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High-efficiency GaInP/GaAs photoconverters of the 600 nm laser line

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Optimized photoconverters for operation under high-power laser radiation in the green-red spectral range based on MOCVD-grown GaInP/GaAs heterostructures are fabricated. The Au(Ge)/Ni/Au and Pd/Ge/Au contact systems have been studied to form the front contact grid of devices. As a result, the laser photoconverter with a Pd/Ge/Au contact showed an efficiency of more than 50% up to an incident radiation power density of 30 W/cm^2 with a maximum value of 54.4% under 7 W/cm^2 for laser line with wavelength of 600 nm.

Keywords: photoconverter, laser radiation, MOCVD, efficiency, spectral sensitivity.

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Laser systems for energy transmission are insensitive to electromagnetic interference and hold promise for wireless power supply of remote sensors and unmanned vehicles and for energy transmission in space. Semiconductor laser-radiation photoconverters (LRPCs) are key components of systems for energy transmission with a laser beam. Thermal losses decrease considerably due to the possibility of matching the bandgap width of the LRPC material to the wavelength of laser radiation, and the efficiency of modern LRPCs is at the level of 60% or higher [1–3]. The majority of studies performed in the past two decades were focused on LRPCs based on GaAs with the long-wavelength absorption edge at 870 nm [1–6]. Wavelengths on the order of 1 μm are also promising for long-range wireless energy transmission, since the atmospheric transmittance is higher in this spectral range and high-power lasers based on yttrium aluminum garnet with a fundamental wavelength of 1064 nm are readily available [7]. LRPCs designed for this wavelength have already been fabricated based on silicon [8], semiconductor A^3B^5 compounds (InGaAsP [9,10] and InAlGaAs [11]) lattice-matched to an InP substrate, and InGaAs materials grown via a metamorphic buffer on GaAs substrates [12–14].

LRPCs based on GaInP lattice-matched to a GaAs substrate are of interest for underwater systems for energy transmission to autonomous underwater vehicles [15]. Lasers operating in the 400–700 nm wavelength range, where the transmittance of sea water is high, are used in such systems. In addition, the potential to use second-harmonic radiation of lasers based on yttrium aluminum garnet with the wavelength located in the green spectral region (532 nm) makes GaInP-based LRPCs promising candidate components of systems for wireless atmospheric energy transfer. Both high levels of LRPC efficiency and the capacity to convert high incident radiation power densities (in excess of 10 W/cm^2) are needed in such applications.

GaInP-based LRPCs with an efficiency of 39.4% (0.1 W/cm^2) at a wavelength of 520 nm, 33.3% (0.1 W/cm^2) at 633 nm [16], and 46.7% (1.5 W/cm^2) at 638 nm [17] have already been fabricated. We have recently [18] demonstrated high-efficiency LRPCs operating at much higher incident radiation power densities: 46.7% (13 W/cm^2), 44.3% (14 W/cm^2), and 40.6% (16 W/cm^2) at wavelengths of 600, 532, and 633 nm, respectively.

The present study is focused on optimizing the heterostructure and the contact system design of GaInP-based LRPCs. Following this optimization, their efficiency exceeded 50%.

The studied optimized LRPC structure was grown by metal organic chemical vapor deposition on a p^+-GaAs (100) substrate. The results of mathematical simulation [19] of LRPCs with an efficiency of 46.7% [18] allowed us to determine the diffusion lengths of minority carriers in photoactive GaInP layers (80 nm for holes in the emitter layer and 1.2 μm for electrons in the base layer) and calculate the optimum thicknesses of these layers. The thickness of the base layer was increased from 600 to 950 nm in order to enhance the absorption of photons with a wavelength of 600–640 nm, and a pulling electric field was built into the base layer by producing a doping level gradient in order to improve the efficiency of collection of photogenerated carriers from the bulk of this layer. The thickness of the emitter layer, which ensures current spreading between contact buses, was also adjusted from 100 to 75 nm.

Thus, the grown optimized structure had electric polarity n/p and featured the following layers deposited sequentially onto a *p*-GaAs substrate: back potential barrier layer p^+-GaInP with its thickness increased to 200 nm, base layer *p*-GaInP with gradient doping (from $1 \cdot 10^{18}$ to $3 \cdot 10^{17}$ cm^{-3}) and a thickness of 400 nm, base layer *p*-GaInP with a constant doping level ($3 \cdot 10^{17}$ cm^{-3}) and a thickness of 550 nm, emitter layer *n*-GaInP with a thickness of 75 nm, wide-gap window layer *n*-AlInP with a thickness

