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Metamorphic InGaAs photodiode with wavelength 1.55 μm, grown on GaAs substrate

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The article presents the results of investigation of photodiodes for 1.55 μm wavelength, grown on GaAs substrates. InGaAs photodiode structures with InAlGaAs metamorphic buffer layer with quasi-root change of In concentration were grown by Metal Organic Chemical Vapor Deposition (MOCVD) has been developed. Photodiodes created based on the obtained structures had photosensitivity region up to 1.68 μm. The dark current density at reverse bias of -2 V was $3 \cdot 10^{-3}$ A/cm^2. The photosensitivity at wavelength of 1.55 μm was 0.6 A/W.

Keywords: MOCVD, nanomaterials, $A^{III}B^{V}$ semiconductors, infrared photodiodes, dark current.

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1. Introduction

Photodiodes operating at a wavelength of 1.55 μm are widely used in fiber-optic communication lines (FOCL). To create detectors for this range, $p-i-n$-structures based on solid solution $In_xGa_{1-x}As$ with a high content of In grown on InP substrates are currently most common. However, due to their mechanical properties, InP substrates are less amenable to post-growth technology than gallium arsenide. InP substrates have a smaller diameter, which reduces the number of chips produced per wafer in the process. In addition, InP substrates are expensive. Thus, the replacement of indium phosphide substrates by GaAs for photodiodes at wavelengths ~ 1.55 μm is highly relevant.

Currently, a common approach for creating mismatched $A^{III}B^{V}$ structures is the use of metamorphic buffer layers (MBL) for smooth [1] or stepwise [2,3] changes in the lattice parameter. It is known that the implementation of metamorphic structures on gallium arsenide, transport and structural characteristics of which would not be inferior to the characteristics of InP-structures, is difficult due to the appearance of surface microrelief and incomplete suppression of dislocations growing into the active layers of the structure [4]. The authors of the paper [5] demonstrated $In_xGa_{1-x}As$ metamorphic photodiode at wavelengths of $1.17-1.29$ μm, the density of dislocations in the near-surface layer of which was 10^6 cm^{-2}. To achieve longer wavelengths, a significant increase in the In concentration in the solid solution $In_xGa_{1-x}As$ is required, which will lead to an increase in the mismatch with the substrate and an increase in the dislocation density in the photosensitive region.

In the present study, the method of forming MBLs with quasi-root In concentration profile on GaAs substrate by MOS hydride epitaxy (MOGPE) to create photodiodes at wavelength 1.55 μm is discussed.

2. Sample preparation and experiment procedure

The investigated photodiode heterostructures were prepared by MOS-hydride epitaxy at reduced pressure (100 mbar) on an AIX 200RF unit. The precursors for group III and V group elements were trimethyl gallium, trimethylindium, trimethylaluminum, and arsine. Hydrogen was used as the carrier gas. Silane and diethylzinc were used for doping the *n*- and *p*-type layers, respectively. The temperature and growth rate of all layers of the photodiode structure were 570 °C and 0.5 nm/s, respectively. For the photodiode structure, the V/III ratio was 100. The general diagram of the photodiode structure is shown in Figure 1. On the GaAs (001) substrate deflected by 2° from the precise orientation in the [110] direction, silicon-doped layers were grown up to a concentration of $n^+ = (1 \div 5) \cdot 10^{18}$ cm^{-3}: buffer layer n^+-GaAs : Si with a thickness of 200 nm, n^+-$In_{0.07}Al_{0.08}Ga_{0.85}As$: Si layer of constant composition with a thickness of 100 nm, MBL n^+-InAlGaAs : Si with a thickness of 1500 nm with the concentration of x (In) changing from 0.07 to 0.56 and an inverse layer n^+-$In_{0.53}Al_{0.08}Ga_{0.39}As$: Si with a thickness of 100 nm. The inverse layer is necessary to reduce mechanical stresses in the epitaxial layers of the structure. It is known that the top of MBL grows in a pseudomorphic [6] manner, which means that the crystal lattice on its surface experiences compressive stress. Therefore, to reduce the degree of mechanical stress on MBL, an inverse transition was formed, i. e., a layer with a lower In content, and thus a lower lattice period, which coincided with the period of the compressed lattice on the surface of MBL, was grown. Subsequent layers were grown with the same In content as in the inverse layer. Next, an

