Development of the technology of manufacturing connecting elements in cascade photodetectors

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Abstract. In this paper, we report on the initial studies of cascade photodetectors. The heterostructures used in this work are based on InP. InP is the most suitable material for converting the solar spectrum in the range from 0.95 to 1.2 $\mu$m. It is proposed to use nanocrystalline inclusions as a connecting element. For this, nanocrystals GaP are best suitable. Because this material (GaP) does not create an absorption of the incident radiation.

1. Introduction

In recent years, interest in wireless transmission of energy through the laser beam has increased. So experts from Laser Motive and Lockheed Martin (USA) charged the batteries of an unmanned aerial vehicle, which is in flight by laser radiation directed at the photodetector. The residence time in the air has increased by 20 times.

The most promising are photoelectric converters for laser radiation with a wavelength of 1.06 $\mu$m. This radiation is "located" at the local maximum transmittance of the Earth's atmosphere, and lasers have a high power of up to 10 kW [1].

To convert high-power radiation (more than 100 W/cm$^2$), it is preferable to use many cascade photodetectors (analogous to cascade solar cells). Tunnel $p$ $++-n$ $++$ junctions are now used to join FPP cascades. But in a tunnel junction at high powers of the incident radiation, the generated photocurrent can exceed the peak current of the tunnel junctions (peak current is not more than 14 A/cm$^2$). This leads to a sharp increase in the resistance of the entire structure and a decrease in the efficiency of photoconversion [2]. To solve this problem, it has been proposed to create conduction channels by introducing an array of nanocrystalline inclusions into the space charge region (SCR) of the connecting $p$-$n$ junctions [3]. In this case, it becomes possible to substantially reduce the extremely high levels of doping of $p$++ and $n$++ layers in tunnel junctions and the effect of smearing of the tunneling doping profile caused by the diffusion of electrically-active impurities. During the subsequent growth of more wide-gap materials. The $p$-$n$ junction is no longer rectifying and provides current transmission through the conduction channels in the layer of nanocrystalline inclusions. In [3], the properties of tunnel and photovoltaic $p$-$n$ junctions in GaSb were fabricated and investigated. Crystalline inclusions were introduced in the SCR of these $p$-$n$ transitions. Based on the results of this work, a patent of the Russian Federation was obtained [4].

The material of crystalline inclusions for creating conduction channels in the space charge region must satisfy the following conditions:

1. Weak absorption of the radiation being converted.
2. It should not form a continuous layer on the boundary with the photoactive material, but only individual crystals with dimensions larger than the thickness of the space charge region.

For InP, this condition is satisfied by GaP. It has a bandgap width of 2.261 eV greater than that of InP (1.351 eV) and, consequently, has a weak absorption of light in the photosensitivity region InP. The lattice constant of GaP 5.45117 Å (in InP 5.86875 Å), which guarantees the production of crystallites, rather than a continuous layer (the Stranski-Krastanov model).

In the present work, data are presented on the technology of growing junction transitions and the results of studies of the photoelectric parameters of the InP-based structures obtained. These structures are used in solar cells and photodetectors of high-power laser radiation with 1.06 μm.

2. Experimental details

All structures of InP were grown by metalorganic chemical vapor deposition (MOCVD) using an AIX-200 setup operating at a reduced pressure. As the In, Ga and P sources, Trimethylindium(TMIn), Triethylgallium (TEGa) and phosphine(PH3) were used. The growth temperature was 600°C, the reactor pressure was 100 mbar. As the substrates, n- InP(Te) (100) misorientation at 4 degrees in the plane (111) wafers with an electron concentration of (1–5) ×10¹⁸ cm⁻³ were used.

To analyze the GaP - inclusion sizes and shape, technological experiments on GaP crystal growth on an n- InP substrate surface were performed. It became possible to vary the GaP - inclusion size by varying the triethylgallium flow, providing low ohmic loss in the connecting p–n junctions. The following conditions of crystal growth were chosen as optimal for the study: the temperature $T_g$=600°C and time $t_g$= 1 min.

