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PHYSICS OF SEMICONDUCTOR DEVICES

Photoconverters Based on Gallium Arsenide Diffused *p–n* Junctions Formed on a Microprofile GaAs Surface

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Abstract—The *p–n* junctions promising for photoconverters have been fabricated using diffusion from the gaseous phase and studied with the analysis of mass transport of the doping impurity (Zn) through the microprofile GaAs surface taken into account. Depending on the conditions of diffusion (the diffusant's mass and diffusion duration), the formation of both a *p–n* junction in a microprofile and a planar *p–n* junction in the GaAs bulk with a heavily doped near-surface p^+ type layer is possible. Photoelectric characteristics of device structures with textured *p–n* junction and a thin wide-gap $Al_xGa_{1-x}As$ window obtained by liquid-phase epitaxy are reported.

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1. INTRODUCTION

At present, intensive development of information instrumentation requires fabrication of ultrafast systems for detection and processing of a useful signal. Attention of researchers is directed to the development of a new generation of devices based on nanotechnology that is very promising in the field of fabrication of miniature semiconductor devices designed for various applications and microchips. In this context, it is of interest to study the diffusion processes in semiconductor structures with a textured surface and microprofile interface; these structures could also be used as the base for obtaining the nanodimensional and close-packed structures. It is expected that formation of a textured photodetecting surface, which increases the absorption of optical radiation, should improve the photoelectric characteristics of a semiconductor device. However, studies have shown that good results can be obtained only if optical and electrical properties are made in agreement with each other in relation to the *p–n* junction's depth and the type of the microprofile.

We showed previously [1–3] that the photoconverters fabricated on the basis of AlGaAs–GaAs heterojunctions, in which case the heterojunction was formed on the textured GaAs growth surface, feature the efficiency (with respect to power) that appreciably exceeds the efficiency of photoconverters formed on the basis of conventional planar heterojunctions. However, it was found that fabrication of heterojunctions on textured substrates presents a complex physicotechnological problem. Therefore, it seems appropriate to search for active elements (alternative to heterojunctions) for photoconverters with retention of microprofile heteroboundaries in these photoconverters and the corresponding advantages of photoconversion. A diffused *p–n* junction represents the simplest and most accessible experimentally analogue of heterojunction structures with a potential barrier.

In this study, we attempted to realize such a GaAs *p–n* junction on the microprofile GaAs surface and fabricate a prototype of the photoconverter on its basis with the front wide-gap window. To this end, we analyzed the features of the mass transport of doping impurity through the textured GaAs surface; diffusion of Zn from the gaseous phase in the vicinity of the microprofile GaAs surface was used to form a *p–n* junction.

It is worth noting that, since the faces differing from the surface orientation are also revealed as a result of texturing the structures' surface, the diffusion processes in the samples with a textured surface should differ from those taking place in traditional planar structures. In order to study this phenomenon, we prepared graphite boats that made it possible to realize the impurity diffusion in the unified process simultaneously for the structures with the flat and microprofile surfaces. The boat made it possible to open or shut the channel connecting the source of the diffusant at any point in time; i.e., it was possible to realize the process of diffusion in two different conditions: the first variant corresponds to the situation where the diffusant's source and the sample are found to be in a connecting mode both under conditions of increasing the temperature and in the course of diffusion (the so-called integrated diffusion) and the second variant corresponds to the situation where the source comes in contact with the diffusant only after the diffusion temperature is attained (the selective diffusion). Thus, selective diffusion is conducted at a given temperature, while integrated diffusion is performed in the course of heating and within a chosen temperature range.

We fabricated and studied a photoconverter prototype based on the formed *p–n* junction. For the sake of comparison, we fabricated similar diffused *p–n* junctions on the flat surface and also on the textured surface (but with a *p–n* junction in the GaAs bulk rather than in the microprofile region). In what follows, we report some results of studying such photoconverters.