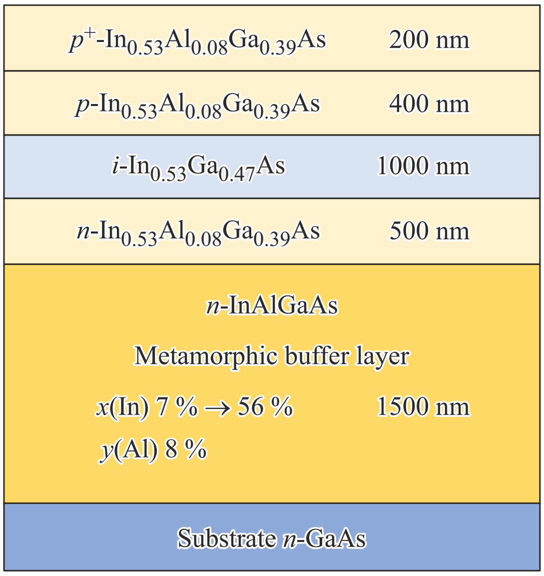

Figure 1. Schematic diagram of the photodiode structure. (A color version of the figure is provided in the online version of the paper).

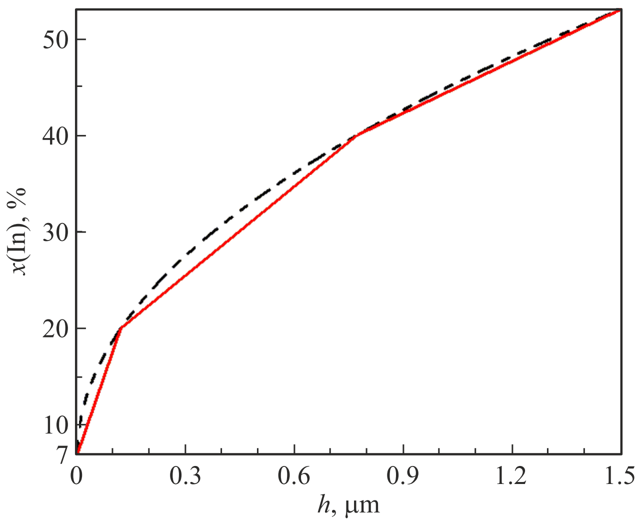

Figure 2. The calculated profile of the In content in MBL — solid line, the approximated function — dashed line.

$p-i-n$-structure was formed with the dopant concentration in p- and n-areas at the $(2-4)\cdot 10^{17}\,cm^{-3}$level, consisting of layers n-$In_{0.53}Al_{0.08}Ga_{0.39}As$:Si with a thickness of 400 nm, i-$In_{0.53}Ga_{0.47}As$ with a thickness of 1000 nm, p-$In_{0.53}Al_{0.08}Ga_{0.39}As$:Zn with a thickness of 400 nm. At the final stage, an p^+-$In_{0.53}Al_{0.08}Ga_{0.39}As$:Zn contact layer with an impurity concentration of $p^+ = (1-5)\cdot 10^{18}\,cm^{-3}$ and a thickness of 200 nm was formed. The thickness of the layers was calculated from the time and growth rate, which were obtained from the study of pre-grown test layers with the same composition. The composition of the test layers was determined by X-ray diffractometry and photoluminescence spectroscopy. Hall effect measurements were used to confirm and evaluate the doping level of the test layers.

The MBL formation process consisted of a gradual increase in the In content according to a quasi-correlated law from 7 to 56%. The calculated distribution of the In concentration in the MBL is represented in Figure 2 by the red line, and the approximated function is depicted by the black dashed line.

MBL provides a transition from the lattice period of GaAs (5.6533 A) to the lattice period of $In_{0.53}Ga_{0.47}As$ (5.8687 A), and the gradual decrease of the In concentration gradient reduces the dislocation density near the growth surface and improves the quality of epitaxial layers (EL) [6–8].

Unlike In, the concentration of Al remained unchanged for all layers where it was present and was $\sim 8\%$. The effects of Al addition to the metamorphic layer, growth temperature, and the use of deflected and undeflected substrates were investigated on test structures that represented the metamorphic layer grown on the substrate.

