New connecting elements for cascade photoelectric converters based on InP

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Abstract. In this paper, we report on the initial studies of connecting elements for cascade photodetectors. The heterostructures used in this work are based on InP. As a connecting element, it is proposed to use nanocrystalline inclusions instead of the tunnel junction. GaP nanocrystals are most suitable for this purpose because this material does not cause absorption of the incident radiation.

1. Introduction

Single-stage p–n or p–i–n structures can be used for conversion of low-power radiation. To increase the converted power of photovoltaic converters (PhVC) (concentrator solar cells), it is preferable to use cascade photodetectors. A p++–n++ tunnel junction is traditionally used as a connecting element of photoelectric converter cascades. However, with a significant increase in the incident power, the generated photocurrent may exceed the peak current of the tunnel junctions, which leads to an increase in the resistance of the structure. As a result, the efficiency of radiation conversion decreases [1].

It was proposed to employ a connecting element by introducing an aggregation of crystalline inclusions into the bulk charge area (BCA) of the p++–n++ connecting junctions between the cascades. In this case, tunnel junctions can be completely excluded and the mechanism of ohmic current flow over conductivity channels in the crystalline inclusion layer in a p–n junction space charge region SCR can be facilitated.

In [3], the properties of tunnel and photovoltaic GaSb p–n junctions with crystalline Si inclusions introduced into their BCA were studied for the first time. An analysis of the dark current–voltage characteristics showed a significant decrease in ohmic losses in such structures.

In this study, a solid solution based on InP was used, as it is suitable for converting the solar spectrum in the range of 0.95 to 1.2 μm. GaP was used for aggregation of nanocrystalline inclusions, because this material does not cause absorption of incident radiation, and because the large difference between the InP and GaP lattice constants (~ 7%) means that an aggregation of nanocrystalline inclusions forms, rather than a continuous layer (Stranski–Krastanov growth).

2. Experimental details

The material for developing conductivity channels in the BCA should satisfy the following conditions: (1) low absorption of optical radiation converted by underlying cascades of a narrower gap; and (2) the crystal material should form only isolated crystals larger than the BCA thickness at the p–n junction...
boundary, rather than a continuous layer. For photoactive InP $p-n$ junctions, GaP satisfies these conditions. It has a wider band gap than indium phosphide, hence, low light absorption in the InP photosensitivity area.

All the InP-based structures were grown by metalorganic chemical vapor deposition (MOCVD) using an AIX-200 setup operating at a reduced pressure. Trimethylindium (TMIn), Triethylgallium (TEGa) and phosphine (PH3) were used as In, Ga and P sources. The growth temperature was 600°C, while the reactor pressure was 100 mbar. $n$-InP(100) (100) wafers misoriented by 4° towards (111) with an electron concentration of $(1–5) \times 10^{18} \text{ cm}^{-3}$ were used as substrates.

Technological experiments on GaP crystal growth on an InP substrate surface were performed in order to analyze the size and shape of GaP inclusions. It became possible to vary the size of GaP inclusions by varying the triethylgallium flow, providing low ohmic losses in the connecting $p-n$ junctions. The following conditions of crystal growth were chosen as optimal for the study: the temperature $T_g=600\degree\text{C}$ and time $t_g=1 \text{ min}$.

Figures 1–3 show micrographs for the GaP crystals in the BCA, obtained using an atomic force microscope. The data presented show that GaP crystals 60–95 nm high and 78–92 nm wide are formed under the chosen growth conditions. Table 1 presents the results of research on GaP nanocrystals shown in figures 1–3.

![Figure 1](image1.png)

**Figure 1.** Photo of GaP nanocrystals grown on the surface of an $n$-InP substrate. Growth parameters: $t_g = 30$ seconds, $V/III = 300$.

![Figure 2](image2.png)

**Figure 2.** Photo of GaP nanocrystals grown on the surface of an $n$-InP substrate. Growth parameters: $t_g = 30$ seconds, $V/III = 590$.

![Figure 3](image3.png)

**Figure 3.** Photo of GaP nanocrystals grown on the surface of an $n$-InP substrate. Growth parameters: $t_g = 45$ seconds, $V/III = 590$. 

Table 1. The results of research on GaP nanocrystals

| Sample No | Number | Average height (nm) | Average width (nm) |
|-----------|--------|---------------------|--------------------|
| 1         | 72     | 60                  | 86                 |
| 2         | 62     | 95                  | 78                 |
| 3         | 69     | 80                  | 92                 |

When growing the multi-junction cells, it is important to retain the qualitative characteristics of the photoactive junctions grown over the layers containing crystalline GaP inclusions. For this study, the structure presented in figure 4 was grown.

![Diagram of n-InP, QD GaP, n-InP](image)

**Figure 4.** A sample of an n-n transition with GaP crystallites.

3. Results and discussion

The study was carried out by sample photoluminescence at 77 K in the wavelength range of 600-1500 nm.

![Photoluminescence spectrum](image)

**Figure 5.** The photoluminescence spectrum ($T = 77$ K) of the samples under study.
Figure 5 shows the photoluminescence spectra of the samples under study. Thus, for InP layers with and without QDs, the intensity of peaks with an energy of 1.41 eV (interband transitions in InP) differs by less than 20%, which may indicate that there are practically no defects arising from growth of epitaxial layers on a layer of GaP nanocrystals.

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

4. Conclusions
In this paper, we report on the initial stages of research on new connecting elements based on nanocrystalline inclusions 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 of 60–80 nm in height and 86–92 nm in width. At the same time, it is shown that the quality of epitaxial, intentionally non-doped InP layers grown on GaP nanocrystals does not deteriorate.

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