2. SIMULATION OF THE DIFFUSION PROCESS

Simulation of the diffusion of atoms (for example, Zn) into a semiconductor (for example, gallium arsenide) was performed in the conditions of nonplanar interfaces that were represented by a specially developed microprofile whose simulated fragment is shown in Fig. 1. It is insufficient to solve the Fick diffusion equation in the one-dimensional case to describe diffusion of Zn in this situation. It is necessary to assume that, prior to diffusion into GaAs, the Zn concentration in GaAs equals zero, the semiconductor borders with the diffusion source along a sawlike surface, and the flux of Zn atoms is zero at boundaries *1–3* (Fig. 1); i.e., the region under consideration is a part of an infinitely extended sample. In accordance with the model of diffusion through the microprofile's surface [2], we numerically calculated the Zn distribution in GaAs. It was found out that the profile of the zinc distribution reproduces the surface profile only at comparatively short diffusion times that naturally depend on the diffusion coefficient and temperature.

In Fig. 1, we show the time dependence of the diffusion process developing at the microprofile's surface at the initial stage of diffusion $t/\tau = 0.002$ (here, the duration of diffusion is expressed in relative units, i.e., the absolute time t is normalized to the characteristic time τ) (Fig. 1a); this stage is more extended in time if $t/\tau = 0.03$ (Fig. 1b). The scaling coefficient is the same along all coordinate axes: $l = 10$ μm. It can be seen that, as the duration of relative diffusion is increased by approximately an order of magnitude, the profile of Zn in GaAs equalizes and practically corresponds to the "flat" case. These modeling concepts were qualitatively verified in the experiment with the formation of a *p–n* junction using the Zn diffusion from the gaseous phase into the microprofile GaAs surface.[1]

[1] The experiment was carried out at the Physicotechnical Institute of the Research and Production Association "Physics-Sun", Academy of Sciences of Uzbekistan.

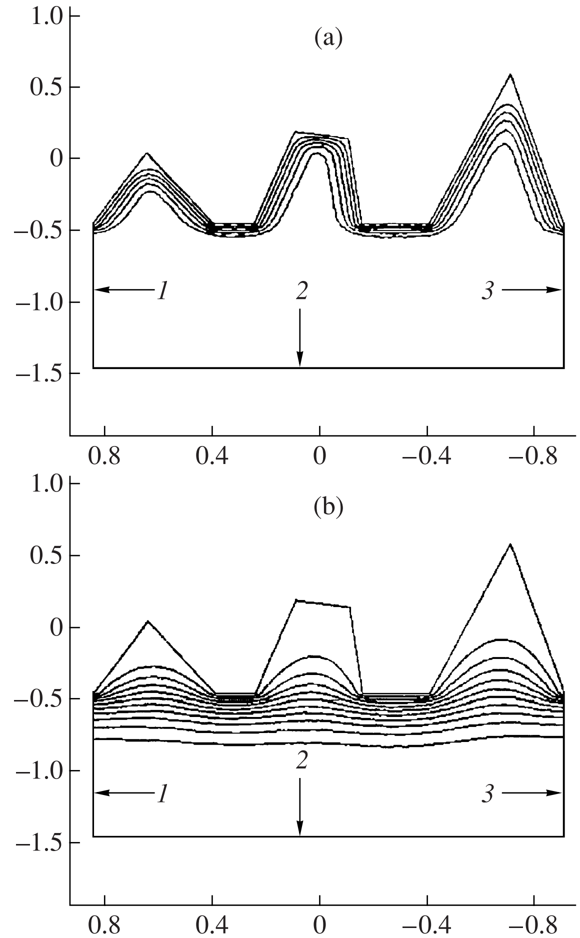

Fig. 1. Dependence of the constant-level lines for a metal on time in a semiconductor at a constant metal concentration at the semiconductor boundary during the diffusion process. The time interval between curves in each series is the same, the total diffusion time t/τ = (a) 0.002 and (b) 0.03. The scales are conditional; the scale $l = 10$ μm.

