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A GaInP−based photo-converter of laser radiation with an efficiency of 46.7% at a wavelength of 600 nm

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GaInP−based laser power converters (LPC) structure grown by MOVPE and device chip design have been optimized for operation under high-power lasers of the green-red spectral range. Light I-V curves records have shown the performance of the LPC at up to 40−50 W/cm^2 of incident power densities. The highest level data were obtained for 532, 600, and 633 nm power laser lines: 44.3%, 46.7%, and 40.6% under 13−16 W/cm^2, respectively. LPC demonstrated an efficiency of more than 40% at the incident laser radiation power density elevated up to 40−50 W/cm^2.

Keywords: laser photoconverter, MOVPE, efficiency, spectral response.

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Recently the task of laser-aided wireless energy transmission both by air and through fiber-optic systems becomes more and more topical. For efficient energy transmission, it is necessary to ensure the performance of the laser radiation photo-converters (LPCs) at the maximum possible incident radiation power density, which makes this LPC parameter no less important than the efficiency. A great number of studies were devoted to developing highly efficient LPCs for the near IR range for which there exist efficient lasing sources matched with absorption minima for both the atmosphere and fiber-optic lines.

For the 800−850 nm spectral band, LPCs based on AlGaAs/GaAs were developed. The maximum efficiency of the optical radiation conversion to electricity, which is 54.9% at 36 W/cm^2 [1] and 60% at 30 W/cm^2 [2], was reached at the wavelength of 810 nm. Using the inverse technology and back-surface mirror, we succeeded in obtaining LPCs with a record-breaking efficiency of 68.9% for the 858 nm lasing at the incident radiation power density of 11.4 W/cm^2 [3].

For a long time, the silicon-based structures were used to create 1064 nm LPCs; these structures exhibited the efficiency of 38.8% (1.3 W/cm^2) [4]. The use of the InGaAs/GaAs metamorphic structures allowed overcoming this barrier and achieving the efficiency of 50% at the laser power density of 6.5 W/cm^2 and 48% at the power density of 13 W/cm^2 [5], as well as efficiency of 55% at the 4 W/cm^2 in converting 4 W/cm^2 for close wavelengths (1020 nm) [6].

At the wavelength of 1550 nm, the efficiency of 45% (0.1 W/cm^2) was obtained for InGaAs/InP−based [7] and GaSb−based [8] LPCs.

At the same time, the visible-range LPCs have been studied not so intensely, though the use of visible-range lasers is preferable in many tasks. There were created LPCs based on GaInP solid solutions that were lattice-matched with the GaAs substrate, whose efficiency was 39.4% (0.1 W/cm^2) for 520 nm and 33.3% (0.1 W/cm^2) for 633 nm [9], and also 46% (1.1 W/cm^2) for 638 nm [10]. Notice that such a high efficiency of GaInP−based LPCs was achieved at a low density of the incident radiation power.

This paper describes the optimization of the GaInP−based LPC structure, as well as its chip, aimed at ensuring efficient conversion of the 532, 600 and 633 nm laser lines at the incident radiation power density of up to 40−50 W/cm^2.

The LPC structure under study was grown by the MOVPE method. The structure and chip designs were optimized so as to get minimal resistive loss that is most critical at high densities of photocurrent generated under high-power laser radiation. The structure had the n/p electrical polarity and was grown on the p^+-GaAs substrate, which made it free of p/p-interfaces between AlGaInP and GaAs which tended to induce barriers for minor charge carriers by increasing the resistive loss [11]. This structure comprised a layer of back-surface potential barrier p^+-GaInP 100 nm thick, p-GaInP base layer 600 nm thick, n-GaInP emitter layer 100 nm thick, wide-bandgap n-AlInP window layer 30 nm thick, and n^+-GaAs contact layer 300 m thick. The structure was optimized so as to obtain the maximal spectral response at 600 nm. For this purpose, the thickness of photoactive GaInP layers was chosen to be 700 nm. The 100 nm thickness of the n-GaInP emitter layer ensured a lower resistance to dissipation between the contact arms. A small number of stibium atoms were added during the epitaxial growth in order to reduce the CuPt ordering in the GaInP layer [12], which allowed increasing the GaInP band gap (E_g), and, hence, the open-circuit voltage (V_{oc}) generated by LPCs.

