Performance of InGaAs metamorphic laser power converters at different conditions.

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Abstract. The topic of the work is the metamorphic InGaAs heterostructures for laser power converters (LPC) and their performance at different measurement conditions. Three different illumination conditions were studied: monochromatic Xe-lamp uniform illumination, laser with quasi-uniform illumination (with laser beam unfocusing) and non-uniform focused laser illumination. For simulating the experimental IV-curves as well as FF-Jg, Voc-Jg and η-Jg dependences, a tube model developed earlier and describing the charge carrier transport along current lines was used for all three illumination regimes. In the absence of losses (Xe-lamp and unfocused laser), the perfect model simulation model exhibiting an experimental efficiency greater than 50% (for λ=1064nm) has been demonstrated. As a result of simulation of LPC characteristics obtained under focused laser illumination, the losses associated with uniform light distribution as well as with an additional resistance, which decrease the LPC efficiency, have been found.

1. Introduction
There are two main practical cases for laser power converters (LPCs) using. First, it is LPCs for fiber optics, when laser radiation wavelength should correspond to one of the fiber optics line transparency windows. Second, it is LPCs for the atmospheric transmission window and can be practically used for wireless energy transmission systems, for example, for recharge household unmanned aerial vehicles. The most studied GaAs photodetectors demonstrating efficiency of up to 60% [1, 2] are suitable only for local networks due to large attenuation of near-IR radiation (λ up to 850nm) in the optical fiber. LPCs tuned to the wavelength range beyond the GaAs absorption edge (λ=1-1.1 µm) can be used for both fiber optics and wireless energy transmission systems.

In the work, laser power converters (LPCs) for high power monochromatic light based on metamorphic InGa₁₋ₓAs heterostructures have been obtained and investigated. The metamorphic growth technology is successfully used for creating high-efficient multijunction heterostructure solar cells [3]. Depending on the composition of the active region, such single p-n junction heterostructures can be tuned to a specific laser radiation wavelength and cover a wide range of the tasks for transmitting energy or information via a direct air channel or fiber optics.

The main purpose of the paper is to study the influence of the laser irradiation conditions on LPC performance. Two different cases were studied: a focused laser (when the laser spot is smaller than the LPC photoactive area), what corresponds to signal transmission with a fiber-optics, and an unfocused one corresponding to transmitting radiation through the atmosphere with a laser beam dispersion. Comparison with the results obtained with uniform illumination with a Xe-lamp was carried out.

Previously [4] we determined that, in using a continuous high-power laser, the main losses are associated with sample overheating. And the thermal coefficient α≈1.2 mV/K of overheating was...
calculated for continuous laser using $V_{oc}-J_g$ dependence. In this work, all LPCs were mounted on an improved heat sink and were only irradiated with a pulsed laser (focused or defocused), what allowed leveling thermal losses. Thus, the main factor affecting the characteristics of the LPCs was only the uniformity of laser light distribution over their surface.

2. Experimental details
LPC structures were grown by the MOVPE and based on In$_{0.23}$Ga$_{0.77}$As solid alloys grown over MB on GaAs-n substrates. The MBs consisted of a sequence of layers slowly increasing in lattice-mismatch with respect to a GaAs wafer to form step-compositional-graded profile of In composition. The developed MB technology allows suppressing threading dislocations in the photoactive region at least at the level of $<1 \times 10^5$ cm$^{-2}$[5]. The LPCs were manufactured 3×3.4nm$^2$ (photoactive area is 0.0784cm$^2$). The LPC IV characteristics were measured for $\lambda=1064$nm in the following regimes: pulsed fiber-guided laser (with 1.5msec pulse duration), the unfocused pulsed laser (this situation simulates realistic wireless energy transmission through an open optical channel) and a Xe flash lamp (uniform illumination over sample surface and absence of overheating at IV-curve recording). Effective heat sinks were used for all LPCs.

3. Results and discussion
In the work, LPCs with improved heat sinks were used, what allowed completely removing the effect of sample overheating. This is confirmed by coincidence of the photovoltaic characteristics, in particular the $V_{oc}-J_g$ ($J_g$ – photogenerated current), for a LPC uniformly illuminated with Xe-lamp and a LPC illuminated with an unfocused laser (Figure 1). Herewith the photovoltaic characteristics of the LPC illuminated with a focused laser do not coincide (Figures 1, 2 and 3).