3. Results and discussion

The structures containing InGaAs-based MBL exhibited a developed surface morphology, with (RMS deviation of surface height) RMS of 40.9 nm, therefore, 8% Al was added to the composition of the metamorphic layer to reduce the surface roughness. The effect of RMS reduction was demonstrated on test samples with similar parameters, differing only by the presence of Al in the composition of the metamorphic layer. To investigate the effect of adding Al to the composition of the metamorphic layer on the RMS of the surface, test structures representing metamorphic layers with a thickness of 1.8 μm on GaAs substrates deviated from the exact orientation in the [110] direction by 2° were grown. In one case the metamorphic layer was based on a ternary InGaAs solution, and in the other — quaternary InAlGaAs. The growth temperature of the test structures was 600 °C, and the rate was in the range of 0.7–0.8 nm/s. By adding Al, it was possible to reduce the RMS from 40.9 to 14.4 nm. The surface morphology was investigated by Atomic Force Microscopy (AFM).

To identify optimal growth modes, surface roughness studies of structures obtained at different temperatures on deflected and non-deflected substrates were performed. To do this, a series of single-type test structures containing InAlGaAs-based MBLs were grown on two types of substrates and at different temperatures. Precisely oriented GaAs (001) substrates and GaAs (001) substrates deviated by 2° from the exact orientation in the direction [110] were used in the experiment. The growth temperatures were 460, 570 and 770 °C. The use of different growth temperatures made it necessary to adjust the organometallic fluxes. The growth parameters were selected using distribution coefficients [9], which relate the ratios of group III group elements in the solid phase to the ratio of the fluxes of the corresponding organometallic compounds in the gas phase.

The samples grown at 460 °C, had the lowest surface roughness among all structures (14.7 and 5.3 nm for the precisely oriented and deflected substrates, respectively), but the low temperature did not allow for sufficient silicon doping of the structure because the monosilane [9], which was used as the precursor of the *n*-type dopant, does not decompose effectively at this temperature. Therefore, in our case, applying low temperatures is not suitable to form photosensitive structures, because the necessary doping level sufficient to form a high-quality *p*–*n*-type transition is not achieved. At a temperature of 770 °C structures had the most developed surface topography. The RMS values exceeded 100 nm for the two types of substrates, and the height differences were > 700 nm in some regions of the structure. Such developed surface topography indicates the low crystalline quality of the material. The samples grown at 570 °C, showed different results on deflected and undeflected substrates. The structure formed on the precisely oriented substrate exhibited a surface covered with islands, with an RMS of 13.7 nm. The presence of islands may indicate that mechanical stress relaxation in MBL was not due to the formation of mismatch dislocations, but to the formation of islands. The sample grown on the deflected substrate showed a grid of dislocations intersecting at an angle of 90°, and the RMS decreased to 7.4 nm. The presence of a pronounced dislocation grid on the AFM image and relatively low RMS value together with a low density of defects in the surface layer (10^6 cm^{-2}) may indicate a good crystalline quality of the obtained structure, which is apparently achieved by relaxation of mechanical stresses through the formation of mismatch dislocations, the vast majority of which remain in the lateral plane and do not penetrate into the working region of the structure. In this case, mismatch dislocations appear on the surface in the form of intersecting lines at an angle 90° and create a microrelief of the surface (Figure 3) [10].

Based on the conducted experiments, a growth temperature of 570 °C and a GaAs (001) substrate with the surface deflected by 2° from orientation in the direction [110] were chosen to form the photosensitive structure.

The density of dislocations in the surface layer was determined by selective etching and AFM methods, which amounted to 10^6 cm^{-2}. This value exceeds the dislocation density of the substrates used in the experiment by only 2 orders, which, according to the literature [5], is a good result for structures with MBL.

Based on the obtained structure, photodiodes were made and their characteristics were investigated. Ohmic contacts were deposited on the sides of the structure and the substrate by thermal evaporation in vacuum. A Ti/Pd/Au film was sputtered on the structure side, and an AuGe film was sputtered on the substrate side. Then a mesastructure with a diameter of 1.4 mm and a depth of 1 μm was etched. To reduce the influence of surface dark currents, the surface of the samples was cleaned and passivated by plasma chemical etching in oxygen plasma followed by thermal oxidation at 250 °C.

Figure 4 shows a typical volt-ampere characteristic of the obtained photodiodes. The dark current at reverse offset −2 V was $4 \cdot 10^{-5}$ A, which corresponds to a current density of $3 \cdot 10^{-3}$ A/cm^2.