In Fig. 2, we show the microphotographs of cleaved surfaces with a chemically revealed *p–n* junction in GaAs; the junction was formed near the microprofile GaAs surface during the initial stage of diffusion in the case when (a) the surface profile is replicated and (b) the *p–n* junction is practically planar after prolonged diffusion through such a microprofile GaAs surface. Technological features of the fabrication of such *p–n* junctions were described by Karimov and Yodgorova [3].

Studies of the load characteristics of photoconverters that include the front wide-gap window and are formed on the above described structures showed that the photoconverters formed on the structures with a *p–n* junction in the microprofile feature more efficient photoconversion (Fig. 2a). The coefficient of filling of the current–voltage characteristic is no smaller than 0.7 in the best samples of such photoconverters.

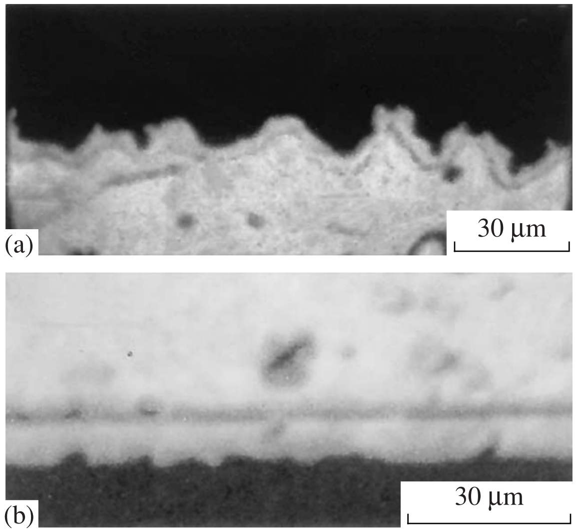

Fig. 2. Microphotographs of the boundary of *p–n* junctions formed on GaAs with microprofile surface as a result of (a) short-term and (b) long-term diffusion of Zn.

3. EXPERIMENTAL

Selective diffusion was carried out in a quasi-closed graphite holder in which there was a shutter between the Zn source and samples. As the specified diffusion temperature (800°C) was attained, the shutter was opened and the substrate was kept at this temperature for 60, 50, or 40 min; after that, the shutter was closed. The diffusion process was performed in the hydrogen flow in the reaction chamber of a setup for liquid epitaxy.

Integrated diffusion was carried out in the same graphite holder with the shutter open. To this end, the holder with the samples and zinc was placed in the reaction chamber and was heated according to the epitaxy mode to 800°C and was then kept at this temperature for 60, 50, 40, or 30 min; finally, the holder was cooled according to the epitaxy mode. In all experiments, the amount of zinc was the same (146 mg). The results of diffusion concerning the formed *p–n* junctions are listed in Table 1.

In these experiments, we carried out diffusion directly into the substrates with a planar and microprofile (quasi-lattice, dendrite, bilattice) surface of *n*-GaAs (the electron concentration 10^{18} cm^{-3}). The *p–n* junctions were revealed in the obtained structures after diffusion (Table 1). It is worth noting that the *p–n* junction obtained by zinc diffusion from the gaseous phase through the microprofile surface replicates the surface profile.

Table 1. Depth of the *p–n* junction in the case of Zn diffusion into GaAs substrates

Diffusion conditions	d, μm		
	planar	a quasi-lattice microprofile	a dendritic microprofile
Integrated	3–5	4	4
Selective	1–1.5	1–1.5	–

Note: Diffusant's mass m_{Zn} = 146 mg, the diffusion duration 60 min, and the temperature of diffusion 800°C.

The depth of the *p–n* junction d as a function of the duration t of zinc diffusion obeys the law $d \propto \sqrt{t}$. Comparison of selective and integrated diffusion indicates that, in the case of integrated diffusion, the diffusion rate is higher, while depths of the *p–n* junction in microprofile structures are comparable. Integrated diffusion is found to be more controllable in the case of zinc diffusion into textured surfaces.