![Figure 1](image_url)

**Figure 1.** Experimental $V_{oc}-J_g$ (squares) and $V_{oc}-J_m$-$J_m$ (circles) photovoltaic dependences for a In$_{0.23}$Ga$_{0.77}$As LPC measured at different regimes: focused 1064nm high-power pulsed laser (red), unfocused 1064nm pulsed laser (blue) and uniform Xe flash lamp (black). The black thick solid lines are the tube model simulation; the black dashed lines show the diffusion (ideality factor A=1) and recombination (A=2) components of the current flow mechanism.
Contribution non-uniformity effect of laser radiation on the LPC efficiency was determined at absence of overheating. For this purpose, the dependences $V_{oc}-J_g$ and $V_{m}(J_g-J_m)$ ($V_m$ and $J_m$ are voltage and current at the maximum load point) have been obtained from experimental dependencies and analysed (Figure 1). Note that the $V_{oc}-J_g$ dependence coincides with the non-resistive dark IV-curve, and the $V_{m}(J_g-J_m)$ dependence deviates from it due to the series resistance [6, 7]. The analysis of the non-resistive part of the $V_{m}(J_g-J_m)$ dependence and the non-resistive $V_{oc}-J_g$ dependence allow determining the parameters of the dark IV-curve.

The non-resistive dark IV-curve was well described by a two-exponential model and absolutely coincided with the non-resistive $V_{oc}-J_g$ dependence recorded at Xe flash lamp. The saturation currents for both diffusion and recombination current flow mechanisms were $J_{01}=1.7 \times 10^{-14}$ A/cm$^2$ and $J_{02}=5.2 \times 10^{-8}$ A/cm$^2$, correspondently.

The obtained values of the saturation currents were used to calculate IV-curves in taking into account the process of current spreading. The calculation was based on the previously developed tube model of current spreading [8]. In the model, current lines through the photovoltaic structure were presented as small thickness tubes, and the resistance parameters of each tube were calculated. In our case of the uniform illumination, the photogenerated current values were set for each tube individually (but not the same for all tubes, as in the case of uniform illumination considered in [8]).

Figure 2 shows the experimental $I-V$ curves (symbols) for all three cases of illumination for the same photogenerated currents. It can be seen that the $I-V$ curve obtained in the case of a focused laser illumination deviates from other curves by voltages in the region near the optimal load point. As a fact, such a deviation can be explained by an increase in resistive losses. However, calculation of the IV-curves by the tube model taking into account the nonuniform illumination has shown that such a deviation can be described by changing the processes of spreading charge carriers between contact bars.

![Figure 2](image.png)

**Figure 2.** Experimental (circles) $I-V$ curves for a In$_{0.23}$Ga$_{0.77}$As LPC measured at different regimes: focused 1064nm high-power pulsed laser (red), unfocused 1064nm pulsed laser (blue) and uniform Xe flash lamp (black). The black thick solid lines are the tube model simulation.

All calculated results are presented in Figures 1, 2 and 3 by the black thick solid lines. In all calculations, the number of tubes was 30, the lateral resistance parameter was $R_L=1.3 \times 10^{-2}$ Ohm $\cdot$ cm$^2$ and the vertical resistance parameter was $R_V=1.1 \times 10^{-3}$ Ohm $\cdot$ cm$^2$. The photogenerated current in the tubes were specified differently for different illumination conditions. For the case of uniform illumination, it was specified by uniform distribution, for the case of focused laser it was specified by a normal distribution. Parameters of the standard distribution were chosen for the best fit of the
experimental IV-curve and normalized in such a way that the total current in the tubes was equal to the experimental photogenerated current of PLC.

For both Xe-lamp uniform illumination and unfocused laser, the calculation agrees well with the experiments. For a focused laser, the calculation is slightly deviated from the experiential data, but in general it describes the observed deviation. Not perfect agreement between the calculation and the experiment can be explained by additional resistive losses for the unfocused laser. The geometry of the current lines seems to change slightly under nonuniform illumination, and the current lines became not optimal. And, consequently, the resistance parameters of each tube can change.

