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InAs/InAsSbP bridge photodiodes: features of the fabrication technology

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The technology has been developed for producing bridge-type photodiodes with a small photosensitive area diameter ($< 100\,\mu$m) based on InAs/InAsSbP heterostructures, enabling high reproducibility of device parameters. It has been shown that complete isolation of the metal bridge during etching allows for a halving of the mesa height, thereby ensuring greater mechanical strength of the bridge photodiode. The use of the proposed technology has resulted in a reduction in the device parameter spread across the wafer, as well as a reduction in the photodiode dark current. Thus, at $U = -0.2$ V, the minimum dark current is $I_d = 200\,\mu$A for an open bridge and $I_d = 1\,\mu$A for devices with full insulation. Suppression of metal-assisted etching enables the fabrication of bridge-type devices on any $\mathrm{A^{III}B^{V}}$, regardless of the material, etchant, or crystallographic orientation of the structure.

Keywords: InAs/InAsSbP heterostructures, chemical etching, bridge photodiode, high-speed response.

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1. Introduction

Semiconductor lasers and modern laser systems capable of operating efficiently in the near and medium IR regions of the spectrum are finding new applications. For example, diode laser spectroscopy is used for screening diagnosis of various diseases at an early stage in the absence of pronounced symptoms [1,2]. Early diagnosis allows not only to avoid irreversible changes in the human body and a decrease in the quality of life, but it also saves the patient's life in some cases. Quantum cascade lasers in the IR range open up new perspectives for communication systems in free space [3,4].

The development of laser technology creates a need for creation of high-speed IR photodetectors and photodetector devices capable of detecting short pulses. When developing photodetectors, the task is to obtain the optimal ratio of parameters such as sensitivity, dark current value, and speed.

It is known that a decrease in the capacity of the $p-i-n$-photodiode and, accordingly, an increase can be achieved by reducing the concentration of charge carriers in the active region of the heterostructure or by reducing the area of the $p-n$-junction (diameter of the sensitive area). Previously, we conducted a study of the characteristics of InAs/InAsSbP photodetectors with a diameter of the sensitive area from 2 mm to 100 μm [5], which used a design with a circle-shaped mesa and an annular frontal contact, as well as pear-shaped mesas with a point contact. However, when the sizes of the photosensitive and contact pads are comparable, it becomes necessary to move the contact pad outside the photosensitive surface in order to avoid too much shading. The formation of two separate (photosensitive and contact) pads is provided for in the bridge design of the device, which was proposed by us for GaInAsSb/GaAlAsSb photodiodes with the spectral range of 1.2–2.4 μm [6]. The dielectric insulating layer was formed only under the contact pad in this study. It was found that the formation of a bridge structure on these materials depends on the orientation of the axis of the device relative to the crystallographic direction of the structure.

When moving to a longer wavelength region of the spectrum, where materials based on InAs and its solid solutions are used, a number of difficulties were identified that lead to low mechanical strength of the structure and a large variation in the parameters of photodiodes.

This work is a continuation of the study presented in Ref. [7]. We have solved the problem of developing a universal technology for creating mechanically durable InAs/InAsSbP bridge photodiodes with high reproducibility of parameters, which will make it possible to create various bridge devices on any materials $\mathrm{A^{III}B^{V}}$ [8].

2. Samples and research methods

n-InAs/p-InAs$_{0.27}$Sb$_{0.23}$P$_{0.50}$ heterostructures were grown by metalorganic chemical vapor deposition (MOCVD). A schematic energy diagram is shown in Figure 1. Optical lithography, high-vacuum thermal and magnetron sputtering, local electrochemical deposition, and liquid chemical etching were used to create bridge photodiodes based on these heterostructures. Ohmic contacts to n- and p-type semiconductor materials were created on the basis of a multilayer system of Cr-Au-Ni-Au, which was thickened by electroplating gold from the front contact and spraying a two-layer system of Cr-Au from the solid back contact side. The stages of manufacturing of bridge photodiodes based on InAs/InAsSbP heterostructures are described in detail in our paper in Ref. [7].