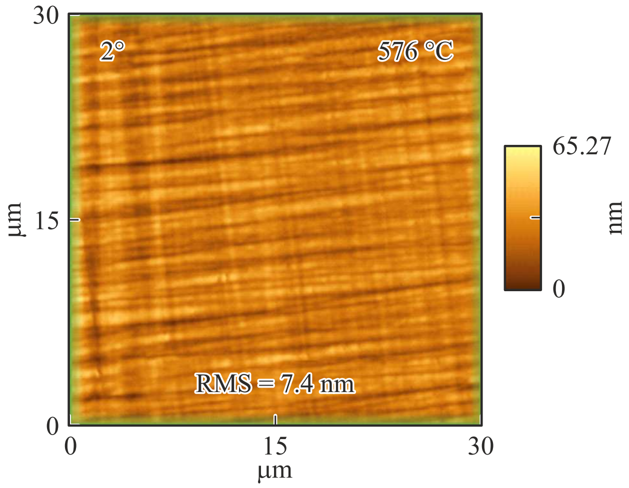

Figure 3. A topogram of the surface of a structure obtained at a growth temperature of 570 °C on a GaAs (001) substrate with a deviation at 2°.

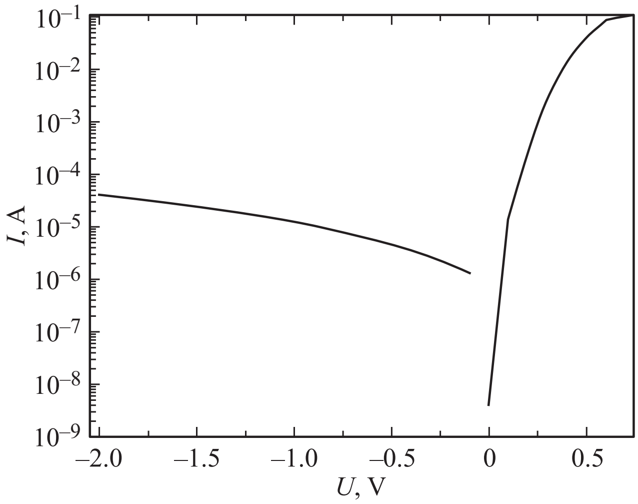

Figure 4. A typical volt-ampere characteristic of the photodiodes at room temperature.

The spectral dependence of the photocurrent of the produced photodiodes measured at room temperature has a photosensitivity region up to 1.68 μm at a level of 50% of the maximum. The wavelength of 1.55 μm is located at 83% of the intensity maximum.

The dependence of the current photosensitivity at the wavelength of 1.55 μm on the incident radiation power [11] was obtained. To do so, the photodiode obtained in this paper and SiO_2/SiON/SiO_2 waveguide have been coupled. The optical loss in the waveguide was 3 dB/cm. The waveguide, in turn, was coupled to an optical fiber, which was fed with radiation from a semiconductor laser with a wavelength of 1.55 μm. The layout diagram of coupling is shown in Figure 5. The results of studying

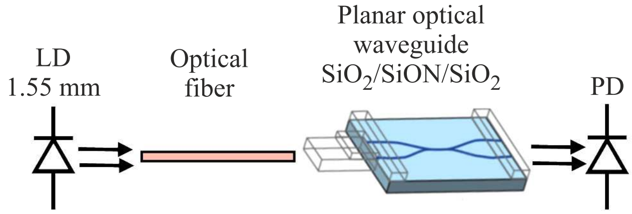

Figure 5. Layout diagram of the joined elements.

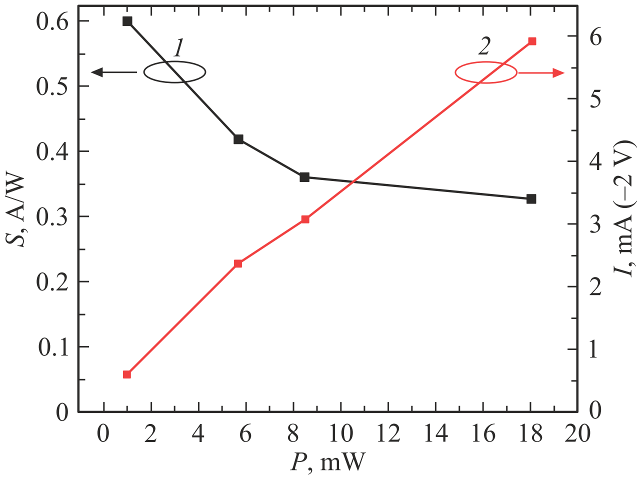

Figure 6. Results of studying the dependence of photosensitivity and photocurrent on the incident radiation power at a wavelength of 1550 nm. Diagram *1* — photosensitivity, Diagram *2* — photocurrent values at the offset −2 V.

the dependence of photosensitivity and photocurrent on the incident radiation power are shown in Figure 6.