The IV-curves were calculated over the entire illumination range. Based on the calculation, the $V_{oc}-J_g$ dependences (Figure 1 - the black thick solid line), as well as the $FF-J_g$ (Figure 3 a - the black thick solid line) were obtained. Instead of the more fundamental $V_{m}-J_g$ dependence, a more practical one $FF-J_g$ was used, because efficiency was calculated being based on the $FF$ values.

![Graph](image1.png)

**Figure 3.** Experimental (circles) $FF-J_g$(a) and $\eta-J_g$ (b) dependencies for a In$_{0.23}$Ga$_{0.77}$As LPC measured at different regimes: focused 1064nm high-power pulsed laser (red), unfocused 1064nm pulsed laser (blue) and uniform Xe flash lamp (black). The black thick solid lines are the tube model simulation.

It can be seen (Figure 3a) that the calculation describes well the $FF-J_g$ dependency for unfocused laser and slightly deviates for focused laser, especially after the maximum. At the same time, the $V_{oc}-J_g$ dependence ideally coincides with the experimental one (Figure 1). All this indicates that, in addition to the influence of the illumination nonuniformity on the characteristics, there are also the influence of the current tube geometry distortion and, consequently, the changes in their resistance parameters. Indeed, resistive losses maximally influence on the position of the optimal load point, and, therefore on resistive characteristics, such as $FF-J_g$ and $V_{oc}-J_g$. At the same time, resistive losses practically have no effect on the resistiveless $V_{oc}-J_g$ dependence.

The calculated $\eta-J_g$ dependences are similar to the $FF-J_g$ dependences for all three measurement conditions (Figure 3b). In the case of an unfocused pulsed laser, there are no additional losses in a LPC with a heat sink. In this case, the efficiency is the highest possible and equal to the monochromatic efficiency under Xe-lamp illumination. The efficiency for both these cases is more than 48% in a wide range of photogenerated currents (1-10 A/cm$^2$) and a laser power densities (1.3–13W/cm$^2$) with a maximum value of 50.4% at 6 W/cm$^2$ ($\lambda = 1064$ nm). The losses discussed above associated with both illumination nonuniformity and additional resistive losses lead to the efficiency decrease in the case of a focused laser down to 49.4% for the maximum point and a significant decrease in the efficiency at more high powers.
4. Conclusions
The influence of the laser irradiation conditions on the InGaAs metamorphic laser power converter performance was studied. Different measurement conditions were compared: a focused pulsed laser with nonuniform illumination distribution, an unfocused pulsed laser and uniform illumination with a Xe-lamp. It is shown that with a pulsed laser and a good heat sink levelling thermal losses, the main factor affecting the characteristics of solar cells, including its efficiency, is the uniformity laser illumination distribution, in the case, when the laser spot is smaller than the LPC photoactive area.

For simulating the experimental $IV$-curves, $FF$-$J_g$, $V_{oc}$-$J_g$ and $\eta$-$J_g$ dependences, the tube model describing the charge carrier transport along current lines was used for all three illumination modes. A perfect fit of simulation results to the experiment in cases of uniform radiation (Xe-lamp and unfocused laser) was demonstrated. In case of the focused laser, it was shown that for the characteristic fit, it is required to set the illumination distribution over the device surface by a normal distribution function assuming that the resistance parameters of the current tubes did not change. However, even in this case, the simulation of the $IV$-curves under the focused laser will not be accurate near the optimal load point. This indicates that we must take into account an additional resistance increase of the tubes, for example, due to unlighted areas of the photoactive surface leading to distortion of the current lines. As a result, resistive characteristics ($FF$-$J_g$, $\eta$-$J_g$) are not accurately simulated at high laser powers.

In the absence of losses, in the case of an unfocused laser the efficiency comparable to the conversion of uniform monochromatic radiation was demonstrated (the maximum efficiency was 50.4% at 6W/cm$^2$). This is the record result of laser conversion for $\lambda = 1064$nm according to the literature data. The unfocused laser mode simulates the practical case of energy transfer through an open optical channel.

For another practical case of energy transfer through a fiber optics (focused laser), the losses caused by radiation nonuniformity and resistivity rise reduce the efficiency by almost 1%. For such an energy transfer method, it is necessary to decrease the PLC photoactive area to the laser beam spot square.

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