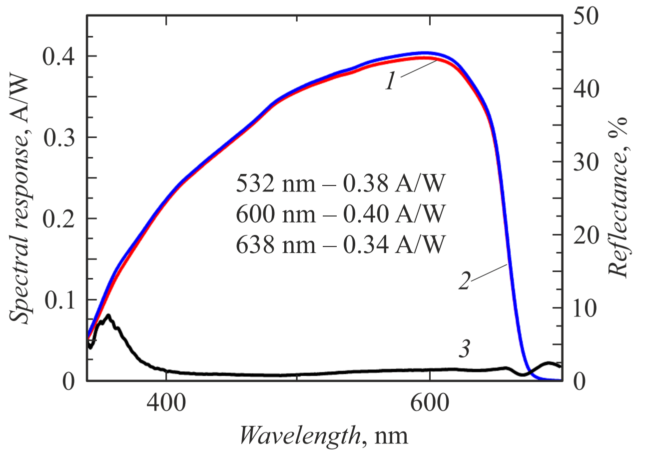

Figure 1. External (*1*) and internal (*2*) spectral response and reflectance spectrum (*3*) of an optimized GaInP-based LRPC.

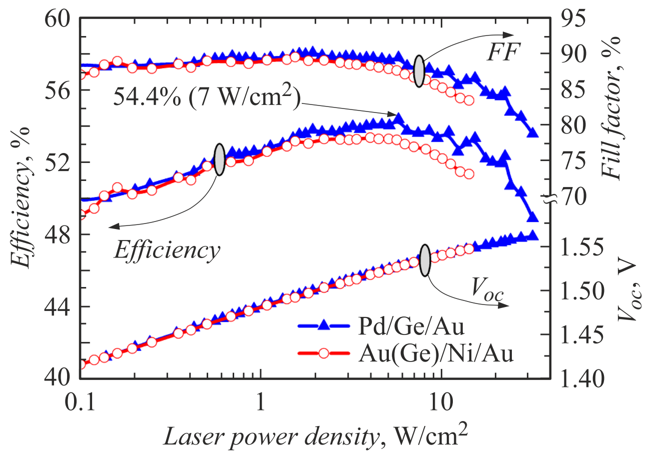

Figure 2. Dependences of the open-circuit voltage, the CVC fill factor, and the efficiency on the incident power density of laser radiation with a wavelength of 600 nm for optimized GaInP-based LRPCs with face metallic contacts based on Pd/Ge/Au and Au(Ge)/Ni/Au.

of 30 nm, and contact layer n^+-GaAs with a thickness of 300 nm.

LRPC chips were fabricated from this structure using two post-growth technologies differing in the type of a metallic face contact: Au(Ge)/Ni/Au and Pd/Ge/Au. The temperature of annealing of the Pd/Ge/Au contact system (190°C) was reduced relative to the one (400°C) for Au(Ge)/Ni/Au. This helped improve the contact morphology and make the distribution of contact resistance over the sample area more uniform. A more detailed description of the chip manufacturing procedure was given in [18].

The spectral response (SR) of LRPCs was measured by comparing their photocurrent to the photocurrent of a calibrated reference sample. A monochromator-based setup was used for the purpose. Current–voltage curves (CVCs) were recorded with a pulse simulator.

The spectral dependences of SR and reflectance for optimized GaInP-based LRPCs with two different types of face contacts were the same. Figure 1 presents the dependences of the measured external spectral response and the internal spectral response determined with account for reflection. Owing to the deposition of antireflective coatings, the reflectance within the 500–700 nm wavelength range was kept at a fairly low level (below 2%). The maximum value of SR = 0.40 A/W corresponds to a wavelength of 600 nm. At 532 nm, the studied LRPC demonstrates an elevated SR = 0.38 A/W, and the SR value at a wavelength of 638 nm is 0.34 A/W.

Optimized LRPC chips also had the same open-circuit voltage V_{oc} and a high CVC fill factor (FF), which was on the order of 90% within the studied range of incident radiation power densities (Fig. 2). The V_{oc} values of optimized LRPC samples with both types of contacts were raised by 10 mV. For example, an unoptimized sample had V_{oc} = 1.528 V [18] at an incident radiation power density of 10 W/cm^2, while optimized LRPCs are characterized by V_{oc} = 1.539 V. However, FF of the sample with an Au(Ge)/Ni/Au-based face contact started decreasing already at an incident radiation power density of 2 W/cm^2, while the LRPC with a Pd/Ge/Au contact maintained a high FF level through to 6 W/cm^2 (Fig. 2).

Thus, the optimization of layer thicknesses in the LRPC structure provided an improvement of the spectral response and an increase in the open-circuit voltage, and the use of a Pd/Ge/Au contact system allowed us to raise the CVC fill factor. The following efficiencies at a wavelength of 600 nm were obtained as a result: 54.4% at an incident radiation power density of 7 W/cm^2 for the LRPC with a Pd/Ge/Au contact and 53.8% at an incident radiation power density of 2 W/cm^2 for the LRPC with an Au(Ge)/Ni/Au contact. These LRPCs maintain a conversion efficiency in excess of 50% at incident radiation power densities up to 30 and 20 A/cm^2, respectively.

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Conflict of interest

The authors declare that they have no conflict of interest.

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