Development of the technology for production power laser conventers on wavelength 1.06 μm

© A.E. Marichev, V.S. Epoletov, B.V. Pushnyi, A.S. Vlasov, A.E. Lihachev

Ioffe Institute,
194021 St. Petersburg, Russia

E-mail: Segregate1@yandex.ru

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The technology for production one and two-cascade power laser converters was presented in this paper. According to the measurement results of the grown samples, an efficiency of 34.5% was achieved. A promising design of a cascade photoelectric converter is proposed, in which the cascades are connected with using conduction channels based on GaP microcrystallites.

Keywords: Light power converter, laser radiation, tunnel diode, microcrystallites, indium phosphide.

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Solar energy is now a reliable and virtually inexhaustible source of energy. A high-power laser can be used to transmit energy to the Earth's surface and between satellites, and a photoelectric laser converter (LR PVC) [1–4] can act as the receiver of the radiation. Such energy transmission systems can be used on Earth for power systems in places with difficult terrain (mountains) and recharging systems for unmanned aerial vehicles.

Yttrium-aluminium garnet (Nd : YAG) lasers operating at a wavelength of 1.06 μm are able to provide a fairly small beam divergence without the use of additional complex optics, which makes it possible to use them in such systems. The quaternary solid solution $Ga_xIn_{1-x}As_yP_{1-y}$ with the band gap width $E_g \sim 1.10$ eV with $x \sim 0.15-0.22$ and $y \sim 0.25-0.46$, coordinated by the lattice period with InP, is a promising material for the creation of LR PVC with the wavelength $\lambda = 1064$ nm.

The system of quaternary GaInAsP solid solutions has large spinodal decay bands [5], and the indicated compositions are near the instability contour, which complicates the preparation of crystalline perfect thick GaInAsP layers with thicknesses necessary for efficient radiation absorption.

We have found [6,7] that solid solution layers for the active band$Ga_{0.22}In_{0.78}As_{0.46}P_{0.54}$ of satisfactory quality can be obtained with thicknesses ≥ 200 nm. A sharp deterioration in the quality of the layers was observed with increasing thickness. To create the required thickness, a method was proposed (see work [7]) to fabricate a lamellar structure consisting of the following layers: a solid solution of the desired composition with a thickness of $d = 200$ nm and layers of InP with $d = 20$ nm, with a total thickness required for complete absorption of radiation at $3.0-3.5\,\mu$m.

The authors proposed to use a variant of the LR PVC with radiation input from the substrate side („reverse" structure). The GaInAsP/InP heterostructure was grown by metalorganic vapour phase epitaxy (MOVPE) [8] on an n-InP substrate. One of the reasons for choosing this substrate is the fact that the substrate is transparent to radiation at the wavelength $\lambda = 1064$ nm. Such a substrate allows the fabrication of a contact grid with a smaller area than that of photodiodes with illumination from the active layer side. The structure of the LR PVC designed to receive radiation from the substrate side is shown in Figure 1. The thicknesses of the layers were calculated using the Bouguer–Lambert–Ber law at the optimum doping degree for InGaAsP solid solution compositions with $E_g = 1.05$ eV, slightly mismatched by the lattice constant with InP. [9].

Due to the fact that in this design the top contact is applied on the substrate instead of on thin emitter layers (as in classical PVC), the contact grid area is reduced. This reduces shading losses in the LR PVC and reduces ohmic losses in the contact itself.

An anti-reflection coating based on Ta_2O_5 film with a thickness of 140 nm was applied to the receiving surface of the LR PVC.

Figure 2 shows the wavelength dependence of spectral sensitivity, Figure 3 — fill factor, no-load voltage and efficiency. Measurements were performed on instruments with 3.5×3.5 mm.

At an optical power density of 10 W/cm^2, a PVC efficiency of 34.5% was recorded when $\lambda = 1064$ nm laser radiation was converted.

In order to increase the irradiation power (optical power) of the LR PVC and to exclude the saturation"' effect, it is preferable to use cascade (lamellar) photodetectors [10][1]. Usually, a tunneling $p-n$-junction is used as the coupling element of cascade devices, but when the incident radiation power is significantly increased, the generated current may exceed the peak current of the tunneling junctions, which leads to an increase in the resistance of the structure and

[1] See O.N. Krokhin [10]: „Apparently, it is possible to try to make the converter in the form of a lamellar structure, in which radiation passes sequentially through several layers, gradually absorbed, and the electrical connection between the layers should be carried out in a serial scheme. Then, such a converter will output a higher voltage".