Diffusion proceeds over "weak" sites of the structures (defects) and depends on the uniformity of distribution of their initial concentration over the area, the dislocation density, resistivity, uncontrolled impurities, conditions of the process, and so on. Consequently, the data obtained for a specific type of structures could not be directly extended to other samples. In relation to the choice of the microprofile type (quasi-lattices, dendrites, and so on), each specific structure requires an individual approach. Here, the effect depends on the depth, density of pits, texture, and so on.

It is established that, in spite of unified technology of the diffusion process, it is necessary to select optimal conditions for each type of the structure. The diffusion depth for zinc is found to be different for different types of structures in the case of identical conditions.

As a result, we obtained the open-circuit voltage in the range from 0.2 to 0.6 V at the illumination intensity of 5×10^4 lx for the photoconverter samples that had a planar surface and were formed by integrated (selective) diffusion; the short-circuit currents were 0.5–2.0 mA. The open-circuit voltage was 0.4–0.5 V and the short-circuit current was ~2.5 mA in the case of quasi-lattice samples.

In the second stage, zinc was diffused using epitaxial buffer layers (Table 2, Fig. 3). Microprofiles were first formed on the surface of buffer layers and then zinc diffusion was carried out. In this stage, we also expected replication of the microprofile after diffusion at the boundary of the diffused *p–n* junction. The aim consisted in determination of diffusion parameters for zinc: the zinc dose and the duration of diffusion to attain the specified depth of the *p–n* junction. To this end, buffer *n*-GaAs layers with an electron concentration 10^{17} cm^{-3} were grown (after cutting to discrete parts with the area of 1 cm^2) on *n*-GaAs ($n = 10^{18}$ cm^{-3}) substrates of the AGChT brand with (100) orientation, thickness of ~400 μm, and the diameter of 36 mm. The temperature corresponding to the onset of the buffer-layer's growth was T = 825–827°C; this temperature decreased by ΔT = 7–8°C in the course of growth. In this case, the buffer-layer's thickness was 10–12 μm. Anisotropic etching in nitric acid of one of the grown buffer layers was carried out for 20–30 s at a temperature of 30°C. Both structures (with planar and dendrite surfaces) were then placed in the chamber for diffusion. Diffusion was carried out at 800°C; as a result, we obtained a structure with a homojunction (diffused p-GaAs layer, 10^{19} cm^{-3})–(n-GaAs buffer layer, 10^{17} cm^{-3})–(n-GaAs substrate, 10^{18} cm^{-3}).

On the assumption of the dissociative mechanism of zinc diffusion, we carried out diffusion at various doses m_{Zn} of the diffusant and at corresponding durations t of the process (Table 2, Fig. 3).

Boundaries of the p–n junctions were revealed for each structure (Fig. 3). It was found out that, in the case of a dendrite surface and at large zinc doses (520 mg) and long diffusion times (15 min), a straight line (in cross section) can be seen at a depth of 2 μm; the dendrite's profile is replicated below at a distance of 3–4 μm. If the diffusion duration is increased to 90 min at the zinc dose of 100 mg, a replication of the dendrite profile is observed at a depth of 2–3 μm; a comparatively straight line is observed at a larger depth, at a distance 3–4 μm from the microprofile line. In both cases, we have two boundaries of zinc diffusion. At intermediate doses (180–310 mg) and within the diffusion-time range 30–60 min, a single line is observed; in particular, a replication of the dendrite profile can be seen at a depth of ~3 μm. On the basis of these data, we may conclude that the optimal dose of zinc in the case under consideration is in the range of 150–300 mg at the diffusion times of 20–70 min. The diffusion front replicating the textured surface depends on the amount of diffusant; i.e., at certain doses (in the case under consideration, 100–200 mg) this front remains intact. At larger doses, diffusion obeys a different law until some depth and the impurity concentration is attained; the diffusion then obeys the dissociative mechanism. A p^+–p junction is formed in rare cases (samples 28 and 31).