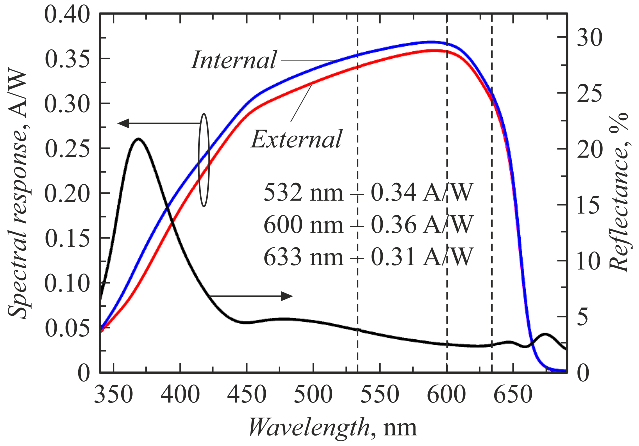

Figure 1. Spectra of the external and internal spectral response (upper lines) and a reflection spectrum (lower line) of GaInP-based LPC.

The Au:Ge/Ni/Au and Ag:Mn/Ni/Au contact systems were applied on the *n*-GaAs contact layer and *p*-GaAs substrate, respectively; after that, the contacts were thickened by electrochemical deposition of 2 μm of gold. The front contact grating was formed by selectively etching the GaAs contact layer with applying the TiO_2/SiO_2 antireflection coating directly on top of the wide-bandgap *n*-AlInP window layer.

The design of the front contact grating was optimized so as to reduce the in-series resistance. For this, a 3D distributed equivalent circuit was created and numerically modeled. This made it possible to balance the dissipation resistance for currents between the contact grating arms and resistance of golden arms 2 μm thick. The found optimized design of the contact grating comprised arms 4 μm wide uniformly distributed over the photoactive surface 3×3 mm in size with the step of 100 μm.

For measurements, the tested LPC was soldered to a heatsink plate in order to prevent overheating under high-power laser radiation. The spectral response (*SR*) was measured by comparing its photocurrent with that of the calibrated reference sample. For this purpose, a monochromator–based setup was used. Volt–ampere (I-V) characteristics were detected with a pulse simulator.

Fig. 1 presents *SR* spectra and a reflection spectrum of a GaInP–based LPC. The maximum value 0.36 A/W corresponding to the external quantum efficiency of 75% was reached at the wavelength of 600 nm. At the 532 nm wavelength, LPC exhibits $SR = 0.34$ A/W. At wavelengths above 600 nm, LPC exhibits an *SR* decrease due to its wavelength optimization for the 600 nm wavelength; this is why *SR* is only 0.31 A/W at the wavelength of 633 nm. Notice that the increase in the total thickness of the photoactive GaInP layers results in an *SR* increase at wavelengths above 600 nm.

Reflection in the wavelength range of 500–600 nm is 2–5% (Fig. 1), which is caused by not fully optimized antireflection coating and results in additional *SR* loss. The „internal“ *SR* spectrum (corresponding to the internal quantum efficiency) demonstrates reachable values 0.35, 0.37 and 0.32 A/W for laser lines at 532, 600 and 633 nm.

The optimized design of the front contact grating ensured the filling factor above 80% for light I-V curves at the photocurrent density of up to $J_{sc} = 10$ A/cm^2 (curve *2* in Fig. 2). The GaInP E_g increase due to inclusion of Sb atoms led to an increase in the generated voltage. For comparison: in [10], V_{oc} was ~ 1.47 V at the incident radiation power density of 10 W/cm^2 at the 633 nm wavelength, while the developed LPC exhibits 1.53 V at the comparable laser radiation parameters (corresponding to $J_{sc} \sim 3$ A/cm^2).

