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Replacing tunnel junctions in InP with conduction channels with GaP crystallites

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The results of investigations by the method of Electron beam-induced current of *p–n*-junctions based on InP with GaP crystallites in the space charge region are presented. It is shown that the introduction of crystallites into the space charge region leads to short-circuiting of the *p–n*-junction. The quality of the material grown on top of the crystallites allows to create of photoactive regions, as evidenced by measurements of the photoluminescence spectra.

Keywords: crystallites, tunnel junction, connecting element.

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Solar cells of the highest efficiency are currently fabricated based on cascade heterostructures. Three or four photoactive *p–n* junctions, which operate in different spectral ranges, are connected in such devices in series by tunnel junctions with extremely high doping levels [1,2]. If the radiation density is sufficiently high, the generated photocurrent may exceed the peak current of tunnel junctions, thus raising the resistance of the structure as a whole and reducing the device efficiency [3].

The specifics of doping of indium phosphide with *p*-type impurities make it hard to fabricate high-quality tunnel junctions in InP-based devices [4,5]. One possible way to solve these problems is to replace tunnel junctions with conduction channels, which are obtained, e.g., by forming an aggregation of crystalline inclusions in the space charge region (SCR) between neighboring photoactive *p–n* junctions [1]. A linear dependence of the current flow in conduction channels may thus be established. The authors of [6,7] were the first to propose and examine experimentally the inclusion of silicon crystallites into SCRs of GaSb-based *p–n* junctions. This process technology was patented in Russia [8].

In order to produce conduction channels, the material of crystallites in the space charge region should satisfy the following requirements: (1) it needs to provide weak absorption of optical radiation; (2) it has to form individual crystallites instead of a single-crystalline layer at *p–n* junction interfaces.

It is also important to preserve the quality of material of photoactive junctions grown on top of nanocrystallite-containing layers, since lower-quality junctions reduce the efficiency of radiation conversion. The specifics of production of GaP crystallite aggregations on an InP layer were discussed in [9,10].

In the present study, we report the results of EBIC (electron beam-induced current) examination of current–voltage curves (CVCs) and the conductivity of a *p–n* junction based on InP with GaP crystallites introduced into the space charge region. The EBIC technique provides an opportunity to analyze the electric parameters of structures in the bulk without Ohmic contacts. It should be noted that low-resistance contacts to *p*-InP [11] are hard to fabricate, and this circumstance affects the CVC measurements. The quality of InP grown on a layer with crystallites was estimated using the photoluminescence method.

Structures were grown by metalorganic vapor phase epitaxy using an AIX-200 (AIXTRON, Germany) system [9] on *n*-InP(100) substrates. Two types of structures, which are presented in Fig. 1, were fabricated: (1) InP-based *p–n* junction, *n* and *p* layers feature a concentration of $5 \cdot 10^{18}$ cm^{-3} and a thickness of 1 μm (*a*); (2) *p–n* junction based on InP with GaP crystallites introduced into the SCR,

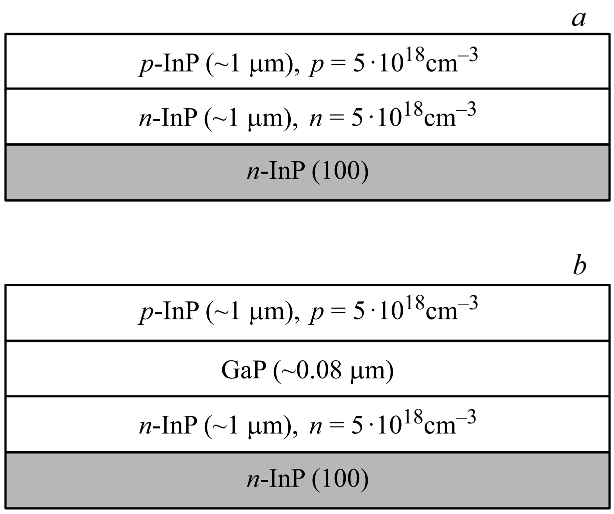

Figure 1. Schematic diagrams of structures grown on *n*-InP substrates. *a* — *p–n* junction, *b* — connecting *p–n* junction with GaP crystallites in the SCR.

