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To cite this article: M A Mintairov et al 2018 J. Phys.: Conf. Ser. 1135 012070

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Heating of photovoltaic converter by laser beam: overheating temperature

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Abstract. The overheating effect of high-power GaAs laser photoconverters has been studied. The dependence of the p-n junction overheating temperature ΔT on the photogenerated current Ig, which is proportional to the laser radiation power, has been obtained. It is shown that the open circuit voltage (Voc) drop is caused by the p-n junction overheating effect at currents greater than 0.3 A. The magnitude of this drop has been determined and the isothermal dependences of Voc-Ig characteristics have been obtained, which coincides with the non-resistive dark IV-curve.

1. Introduction
One of the applications of photovoltaic (using p-n junctions) laser radiation converters is optoelectronic devices for wireless transfer of electrical energy. Among problems in using such devices, which need to be solved, is the p-n junction heating by incident laser radiation, which leads to an efficiency decrease.

With respect to heating, the open circuit mode is more hard than the operating mode (the maximum power on the load), since in the operating mode a part of the absorbed light energy goes into the load and therefore does not heat the p-n junction.

In the temperature range close to room temperature, the open circuit voltage depends linearly on the temperature [1]. The corresponding temperature coefficient α = |ΔVoc/ΔT| can be calculated [1].

In this paper, the experimental (not isothermal) dependences of the open circuit voltage (Voc) on the intensity of the incident laser radiation (Pin) for GaAs photoelectric converters are analyzed. Pin is proportional to the photogenerated current, Ig, which under certain conditions (performed in this work) is equal to the short-circuit current, Isc. The temperature coefficient α has been calculated and used to determine the overheating temperature ΔT at different intensities. As a result, the ΔT-Ig dependence for GaAs photoconverters has been obtained. It has been determined that the shape of this dependence is the same for all devices under study. Also the value of the open circuit voltage drop ΔVoc has been determined, and isothermal Voc-Isc characteristics have been obtained.

2. Objects of study
GaAs p-i-n structures were grown by the metal-organic vapor phase epitaxy in a low pressure reactor. All structures were grown on n-GaAs substrates and included a back surface field barrier n-Al0.2Ga0.8As; n-GaAs base; i-GaAs undoped area; p-GaAs emitter; an optical window layer p-Al0.16Ga0.84As and a p-GaAs contact layer.

The study was carried out on six samples of two types of photoconverters having different contact grid patterns. One pattern had an area of the illuminated surface \(19.6 \times 10^{-4} \text{ cm}^2\) another one had...
7.07 \times 10^{-4} \text{ cm}^2. \text{ However, the difference in the contact grid patterns did not affect the results of the work.}

3. Dependence of the open circuit voltage on a laser beam intensity

As can be seen from Fig. 1, the \( V_{oc} - I_{sc} \) dependence contains a linear portion equivalent to the exponential characteristic \( I_g = I_0 \cdot \exp \left( \frac{V_{oc}}{(A \cdot k \cdot T)} \right) \), for which the ideality factor is \( A = 1 \). Note that at currents smaller than \( \sim 0.07 \text{ A} \), the dependence can be described with using another exponent with ideality factor \( A = 2 \). To study the p-n junction overheating effect, it is enough to analyze only the portion with larger currents. It should be also noted that, according to the general concepts of a current flowing through a p-n junction, \( A \) can not be less than one [2].

![Figure 1](image)

**Figure 1.** Experimental (symbols) dependences of the open circuit voltage, \( V_{oc} \), on the photogenerated current, \( I_m \) and exponential approximation (lines) of the dependences by formula with an ideality factor \( A = 1 \).

The deviation \( \Delta V_{oc} \) from the exponential dependence with \( A = 1 \) is shown in Fig. 2. This deviation is caused by overheating of the structure over the environment temperature. As can be seen, \( \Delta V_{oc} \) depends linearly on the photogenerated current (intensity of the laser beam). If we assume that the temperature coefficient alpha \([1,3]\) is practically independent of the beam intensity (only in a certain temperature range), the experimentally obtained linearity confirms the validity of this approximation.
4. P-n junction overheating temperature determination

To determine the overheating temperature, the approach described in [1] was used. The definition was based on calculation, which allows dependence to determine p-n junction overheating temperature $\Delta T$ for each point of the $\Delta V_{oc}$-$I_g$ dependence. For this purpose, the temperature coefficient $\alpha$ has been calculated and used in $\Delta V_{oc} = -\alpha \Delta T \ (\alpha > 0)$ relationship. As shown in [1], $\alpha$ can be obtained by the following expression:

$$\frac{\beta}{\ln\left(\frac{A}{J_g}\right)}$$  \hspace{1cm} (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, $I_0^*$ is the multiplier of the expression for the "saturation" current $I_0 = I_0^* \exp\left(-\frac{\beta}{q}\right)$ (we assume $I_0^*$ as constant because, in the above mentioned temperature range, it depends on temperature in accordance with the power law, which is weaker in comparison with the exponential multiplier [2]), $J_g$ - photogenerated current, $E_g$ - forbidden gap. The value of $\alpha = 17.9 \times 10^{-4} \ V/K$ was obtained for the GaAs p-n junction using parameters cited in [1]. This value has been used to calculate the p-n junctions overheating temperature. Fig. 3 shows the result of calculation of the overheating temperature for one of the samples. The remaining samples had the similar $\Delta T-I_g$ dependence (this is evident from the coincidence of the dependencies in Fig. 2).
As can be seen from Fig. 3, the $\Delta T-I_g$ dependence is linear but not proportional (does not come from the coordinates origin). Most likely this is due to incorrect exponential approximation of the initial $V_{oc}-I_g$ characteristics (Fig. 1). Indeed, due to the presence of $V_{oc}$ drop, the portion with the ideality factor $A=1$ (in fact, with a unity logarithmic slope of the curve) may be masked, and the portion with a large slope can reduce their slope due to distortion by heating.