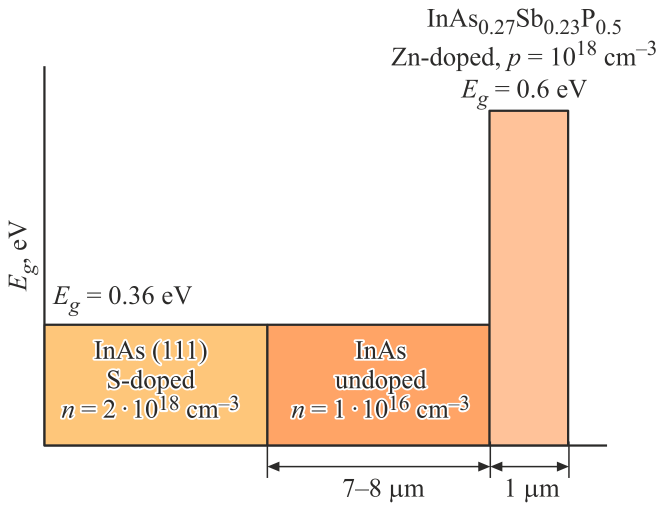

Figure 1. Schematic energy diagram of the InAs/InAsSbP heterostructure.

The volt-ampere characteristics (VAC) of the manufactured photodiodes were studied using an automated VAC meter. The differential resistance R_0 was determined by the slope of the linear section of the VAC in the range of ± 10 mV. The capacity was measured using an Agilent E4980A LCR meter.

The dynamic characteristics of InAs/InAsSbP bridge photodiodes were studied on a test bench using a laser pulse source based on a single-mode laser diode ($\lambda = 1.55\,\mu$m, pulse duration 70 ps at half maximum, rise front 40 ps at the level of 10−90 %, peak power of 75 mW). The measuring test bench also included an Agilent 86117A stroboscopic oscilloscope with a 50 GHz band, an optical circuit that focuses the laser beam on the photodetector site (spot diameter $5\,\mu$m), and a linear translator for scanning the laser beam across the site. The positioning accuracy was $\leq 1\,\mu$m. The samples in the TO-18 case were mounted on a high-frequency line (HF) with an SMA (sub-miniature version A) output.

3. Experimental results and discussion

The bridge structure is formed by liquid etching of the heterostructure onto the entire thickness of the epitaxial layers. The main feature of this method is lateral etching, which removes the semiconductor material under the bridge contact simultaneously with the formation of a working mesastructure. It is necessary to form an air etchant under the metal beam to provide electrical insulation of the heterostructure layers between the photosensitive and contact mesas. At the same time, the possibility of implementing this task will depend on the choice of etcher and the selection of etching depth.

Liquid chemical etching is based on the interaction of an etching solution with the surface of a semiconductor. Most etchants consist of an oxidizer (for oxidation of the semiconductor surface) and a complexing agent (for the formation of soluble compounds with oxidation products). The $HBr{:}H_2O_2{:}H_2O$ composition is widely used for InAs and its solid solutions where the etching rates of different layers of the heterostructure are close in magnitude, which makes it possible to obtain an even mirror-smooth lateral surface of the mesostructure.

The formation of an air tunnel under the outlet of the contact pad (bridge) is ensured by lateral etching. In this case, the physico-chemical processes occurring in the etching solution are of key importance. We found that when exposed areas of gold are present in the etcher, both as a bridge material and on technical labels necessary for sequential photolithography processes, the lateral etching rate in the $HBr{:}H_2O_2{:}H_2O$ etcher is significantly reduced. This leads to the fact that for InAs/InAsSbP heterostructures, an air tunnel under a metal bridge with a heterostructure layer total thickness of $\sim 5-7\,\mu$m can be obtained only in case of etching to a greater depth of $\sim 50\,\mu$m, which significantly reduces the mechanical strength of the entire structure.