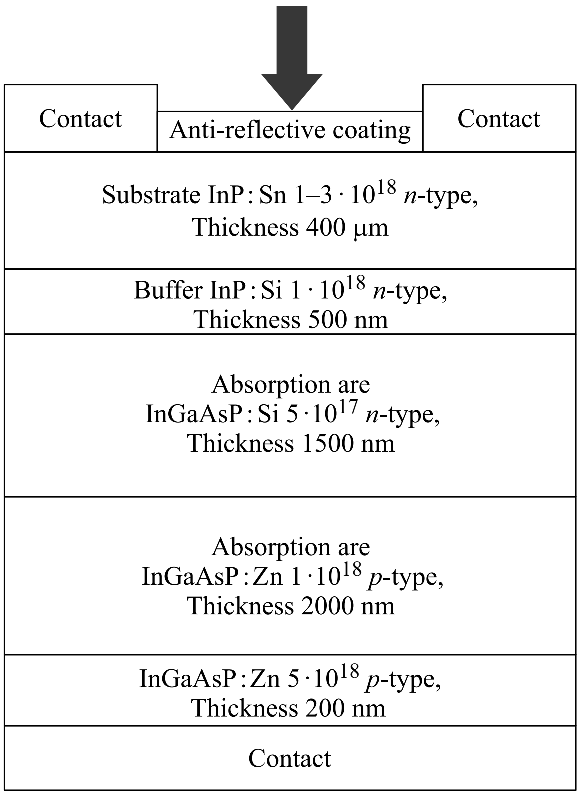

Figure 1. Structure of a GaInAsP-based inversion-illuminated LR PVC.

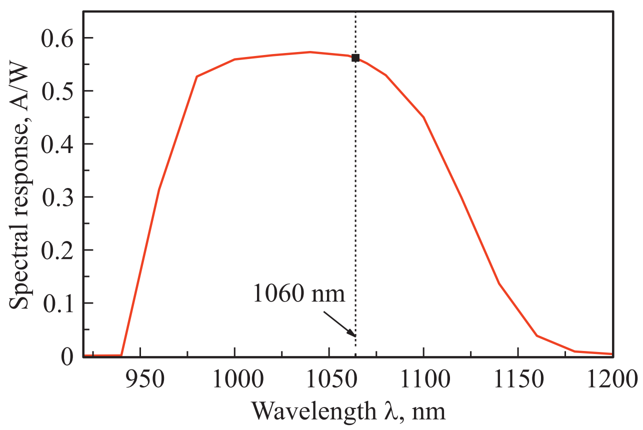

Figure 2. Dependence of the spectral response on the radiation wavelength under uniform irradiation.

a decrease in the radiation conversion efficiency [11]. The solution to this problem is to fabricate conduction channels by introducing an array of microcrystalline inclusions in the space charge band (SCB) between neighboring p–n-junctions. This allows us to completely eliminate tunneling p–n-junctions and provide ohmic current flow through these channels.

To create such a connecting element, it is necessary to decide on the material from which the microcrystallites should be made. This material must meet the following conditions.

1. Weak absorption of optical radiation transformed by absorption bands.

2. The material should not form a continuous layer at the interface with the photoactive material, but only individual, suitably sized crystals.

GaP, which has a significant difference in lattice constant from InP and a large band gap width ($E_g = 2.261$ eV), is suitable for the creation of microcrystallites, which makes it possible to obtain microcrystallites that will not absorb the received laser energy.

All structures were grown by the MOVPE method. The growth temperature was 600°C, the reactor pressure was 100 mbar, and the substrate rotation speed was 100 rpm.The carrier gas was hydrogen with a dew point not worse than 100°C, the total flow through the reactor was 5.5 l/min.

A prototype of a two-cascade LR PVC with a coupling element based on GaP microcrystallites shorting the p–n-junction InP OPZ was fabricated. The structure of the prototype is shown in Figure 4.

This LR PVC design solves several problems existing in the single stage LR PVC:

1) reduces the likelihood of a saturation effect;

2) The electrical capacitance is reduced and hence the frequency characteristics for signal transmission circuits are improved;

3) heating losses due to reduced photocurrent are reduced.