**Figure 3.** Dependencis of overheating temperature $\Delta T$ on photogenerated current $I_g$. Symbols are values obtained from the experimental data (the color of the symbols corresponds to that given in the same color in other figures). The solid line is a linear approximation of the obtained dependence. The dashed line is the shifted solid line. The shift is performed in such a way that the line would come from the origin of coordinates.

Let us note that the linearity of $\Delta T-I_g$ itself is an important fact, which demonstrates the validity of the assumptions that the coefficient $\alpha$ can by convention be considered as constant in the temperature range close to room temperature.

5. Isothermal $V_{oc}$-$I_{sc}$ characteristic

Despite the fact that the obtained $\Delta T-I_g$ dependence does not come from zero, its linearity can be used both to obtain correct values of $\Delta T$ and to exclude the influence of heating on the initial $V_{oc}-I_g$ characteristic. It is sufficient for this to shift the resulting linear dependence (Fig.3) to a position, when it will pass through the origin (Fig.3, dashed line). This operation is completely correct, since the position of the $\Delta T-I_g$ line is determined by the difference in the calculated (exponent with $A=1$) and experimental $V_{oc}-I_g$ characteristics (Fig. 1). This means that the position of the $\Delta T-I_g$ is determined only by the position of the calculated exponential $V_{oc}-I_g$ dependence. By shifting the dependence (if A
$= 1$ is preserved), one can choose such its positions that $\Delta T - I_g$ will, as required, come from the coordinates origin.

Taking into account the reasoning given above that the position of the calculated characteristic depends on the analysis of the non-isothermal $V_{oc} - I_g$ dependence, we suggest the following procedure for carrying out the analysis:

1. Determination of the linear dependence of $\Delta T - I_g$ by using any rated characteristics of $V_{oc} - I_g$ characteristic with the ideality factor $A=1$.
2. Shifting of the obtained linear dependence to the origin.
3. Using obtained dependence to determine $\Delta T$ and to calculate it by the formula $\Delta V_{oc} = \alpha \Delta T$.
4. Adding $\Delta V_{oc}$ to the experimental $V_{oc}$ and obtaining the isothermal $V_{oc} - I_g$ dependence.

The result of applying such a procedure is shown in Fig. 4. It is seen that the isothermal curve starting from current 0.02 $A$ is well described by the sum of two exponents with ideality coefficients $A=2$ and $A=1$, respectively. This corresponds to the general concept of current flow in $p$-$n$ junctions. At currents below 0.02 $A$, the tunnelling current flow mechanisms affect the characteristic.

![Figure 4](image_url)

**Figure 4.** Experimental (circles), isothermal (squares) and rated (lines) $V_{oc} - I_g$ dependencies. Dashed lines - calculation for diffusion ($A = 1$) and recombination ($A=2$) current flow components, solid line is a sum of both components.

Fig. 5 shows the result of obtaining the isothermal $V_{oc} - I_g$ dependencies for all studied samples. Note that obtaining isothermal $V_{oc} - I_g$ dependencies is an important task. This is due to the fact that, as it is known, these dependences coincide with the non-resistive dark IV curve.
6. Conclusion

The overheating effect of GaAs photovoltaic high-power laser converters has been studied. A distortion of the $V_{oc}$-$I_g$ (open circuit voltage on photogenerated current) characteristic is observed. So, with an increase in the laser radiation power, $V_{oc}$ first stops to grow logarithmically and then begins to drop.

It was demonstrated that the voltage deviation of the experimental $V_{oc}$-$I_g$ dependence from the exponential one with the ideality factor $A=1$ is a linear function (Fig 2.). As was shown in previous studies the linearity of the deviation indicates the presence of the p-n junction overheating and the magnitude of the deviation $\Delta V_{oc}$ can be used to obtain the overheating temperature.

As a result, the $\Delta V_{oc}$-$I_g$ dependence has been obtained. The dependence was the same for all the samples under study, which differed by the contact grid pattern.

For all samples, the dependence of overheating temperature $\Delta T$ on $I_g$ and the isothermal $V_{oc}$-$I_g$ dependence have been obtained. A procedure for obtaining these dependencies is proposed. The isothermal new ($V_{oc}$-$I_g$) characteristic is especially important because, as it is known, it coincides with the non-resistive dark IV-characteristic of the a p-n junction.

Acknowledgments

The paper has been prepared with the support of the fundamental research program of the Presidium of the Russian Academy of Sciences "Fundamental principles of breakthrough technologies in the interests of national security”.

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