If for GaSb-based structures the ratio of the mesastructure depth and the amount of etchant under the bridge was 2 : 1, then with a similar device design for InAs-based structures, the minimum ratio is 4 : 1, which makes the structure less mechanically robust. We believe that the effect of gold on lateral etching under the bridge is due to the presence of open areas of the metal bridge, which affect the processes in both the etcher and the semiconductor material, participating in the redistribution of carriers between them.

The use of a metal mask in liquid chemical etching of semiconductor materials for obtaining nanoscale structures has been actively studied since the early 2000s. It is known that in the Metal Assisted Chemical Etching (MACE, i-MACE), a noble metal (not etched) deposited on the surface of a semiconductor catalyzes the reduction of an oxidizer and increases the rate of dissolution of the semiconductor near the metal film [9]. The key feature of this method is the very small amount of lateral etching, which makes it possible to obtain mesastructures with a higher aspect ratio (the ratio of the horizontal size of the resulting relief to its depth). The mechanisms of metal-stimulated etching for various materials and etching compounds are actively discussed [10], however, a number of aspects of this method remain unclear to date. The efficiency of vertical etching is determined by two key mechanisms — hole generation and mass transfer [11]. Thus, as the area of the catalyst increases, the rate of hole generation increases; however, if mass transfer is limited, then removal of products of electrochemical reactions occurring on the surface of the semiconductor in the presence of a metal catalyst is difficult, which potentially reduces the etching rate.

Previously, we used insulation using a dielectric layer only of the contact pad from the reference mesa. The results of a number of experiments have shown that the possibility of obtaining an air tunnel under the bridge contact for the InAs/InAsSbP heterostructure in the $HBr{:}H_2O_2{:}H_2O$ etcher

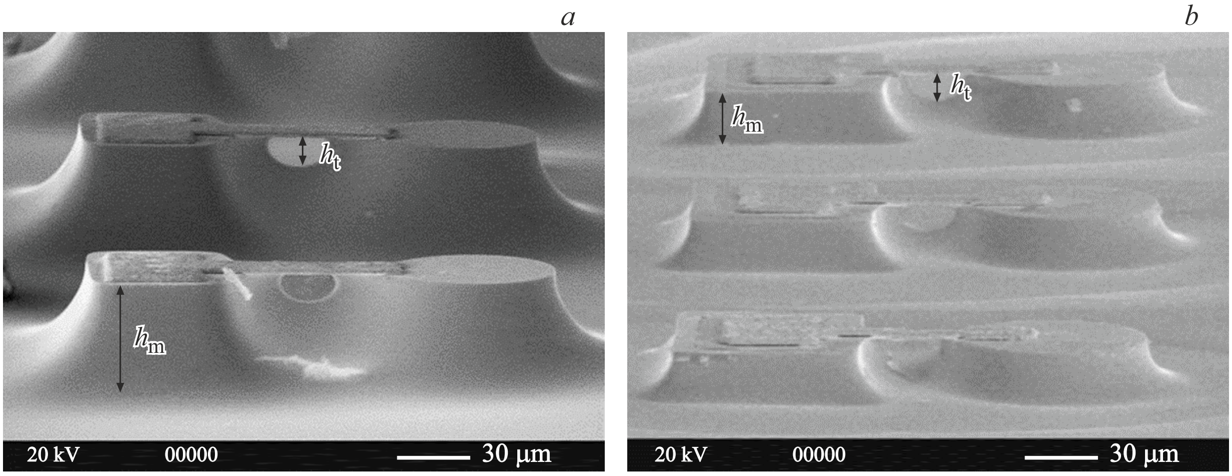

Figure 2. SEM images of InAs/InAsSbP bridge photodetectors obtained by: *a* — without complete isolation of the metal bridge; *b* — with complete isolation of the metal bridge.