Table 2. Parameters of the Zn diffusion into the structures with a buffer layer

Sample no.	t, min	m_{Zn}, mg
28	90	100
29	60	180
30	30	310
31	15	520

Note: The diffusion temperature was 800°C.

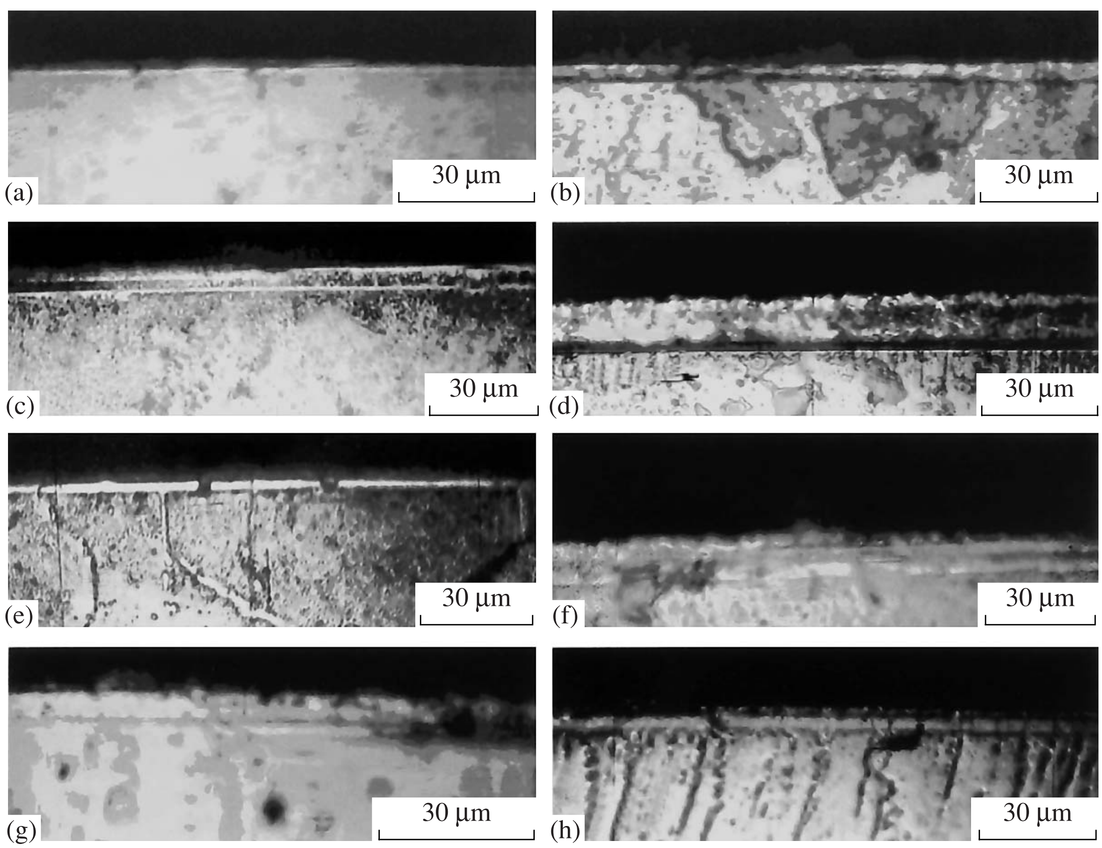

Fig. 3. Microphotographs of the boundary of p–n junctions formed by Zn diffusion into GaAs structures with the buffer epitaxial layer. The sample nos. are (a, b) 28, (c, d) 29, (e, f) 30, and (g, h) 31. The photographs *a*, *c*, *e*, and *g* correspond to the planar diffusion surface, while photographs *b*, *d*, *f*, and *h* correspond to the microprofile (dendritic) surface.

