{An}} \qquad \kappa_i = \frac{J_{g,i}}{J_{g,min}} \qquad J_{g,min} = \min\{J_{g,1}, J_{g,2}\ \dots\ J_{g,n}\},$$

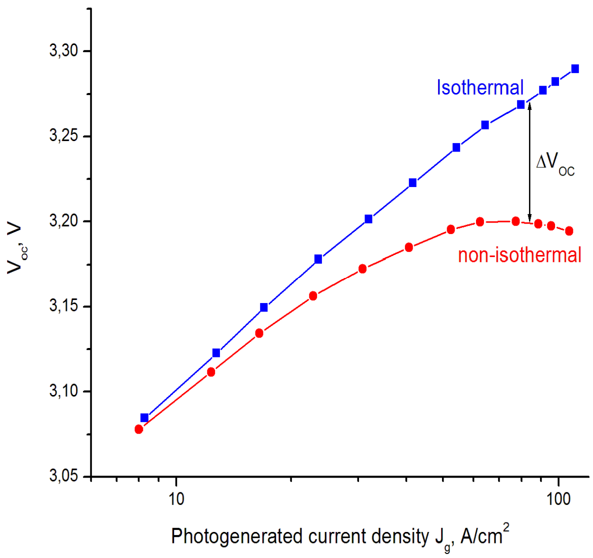
where n – number of subcells, i –subcell index.

It should be noted that the proposed simplifications do not decrease the high accuracy of the formula (1). Thus, the experimentally obtained dependences "α" vs "$lg(J_g)$" for GaAs and GaInP/GaAs/Ge SCs [3, Fig. 6] correspond to the formula (1).

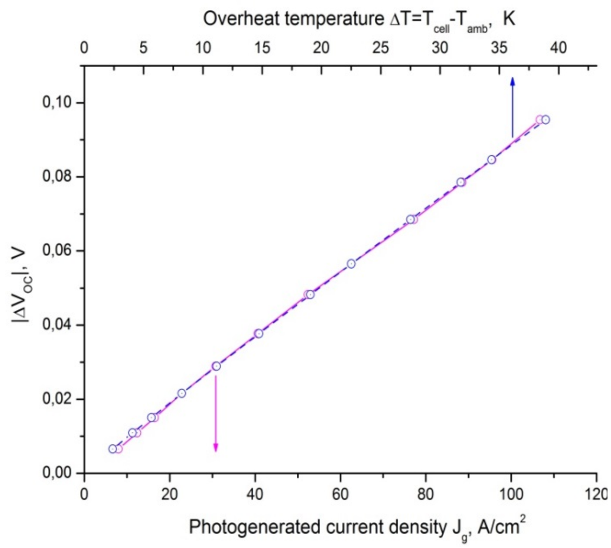
TABLE 1. The parameters used for the V_{oc} temperature coefficient calculation with the eq. (1).

SC	*β, eV/K*	J_{01}*, A/cm²*	E_g*, eV*	J_{01}^**, A/cm2*
Ge	$4.8 \cdot 10^{-4}$	$1.0 \cdot 10^{-6}$	0.661	$3.0 \cdot 10^{5}$
GaAs	$5.4 \cdot 10^{-4}$	$1.0 \cdot 10^{-20}$	1.424	$5.5 \cdot 10^{4}$
GaInP	$5.4 \cdot 10^{-4}$	$1.0 \cdot 10^{-25}$	1.77	$5.6 \cdot 10^{5}$
GaInP/GaAs/Ge	$1.6 \cdot 10^{-3}$	$1.0 \cdot 10^{-17}$	1.285	$2.1 \cdot 10^{5}$

Finally, the coefficient α was calculated, and the dependence ΔV_{oc}-ΔT was obtained. This was done with using the data from Table 1. Both calculated and obtained curves are almost linear (Fig. 2b), which is associated with a weak (logarithmic) dependence of α coefficient on J_g (see eq. 1). Thus, in the range of the studied photocurrents (approximately from $10\ A/cm^2$ to $110\ A/cm^2$), the heating of a SC due to incident radiation is described by a linear and proportional function, and the temperature coefficient α can be considered as a constant. Determined p-n junction overheating temperature was about 40 degrees (Fig 2b).