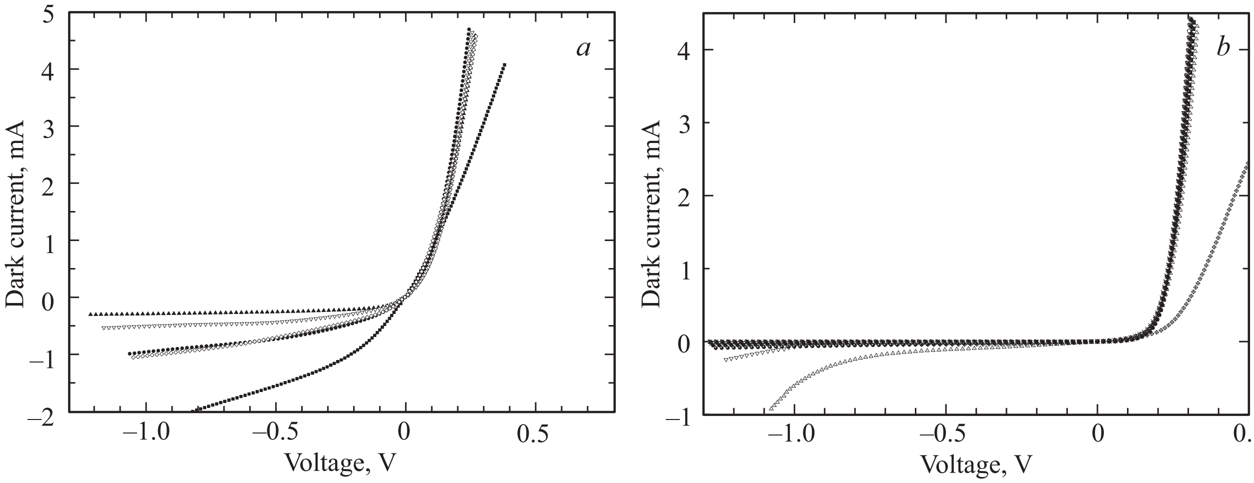

Figure 3. Volt-ampere characteristics of InAs/InAsSbP photodiodes: *a* — without metal bridge insulation; *b* — with full metal bridge insulation.

is determined not only by the isolation of the gold bridge from the semiconductor, but also by its isolation from the etching solution.

The plates of the *n*-InAs/*p*-InAsSbP heterostructure were divided into two parts each at the photolithography stage. Photodiodes were made with an open gold bridge on one part of the plate, the bridge contact was completely isolated during etching on the other part of the plate to exclude the influence of gold on the formation of mesastructures.

A TiO_2/SiO_2 dielectric lining was additionally formed under the bridge, and a photoresist mask was applied on top of it, insulating the metal from the upper and sides [12].

Figure 2 shows SEM images (scanning electron microscope) of InAs/InAsSbP photodiodes obtained using scanning electron microscopy.

As can be seen from Figure 2, deep mesas are obtained when etching InAs/InAsSbP mesastructures without completely isolating the metal bridge from the semiconductor and etchant with a small etch under the bridge (Figure 2, *a*). The ratio of the depth of the mesastructure h_m to the etching depth h_t is 4 : 1. In the case of complete isolation, an air tunnel was obtained under the bridge at a significantly lower mesa depth (Figure 2, *b*). In this case, the ratio of the depth of the mesastructure to the etching depth under the bridge is 2 : 1. Thus, the suppression of metal-stimulated etching leads to a decrease in the depth of the holes and an increase in the mechanical strength of the structure.

In addition, it has been experimentally shown that, unlike the initial approach, when the dielectric layer is formed only under the contact pad, when the metal bridge is completely isolated, orientation relative to crystallographic directions is not required during etching.