The V_{oc} dependence on J_{sc} consists of three regions (curve *1* in Fig. 2). This dependence is known to coincide with the resistanceless dark I-V curve [13]. The regions at current densities < 1.7 A/cm^2 and of 1.7–6.5 A/cm^2 are properly describable by linear dependences and correspond to the Shockley–Hall–Read current flow mechanism and Shockley mechanism, respectively. The „bend“ in the $V_{oc}(J_{sc})$ dependence at the current density > 6.5 A/cm^2 may be explained by the sample overheating under high-power incident radiation [13]. The maximal efficiency exhibited by LPCs was 46.7% (13 W/cm^2), 44.3% (14 W/cm^2) and 40.6% (16 W/cm^2) at the wavelengths of 600, 532 and 633 nm, respectively (Fig. 3). Therewith, the LPC exhibits the efficiency above 40% at the incident radiation power densities of up to 60 W/cm^2 at the wavelength of 600 nm, 50 W/cm^2 at the wavelength of 532 nm, and 25 W/cm^2 at the wavelength of 633 nm.

To the authors' knowledge, the conversion efficiencies reached at wavelengths of 600 and 532 nm are at present the maximal ones among all the published data. Notice also that further optimization of the GaInP–based LPC structure and antireflection coating will provide an efficiency above 50% in the spectral range of 500–650 nm.

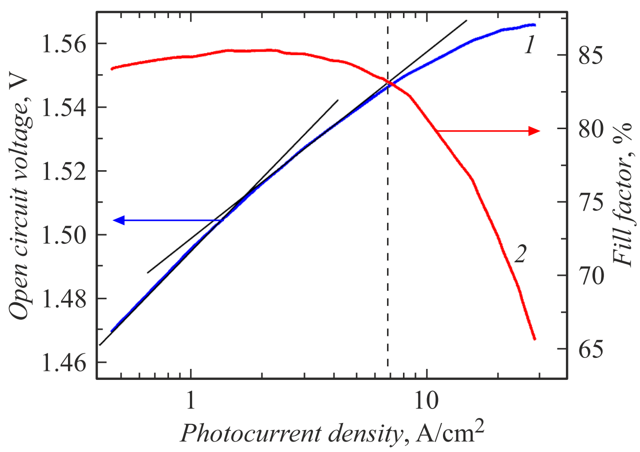

Figure 2. Dependences of the open–circuit voltage (*1*) and I-V characteristic filling factor (*2*) on photocurrent density derived from light I-V curves of the GaInP–based LPCs.

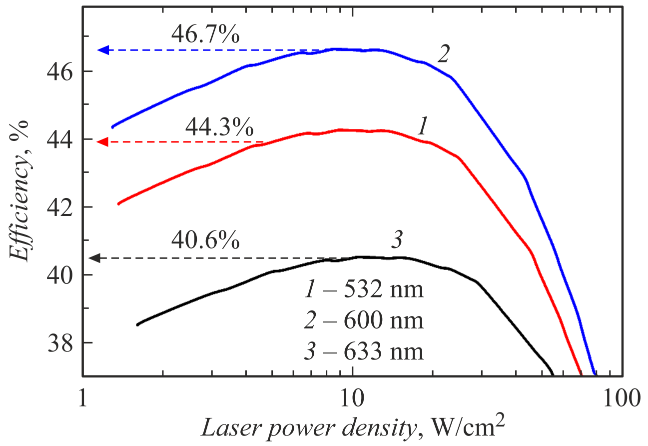

Figure 3. LPC efficiency at the wavelengths of 532 (*1*), 600 (*2*) and 633 nm (*3*) versus the incident radiation power density.

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Conflict of interests

The authors declare that they have no conflict of interests.

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