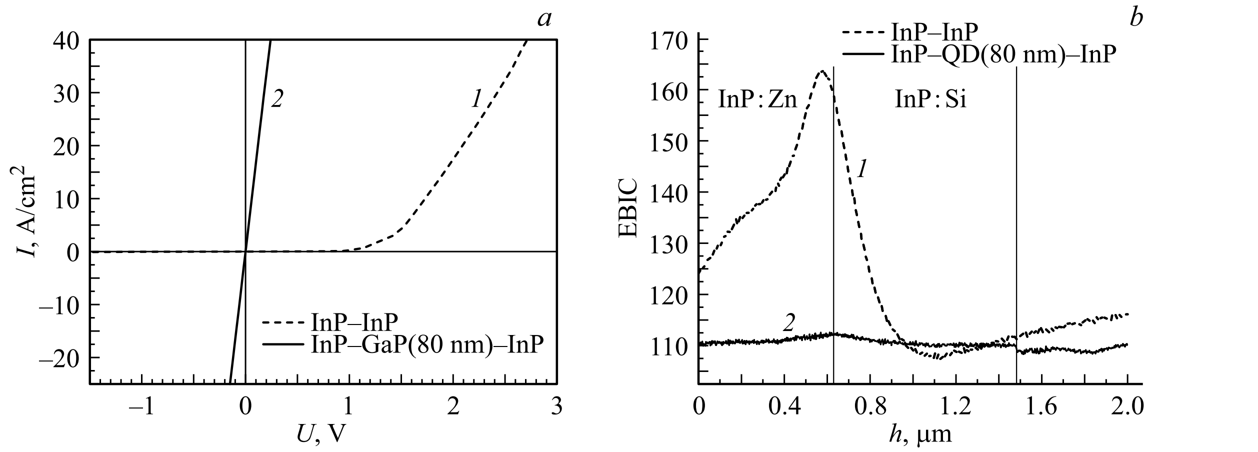

Figure 2. *a* — BAX, *b* — EBIC signal of InP-based structures grown on *n*-type substrates. *1* — *p–n* junction; *2* — *p–n* junction with GaP crystallites in the SCR.

n and *p* layers feature a concentration of $5 \cdot 10^{18}$ cm^{-3} and a thickness of 1 μm, and the thickness of crystallites is 80 nm (*b*).

CVC measurements were performed at room temperature and current densities ranging from 10^{-8} to 40 A/cm^2. The obtained data are presented in Fig. 2, *a* (curve *1* corresponds to the CVC of the *p–n* junction without crystallites in the SCR, while curve *2* represents the CVC of the *p–n* junction with crystallites in the SCR and is linear in nature).

EBIC studies were carried out using a CAMSCAN Series 4-88 DV100 (Great Britain) scanning electron microscope with an „EBIC" amplifier unit (Ioffe Institute, Russia) and an electron energy of 5 keV. Figure 2, *b* shows the EBIC signal of the studied structures: *p–n* junction without crystallites in the SCR (curve *1*) and *p–n* junction with crystallites introduced into the SCR (curve *2*). It can be seen that the introduction of crystallites leads to short-circuiting of the *p–n* junction.

The quality of material of the upper layer of the structure, which was composed of an epitaxial *p*-InP layer 1 μm in thickness with a concentration of $5 \cdot 10^{18}$ cm^{-3} grown on a layer of GaP crystallites 80 nm in size, was estimated using the photoluminescence method in the wavelength range of 600–1500 nm at liquid nitrogen temperature (77 K). An Nd:YAG laser with an operating wavelength of 532 nm and a power up to 130 mW was used to excite luminescence. The excitation power density was $\sim$ 100 W/cm^2, and a PbS photoresistor served as a detector.

Figure 3 presents a comparison between the photoluminescence spectra of the reference sample without an intermediate GaP sublayer (curve *1*) and the studied sample with GaP crystallites 80 nm in height (curve *2*). The spectrum of the reference sample features three bands: 1.41 eV (interband recombination), 1.38 eV (transition involving a shallow acceptor level), and 1.28 eV (band that is often ascribed to intrinsic antisite substitutional defects in InP [12]).

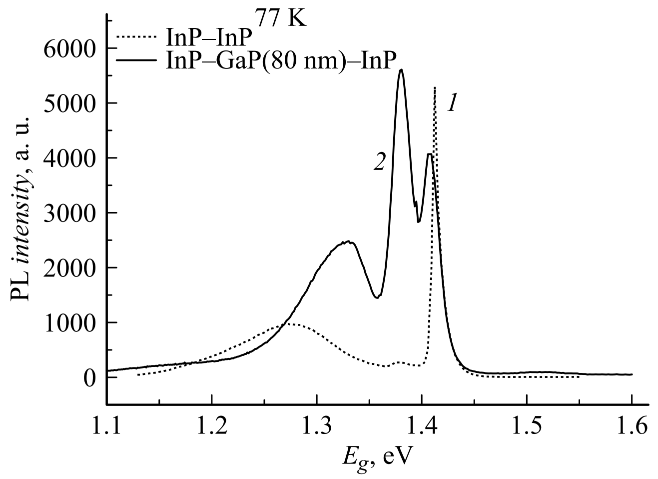

Figure 3. Photoluminescence spectra of the reference *p–n* junction sample without GaP crystallites (*1*) and the sample with GaP crystallites 80 nm in height (*2*).

The photoluminescence spectrum of the material with GaP crystallites is somewhat different. The primary 1.41 eV band is broadened and shifts toward lower energies, and the 1.38 eV band intensity increases. This behavior is indicative of an increase in the concentration of holes in the upper InP layer and agrees with the results of ab initio calculations [13]. Crucially, the photoluminescence intensity does not decrease. This suggests that the introduction of GaP crystallites into the intermediate layer does not result in an emergence of any significant quantity of nonradiative recombination centers (e.g., dislocations). Following the introduction of the GaP crystallite layer, the 1.28 eV band becomes more intense and shifts toward higher energies. An additional band at 1.33 eV also emerges.

Thus, it was demonstrated that the EBIC method allows one to reveal the features of current passage through a *p–n* junction in a structure with GaP crystallites introduced into its SCR. If the size of crystallites exceeds the SCR width, the $p-n$ junction gets short-circuited. This was verified by EBIC data and the results of CVC analysis. The examination of photoluminescence spectra revealed that the quality of the material grown on top of crystallites is sufficiently high to produce photoactive regions.

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Conflict of interest

The authors declare that they have no conflict of interest.

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