Figure 5 shows that the photosensitivity decreases as the incident radiation power increases, which may be due to the photodiode approaching the saturation mode. The maximum of photosensitivity in the power range 1−18 mW is reached at a radiation power of 1 mW, and the value of photosensitivity is 0.6 A/W. This photosensitivity value can be compared with the photosensitivity at this wavelength of industrial [12] photodiodes grown on matched InP substrates, which is $\sim$ 1 A/W.

This photosensitivity value together with a low value of the dark current density indicates that the approaches used in this study are promising for the creation of photodiodes at a wavelength of 1.55 μm grown on a GaAs substrate.

4. Conclusion

InGaAs photodiode structures based on InAlGaAs-based metamorphic layer with quasi-corneal In concentration profile were formed on GaAs substrate by MOS-hydride epitaxy method. Application of such MBL structure, addition of Al, selection of optimal growth temperature and substrate orientation allowed creating photodiodes at wavelengths up to 1.68 μm with low dark current. For photodiodes with a mesastructure diameter of 1.4 mm, the dark current at room temperature and reverse offset −2 V was $4 \cdot 10^{-5}$ A, which corresponds to a current density of $3 \cdot 10^{-3}$ A/cm^2. Thus, the proposed MBL design is promising for the formation of photosensitive structures at wavelength 1.55 μm.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] N.J. Quitoriano, E.A. Fitzgerald. J. Appl. Phys., **102**, 033511 (2007).
[2] H.G. Nguyen, H.W. Yu, Q.H. Luc, Y.Z. Tang, V.T.H. Phan, C.H. Hsu, E.Y. Chang, Y.C. Tseng. Nanotechnology, **25**, 48520 (2014).
[3] I.V. Samartsev, S.M. Nekorkin, B.N. Zvonkov, V.Ya. Aleshkin, A.A. Dubinov, I.J. Pashenkin, N.V. Dikareva, A.B. Chigineva. Semiconductors, **52** (12), 1564 (2018).
[4] Yang He, Yurun Sun, Yan Song, Yongming Zhao, Shuzhen Yu, Jianrong Dong. Jpn. J. Appl. Phys., **55**, 065501 (2016).
[5] I.V. Samartsev, B.N. Zvonkov, N.V. Baidus, A.B. Chigineva, K.S. Zhidyaev, N.V. Dikareva, A.V. Zdoroveyshchev, A.V. Rykov, S.M. Plankina, A.V. Nezhdanov, A.V. Ershov. Semiconductors, **57** (6), 488 (2023).
[6] J. Tersoff. Appl. Phys. Lett., **62**, 693 (1993).
[7] A. Bosacchi, A.C. De Riccardis, P. Frigeri, S. Franchi, C. Ferrari, S. Gennari, L. Lazzarini, L. Nasi, G. Salviati, A.V. Drigo, F. Romanato. J. Cryst. Growth, **175** (176), 1009 (1997).
[8] L. Lazzarini, C. Ferrari, S. Gennari, A. Bosacchi, S. Franchi, M. Berti, A.V. Drigo, F. Romanato, G. Salviati. Microsc. Semicond. Mater. Conf. (Oxford, April 7−10, 1997). [Inst. Phys. Conf. Ser. № 157].
[9] R.Kh. Akchurin, A.A. Marmalyuk. *MOS-gidridnaya epitaksiya v tekhnologii materialov fotoniki i elektroniki* (M., Tekhsfera, 2018). (in Russian)
[10] R. Kumar, A. Bag, P. Mukhopadhyay, S. Das, D. Biswas. Electron. Mater. Lett., **12**, 356 (2016).
[11] J. Zhang, J. Verbist, B. Moeneclaey, J. Van Weerdenburg, R. Van Uden, H. Chen, J. Van Campenhout, C. Okonkwo, X. Yin, J. Bauwelinck, G. Roelkens. IEEE Photonics J., **8** (1), 1 (2016).
[12] https://azimp.ru/

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