An electron beam induced current (EBIC) study was performed to confirm the absence of a counter-acting p–n-junction and to determine the position of the spatial charge bands. EBIC studies were carried out on a Series 4-88 DV100 scanning-electron microscope (CAMSCAN, England) with a „EBIC" amplifier unit. Dependences of intensity on depth are presented in Figure 5. Thus, on the curve *1*, in addition to the peaks inherent to p–n transitions (Pick-1, Pick-2), there is an additional peak (Pick-3) of the

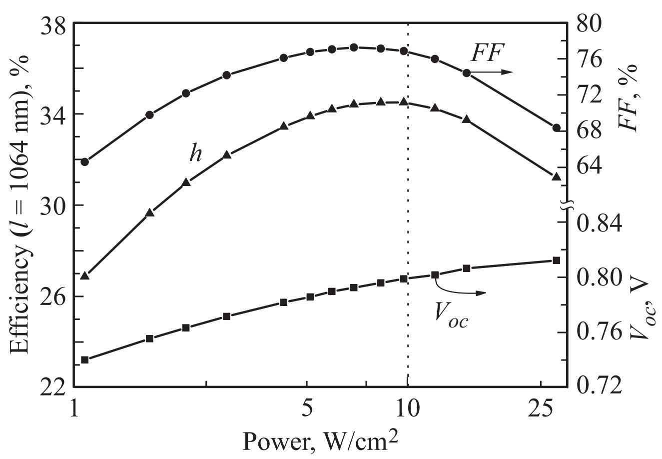

Figure 3. Dependence of the efficiency of V_{oc} and FF-photoconverters operating at a wavelength of 1.06 μm on the power LR.

$p-n$ transition operating in the opposite direction. The Pika-3 features are characteristic of a non-closed connection element. This indicates that the microcrystallites do not short-circuit the junction, and the curve 2 lacks the peak inherent in the $p-n$-transition. In addition, the Pick-1 and