![Figure 1](image1.png)

**Figure 1.** AFM image of GaP nanocrystals grown on the surface of the n-InP substrate – the ratio of PH3/TEGa flows is 300, $t_g$ = 60 seconds

![Figure 2](image2.png)

**Figure 2.** AFM image of GaP nanocrystals grown on the surface of the n-InP substrate – the ratio of PH3/TEGa flows is 300, $t_g$ = 30 seconds

![Figure 3](image3.png)

**Figure 3.** AFM image of GaP nanocrystals grown on the surface of the n-InP substrate – the ratio of PH3/TEGa flows is 590, $t_g$ = 30 seconds
Figure 1–3 shows a micrograph for the GaP crystals in the SCR, obtained using an atomic force microscope. As a result of the analysis of the surface images of the analogous ones shown in the figure, graphs of the dependence of the effect of growth conditions on geometric dimensions (figure 4) and the density of GaP nanocrystals (figure 5) were plotted. Thus, it was found that an increase in the growth time at a constant PH3/TEGa ratio leads to an increase in the average dimensions of GaP nanocrystals (height by an average of 40%, and width by an average of 15%) (figure 4). From the dependencies shown in figure 4-5, it can also be noted that an increase in the PH3/TEGa ratio from 300 to 590 leads to a decrease in geometric dimensions.

The ratio of PH3/TEGa was changed due to a decrease in TEGa in the gas phase, as a result of which less material of the element of the third group entered the growth zone, which is equivalent to a decrease in the growth rate. The density of GaP nanocrystals decreased with increasing growth time, due to an increase in the geometric dimensions of the crystallites. It was also noted that an increase in the PH3/TEGa ratio led to an increase in the density of GaP nanocrystals, for example, figure 1-3.

As noted earlier, preservation of the qualitative characteristics of photoactive transitions grown on top of the layers containing GaP nanocrystals is extremely important. So after determining the growth regimes of GaP nanocrystals, optical characteristics (from the photoluminescence spectra) of epitaxial layers grown over layers containing GaP nanocrystals were studied. For these studies it was grown structure presented in figure 6.

Figure 4. Dependence of the size of nanocrystals on the growth time.  
Figure 5. Dependences of crystal densities on growth time.

For these studies it was grown structure presented in figure 6.

| Layer            | Characteristics |
|------------------|-----------------|
| InP n 1-5·10^{16} cm^{-3} | ~2μm           |
| GaP QD           | ~10-50nm        |
| InP n 1-5·10^{16} cm^{-3} | ~1μm           |
| n InP            |                 |

Figure 6. A sample of the n-n transition with GaP crystallites.
The studies were carried out by photoluminescence at 77 K in the wavelength range 600-1500 nm. Figure 7 shows the photoluminescence spectra of the samples under study. Thus, for InP layers without QDs and with QDs (2 and 3 in the graph in figure 7), the intensities of peaks with an energy of 1.41 eV (interband transitions in InP) differ by less than 20%, which may indicate that the defects arising from the growth epitaxial layers on a layer of GaP nanocrystals, is practically absent.

When the layer of GaP nanocrystals is introduced into the InP layers, which is equivalent, in fact, to the introduction of defects, the quality of the obtained layers does not deteriorate, as evidenced by a change in the photoluminescence half-width by 1 meV laying within the measurement error.

![Figure 7](image-url)

**Figure 7.** The photoluminescence spectrum of the samples under study. 1 - InP substrate spectra, 2 - spectrum of the InP layer grown on the InP substrate, 3 - the QD spectrum grown between two layers of InP.

**Conclusion**

The paper presents the initial stages of work on the creation of new connecting elements for use in monolithic multi-transient solar cells and photoconverters of powerful optical radiation based on InP. GaP nanocrystals were grown as conductivity channels in the IPF, with dimensions 60-85 nm in height and 78-92 nm in width. At the same time, it is shown that the quality of epitaxial, intentionally non-doped InP layers grown on GaP nanocrystals is not deteriorated.

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