(a)

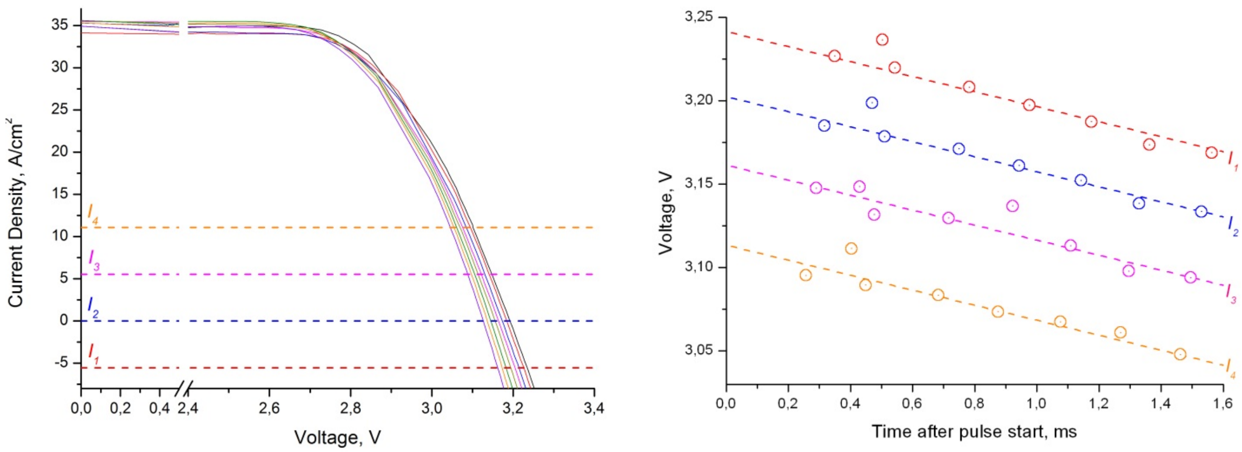


(b)

FIGURE 2. a) V_{oc}-J_g dependences: blue – isothermal (measured by the method described in [1]), red – "heated" (measured by the standard method); for GaInP/GaAs/Ge SC. b) Dependence of $|\Delta V_{oc}|$ on overheat temperature (blue) and on photogenerated current (violet) for GaInP/GaAs/Ge SC

OBTAINING OF THE ISOTHERMAL IV-CURVE

In this paper, as well as in previously published one [1], it was established that, when a pulsed simulator used for recording IV-curves, a linear decrease of voltage is observed. Also it was shown that the overheating temperature is proportional to the voltage decrease value. Therefore the abovementioned linear decrease of voltage means the linear increase of the p-n junction temperature. As a result, the recorded IV-curves are not isothermal. To investigate this experimentally, a number of IV-curves were measured on a pulse simulator. In each measurement, identical light pulse was used, but IV-curve recording began at different time. The measurement starting time ranged from 0 to 1.6 ms after triggering a pulse. The dependences "voltage" vs "time after pulse switch on" were plotted (Fig. 3b).



(a) (b)

FIGURE 3. a) IV-curve measured at different times after switching on of a pulse. The measurement start time was varied from *0 ms* (the most right IV-curve) though to *0.2 ms* and up to *1.6 ms* (the most left IV-curve). b) Dependences "Voltage" vs "time of voltage recording". The dependencies were obtained for fixed current values, which are indicated as I_1, I_2, I_3, I_4 on both plots.

Figure 3a shows that the smaller the initial measurement time (initial temperature), the greter IV-curve shift to the right. For four currents (I_1, $I_2=0$, I_3, I_4 - dashed lines in Fig. 3a), the voltage and time of its recording (from switching on a pulse) were determined and plotted (Fig. 3b). It is seen that the slope of all dependencies is the same as the slope for V_{oc} case ($I_2=0$ - blue dashed line). So, all IV-curve voltages could be corrected to "unheated" values, just by finding their values at *0 ms* time (assuming that, at zero-time, there was no overheating).