It is important to note that the developed technology for creating InAs/InAsSbP bridge photodiodes makes it

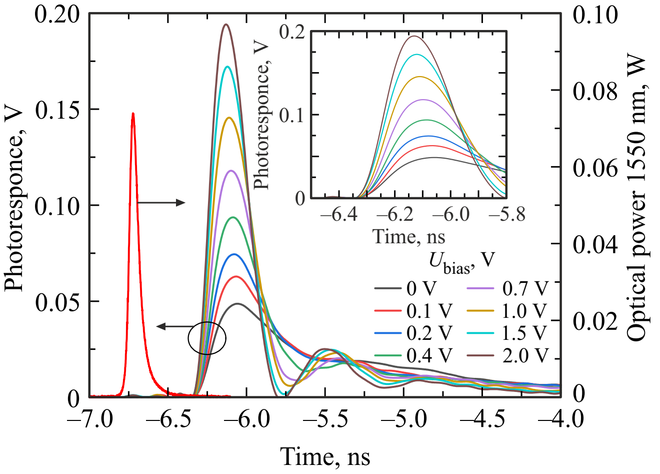

Figure 4. Photoconductive response pulses at various reverse bias voltages U_{rev}, as well as the shape of the laser pulse used in the experiment. The inset shows the photoconductive response pulses on a larger scale.

possible to manufacture various bridge-type devices with high reproducibility of parameters on any $A^{III}B^{V}$ materials.

Figure 3 shows the volt-ampere characteristics of InAs/InAsSbP photodiodes made without insulation of a metal beam (Figure 3, *a*) and with insulation (Figure 3, *b*).

As can be seen from Figure 3, the developed technology made it possible to achieve a smaller spread of device parameters across the plate, as well as to reduce the dark currents of the photodiodes. The minimum dark current is $I_d = 200\,\mu$A at $U = -0.2$ V with the bridge open and it equals to $I_d = 1\,\mu$A in devices with full insulation. We believe that the decrease in the spread of parameters across the plate is due to the fact that with complete isolation, the etching depth required to obtain an air tunnel under the bridge is significantly less. In this case, the spread of the diameter of the photosensitive site from mesa to mesa decreases and, accordingly, the spread of device parameters, in particular the magnitude of the dark current. The differential resistance of the photodetectors is $R_0 = 1.0{-}5.6$ kOhm.

The spectral sensitivity of the created InAs/InAsSbP photodiodes lies in the wavelength range of $1.1{-}3.8\,\mu$m with a maximum in the region of $2.8{-}3.1\,\mu$m. The current monochromatic sensitivity reaches $S_I = 1.0{-}1.2$ A/W.

Figure 4 shows typical photoconductive response pulses demonstrated by the developed InAs/InAsSbP bridge photodetectors (diameter of the photosensitive pad $\sim 80\,\mu$m) at various inverse voltages, as well as the shape of the laser pulse. The position of the laser pulse relative to the photoconductive response pulse was chosen artificially, since signal delays were not evaluated as part of the conducted studies.

As can be seen from Figure 4, the maximum amplitude of the photoconductive response pulse is 0.19 V at a inverse voltage of 2 V. At the same time, the maximum speed of the photodiodes, defined as the rise time of the photoconductive response pulse $\tau_{0.1-0.9}$, reaches 100 ps (see the inset to Figure 4).

Thus, a technology for creating bridge-type devices has been developed, which makes it possible to suppress the effect of metal-stimulated etching and thereby increase the mechanical strength of the structure by reducing the height of the mesa. At the same time, the spread and magnitude of the reverse dark currents are reduced.

4. Conclusion

A technology has been developed for creating InAs/InAsSbP bridge photodiodes with high reproducibility of instrument parameters for the spectral range of $1.1{-}3.8\,\mu$m.

It was found that the presence of open areas of gold during etching of InAs/InAsSbP heterostructures in the $HBr{:}H_2O_2{:}H_2O$ system prevents lateral etching. It is shown that it is necessary to completely suppress metal-stimulated etching for obtaining a photodiode design with a bridged metal contact, namely, it necessary to eliminate the influence of gold on the etching process of the semiconductor. Thus, the ratio of the depth of the mesastructure to the etching depth is 4 : 1 without complete isolation of the metal bridge and 2 : 1 with its complete isolation.

It is shown that the magnitude and spread of the reverse dark currents decrease when the bridge is completely isolated at the mesastructure etching stage. So, with an open bridge, the minimum dark current was $I_d = 200\,\mu$A at $U = -0.2$ V, whereas for a fully insulated structure $I_d = 1\,\mu$A at $U = -0.2$ V.