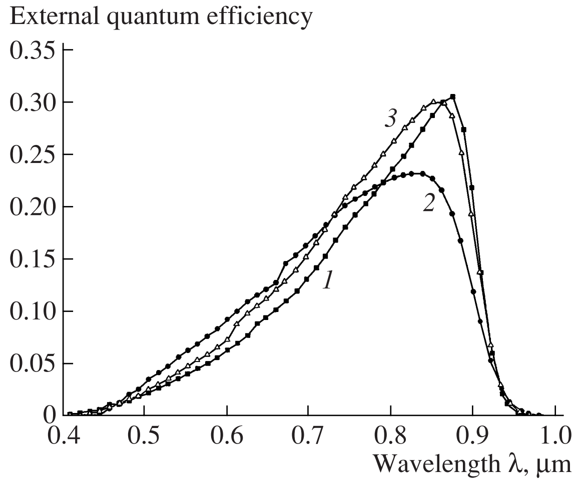

Fig. 4. Spectra of external quantum efficiency for diffused p–n GaAs structures: (*1*) the planar surface, (*2*) the surface with a microprofile of the quasi-lattice type, and (*3*) the surface with the buffer epitaxial layer.

It was found out that, in buffer epitaxial layers, one can also retain the microprofiles (specified on the surface) in the form of buried diffused p–n junctions. Varying the conditions of the diffusion process, one can control the depth of the p–n junction.

Studies of the load characteristics of obtained structures showed that the filling coefficient in excess of 0.6–0.7 is obtained in the samples in which the charge-carrier's concentration in the buffer layer is in the region $\lesssim 10^{17}$ cm^{-3}. The depth of the p–n junction should be ~2 μm according to the results of calculations. However, this depth equals 3 μm at a temperature of 800°C and the time of zinc diffusion 60 min in the experiment with microprofile structures. In this case, the boundary of the diffused junction replicates the microprofile of the buffer-layer's surface. An increase in the charge-carrier concentration higher than 10^{17} cm^{-3} brings about a decrease in the filling coefficient for the current–voltage characteristic under illumination. As for the open-circuit voltage, its value can be as large as 0.7 V in the case of microprofile structures under illumination with the intensity of 19 200 lx. In general, for two types of structures, the opposite character of behavior is observed: an improvement of parameters takes place for planar structures, whereas certain degradation of parameters for microprofile structures is observed, and vice versa.

The spectra of the short-circuit photocurrent of obtained structures (this photocurrent is represented as the external quantum efficiency) are shown in Fig. 4. These spectra are represented by a comparatively narrow band, which is indicative of a large thickness of a diffused p-type layer compared with the diffusion length of minority charge carriers in this layer. As a result, this leads to moderate values of short-circuit photocurrent and, correspondingly, to low quantum