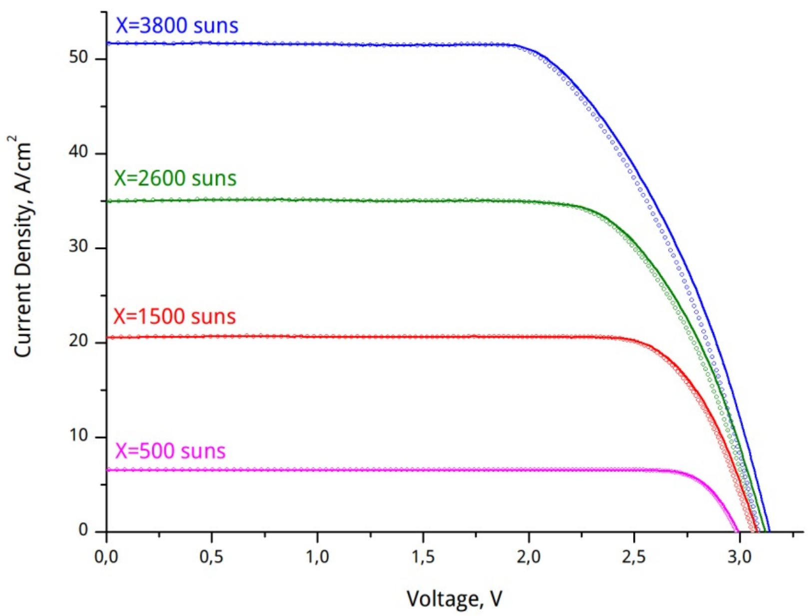


FIGURE 4. Measured in the conventional way (symbols) and corrected isothermal (lines) IV curves.

dV/dt for all the dependences was *0.045 V/ms*, which corresponds to the value dV_{oc}/dt at J_g equal to IV-curves $J_g=35.2\ A/cm^2$ (Fig. 1). Thus, the dependence presented in Figure 1 can be used for calculating the overheating at any point of measured IV-curves. For this, it is sufficient for all points to make a correction by the formula

$$V_{j,corrected} = V_j + t_j \cdot (dV/dt)_{FIX} \quad (2)$$

where $(dV/dt)_{FIX}$ is the value dV/dt for the illumination level, at which the IV-curve is measured, t_j is the time from the beginning of a pulse for the recorded point, V_j is the recorded voltage. The expression (2) and the dependence dV_{oc}/dt (Fig. 1) were used to determine a set of isothermal IV-curves. The result is shown in figure 4. One can see that, at 500 suns, the overheating effect can be neglected, and, at ~2000, suns this effect is quite significant.

CONCLUSION

The paper completes the study of the PV converter overheating during recording an IV-curve on a pulsed simulator of solar radiation. It has been experimentally found that, after the light pulse beginning, the photoconverter voltage decreases linearly with time. The voltage decrease rate is proportional to the photogenerated current. The theoretical calculation has shown that this indicated by the weak logarithmic dependence of the temperature coefficient α on the photogenerated current, and, in general, α can be considered as a constant.

Constancy of α allows using a simple way to correct recorded voltages and obtaining isothermal IV-curves. This was experimentally confirmed by measuring a set of IV-curves. IV-curve recording started at different times after switching on the light (beginning of a pulse). So IV-curves have been recorded at different temperatures. The experiment has shown that overheating equally affects all points of IV-curves, and to obtain "non-heated" voltage values it is sufficient to use a simple correction $t \cdot (dV/dt)_{FIX}$, where t is the time of the voltage recording, $(dV/dt)_{FIX}$ – correction coefficient. The coefficient can be experimentally measured, for example, it is enough to measure the V_{oc} decrease rate, as it was done in [1]. It is important to note that such a coefficient is proportional to the photogenerated current. Therefore it is enough to measure it for one current and then to use the proportional law for other ones. In using this method, the isothermal IV-curves for triple-junction GaInP/GaAs/Ge SC were obtained. It is shown that the overheating effect can be neglected at the sunlight concentration ratio less than 500 suns (photogenerated current less than $6.5\ A/cm^2$). Also, the values of p-n junction overheating were calculated, and it has been shown, that at high concentrations, overheating temperature can reach 40 degrees.

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