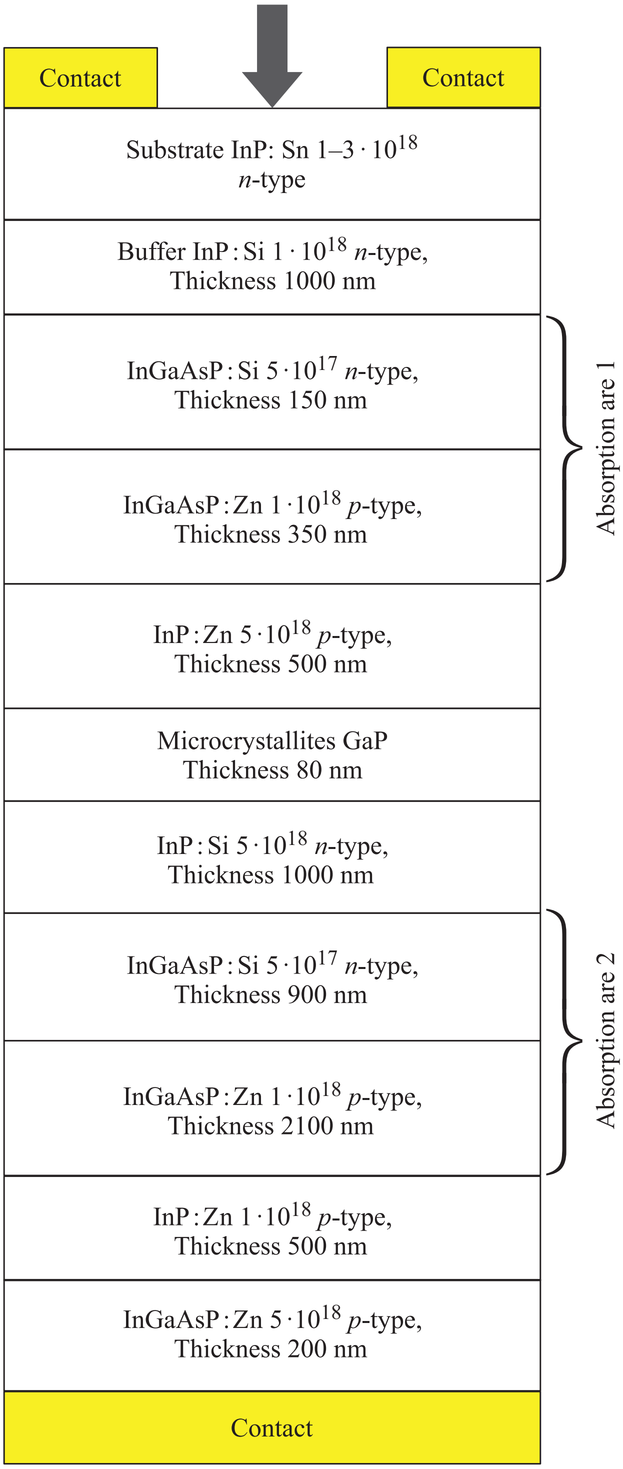

Figure 4. Structure of PVC with two $p-n$-junctions (cascades). The thickness of the absorption band $1-0.5\,\mu$m, the thickness of the absorption band $2-3\,\mu$m. Contact 1 to the n-layer — AuGe/Ni/Au, contact 2 to the p-layer — AgMn/Ni/Au.

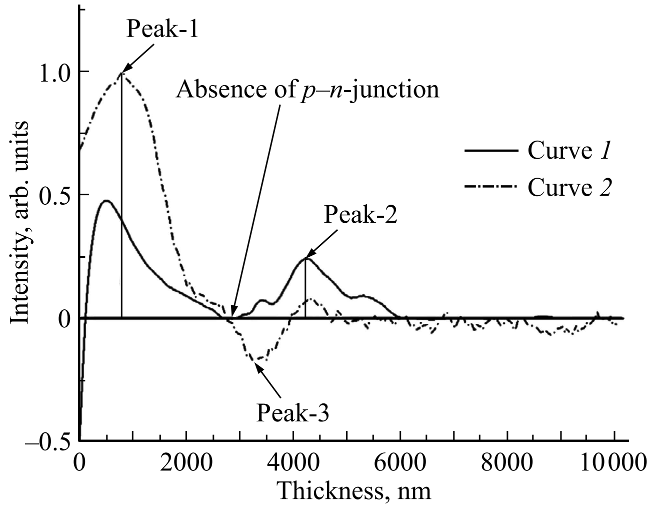

Figure 5. EBIC plots of two-stage PVCs with open (*1*) and closed (*2*) couplers. Structure of PVC with two $p-n$-junctions (cascades).

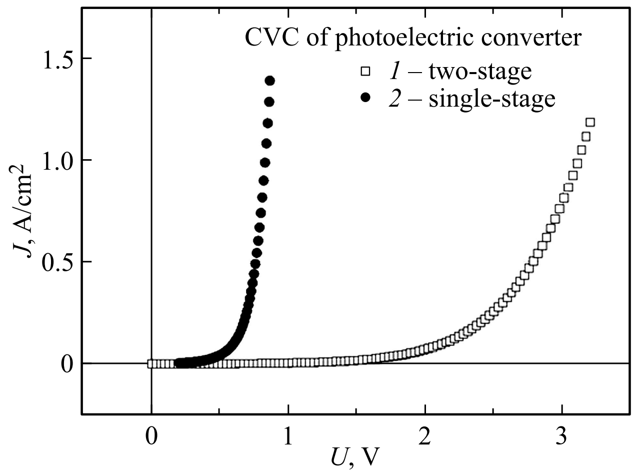

Figure 6. PVC CVC with one (*1*) and two (*2*) $p-n$ transitions (cascades).

Pick-2 are approximately the same, indicating that both stages work.

When comparing the CVC characteristics of single stage LR PVC (Figure 1) and two stage LR PVC (see Figure 4), an increase in the cut-off voltage is observed in the CVC (see Figure 6) of the two stage LR PVC, which indicates the operation of both stages.

As a result of the work done:

1) technology for manufacturing photodetectors of high-power laser radiation at the wavelength $\lambda = 1064$ nm was developed. According to the measurement results, an efficiency of 34.5% was achieved at a luminous power of 10 W/cm^2.

2) LR PVC design with a microcrystallite-based coupler is shown to work, with both stages operating.

Acknowledgments

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Conflict of interest

The authors declare that they have no conflict of interest.

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