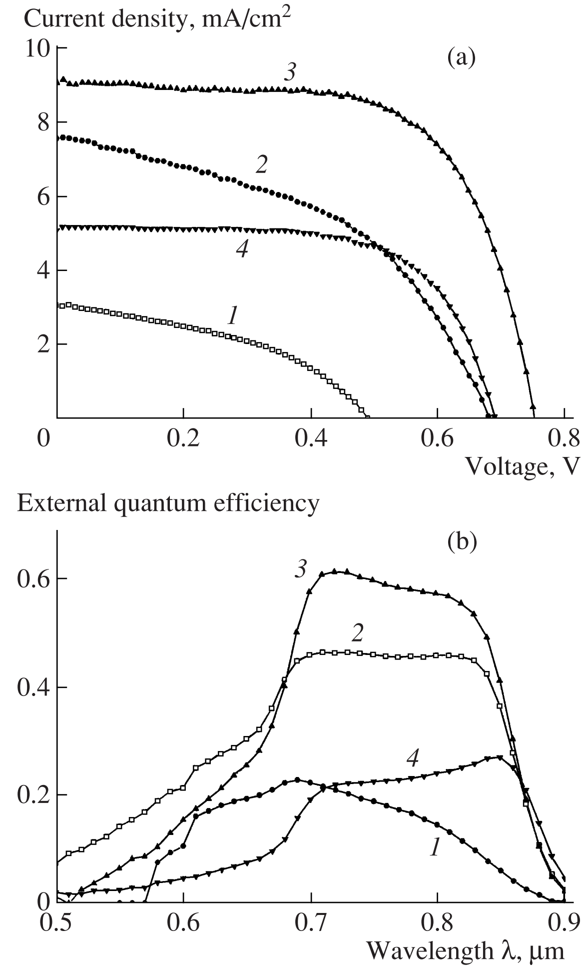

Fig. 5. (a) Current–voltage characteristics and (b) the spectra of external quantum efficiency of the p^+-$Al_xGa_{1-x}As$/p-GaAs/n-GaAs/n^+-GaAs structures. Curves *1* correspond to sample 23 with the planar surface, curves *2* correspond to sample 23 with dendritic microprofile, curves 3 correspond to sample 25 with the planar surface, and curves *4* correspond to sample 25 with the microprofile of the dendrite type.

efficiencies of these structures. It can be seen that introduction of a buffer layer into the structure and, especially, the microprofile of the surface and interfaces contribute to expanding the spectral range of photocurrent.

An additional increase in the short-circuit photocurrent in the short-wavelength region of the spectrum can be obtained by reducing the surface-recombination velocity with the use of an epitaxial $Al_xGa_{1-x}As$ layer that acts as a wide-gap window. In this case, the thickness of the $Al_xGa_{1-x}As$ epitaxial layer should be also <1 μm thick in order to retain the advantages of optical characteristics of the microprofile surface, in which the profile depth does not exceed 1–3 μm (depending on the morphological parameters of the microprofile). In Fig. 5, we show photoelectric characteristics of these structures obtained in a single cycle of formation of a diffused GaAs p–n junction and growth of an $Al_xGa_{1-x}As$

layer on top of this junction by the method of liquid-phase epitaxy. It can be seen that both the value and spectral region of the highest quantum efficiency for heteroepitaxial structures are larger than in the case of diffused structures (Fig. 4). Apparently, this is related not only to a decrease in the velocity of surface recombination at the heteroboundary but also to a decrease in the thickness of the diffusion *p*-GaAs layer in the course of heteroepitaxy. In addition, retention of the microprofile of the front surface and interfaces affects the spectral dependence of the photocurrent (Fig. 5b) and results in a relative increase in this current in the long-wavelength region of the spectrum in the case of the microprofile of the dendritic type. In order to broaden further the spectral region of photoconductivity and increase the quantum efficiency of the structures, it is necessary to optimize the conditions of diffusion and epitaxy as applied to the chosen type of the microprofile.

4. CONCLUSIONS

According to the modeling calculation, the profile of *p–n* junction replicates the surface profile only at comparatively short diffusion times in the case of formation of a *p–n* junction in a semiconductor (*n*-GaAs) by diffusion of a doping impurity (Zn) from a gaseous phase. An experimental study of the dependence of the *p–n*-junction profile in the structures with textured *n*-GaAs surface on conditions of Zn diffusion (integrated or selective modes, diffusant's mass, and the diffusion duration) showed that, depending on the relation between the diffusant's mass and diffusion duration, we can observe either the formation of two interfaces (one of which is planar and the other replicates the surface profile) or formation of the single profile boundary of the *p–n* junction. A study of photoelectric characteristics of the structures with such *p–n* GaAs junction (including structures with a wide-gap window made of epitaxial $Al_xGa_{1-x}As$) showed that the optimal conditions of diffusion in the case of textured surface should be additionally corrected in accordance with the chosen morphology of the microprofile.

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