The suppression of metal-stimulated etching makes it possible to manufacture bridge-type devices on any $A^{III}B^{V}$ compounds, regardless of the material used, etchant, and crystallographic orientation of the heterostructure.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] I.I. Ponurovsky, A.I. Nadezhdinsky, D.B. Stavrovsky, Yu.P. Shapovalov, M.V. Spiridonov, A.S. Kuzmichev, A.A. Karabinenko, Yu.M. Petrenko. STM, **12** (5), 71 (2020). (in Russian).

[2] B. Sumpf, M. Braune, M. Maiwald, M.E. Darvin, J. Lademann, G. Tränkle. Proc. SPIE, **11257**, Plasmonics in Biology and Medicine XVII; 1125707 (2020).
DOI: 10.1117/12.2554015 (Event: SPIE BiOS, 2020, San Francisco, California, United States).

[3] O. Spitz, P. Didier, L. Durupt, D. Andrés Díaz-Thomas, A.N. Baranov, L. Cerutti, F. Grillot. IEEE J. Select.Topics Quant. Electron., **28** (1), 1200109 (2022).
DOI: 10.1109/JSTQE.2021.3096316

[4] M. Turville-Heitz, R. Marsland, J.H. Ryu, S.A. Jacobs, J.D. Kirch, T. Earles, S. Ruder, K. Oresick, B. Knipfer, D. Botez, L.J. Mawst. Photonics, **12** (1), 51 (2025). DOI: 10.3390/photonics12010051

[5] I.A. Andreev, O.Yu. Serebrennikova, N.D. Ilyinskaya, A.A. Pivovarova, G.G. Konovalov, E.V. Kunitsyna, V.V. Sherstnev, Yu.P. Yakovlev. FTP, **49** (12), 1720 (2015). (in Russian).

[6] I.A. Andreev, O.Yu. Serebrennikova, G.S. Sokolovsky, V.V. Dudelev, N.D. Ilyinskaya, G.G. Konovalov, E.V. Kunitsyna, Yu.P. Yakovlev. FTP, **47** (8), 1109 (2013). (in Russian).

[7] A.A. Pivovarova, E.V. Kunitsyna, G.G. Konovalov, S.O. Slipchenko, A.A. Podoskin, I.A. Andreev, N.A. Pikhtin, N.D. Ilyinskaya, A.E. Chernyakov, Yu.P. Yakovlev. ZhPS, **90** (1), 102 (2023). (in Russian).

[8] A.A. Obraztsova, A.A. Pivovarova, S.D. Komarov, I.S. Fedosov, K.A. Ivanov, N.A. Kalyuzhny, S.A. Mintairov, N.D. Ilyinskaya, Yu.P. Yakovlev, I.S. Makhov, N.V. Kryzhanovskaya, A.E. Zhukov. FTP, **59** (1), 37 (2025). (in Russian). DOI: 10.61011/FTP.2025.01.60498.7587

[9] L. Kong, B. Dasgupta, Y. Ren, P.K. Mohseni, M. Hong, X. Li, W.K. Chim, S.Y. Chiam. Sci. Rep., **6**, 36582 (2016). DOI: 10.1038/srep36582

[10] S. Znati, J. Wharwood, K.G. Tezanos, X. Lie, P.K. Mohseni. Nanoscale, **16**, 10901 (2024). DOI: 10.1039/D4NR00857J

[11] J.D. Kim, P.K. Mohseni, K. Balasundaram, S. Ranganathan, J. Pachamuthu, J.J. Coleman, X. Li. Adv. Funct. Mater., **27** (12), 1605614 (2017). DOI: 10.1002/adfm.201605614

[12] N.D. Ilyinskaya, A.A. Pivovarova, E.V. Kunitsyna, I.A. Andreev, Yu.P. Yakovlev. *Poluprovodnikovyj fotodiod dlya infrakrasnogo izlucheniya*. Patent No. 221645 RF, invention priority: September 01, 2023.

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