Semiconductors, 2025, Vol. 59, No. 6

High operating temperature photodiodes based on *n*-InAsSbP/InAs/*p*-InAsSbP heterostructures

© *A.A. Klimov, R.E. Kunkov, T.S. Lukhmyrina, B.A. Matveev, M.A. Remennyy*

Ioffe Institute,
194021 St. Petersburg, Russia

E-mail: a.klimov@mail.ioffe.ru

Received May 5, 2025
Revised June 24, 2025
Accepted September 18, 2025

The results of development and research of photodiodes based on n^+-InAs/n-InAsSbP/InAs/p-InAsSbP heterostructure in the temperature range of 125−500 K are presented. The design features of the epitaxial structure and photodetector chip are discussed, which provided values of current sensitivity and detectability of $Si = 1.6$ A/W and $D^* = 1.5 \cdot 10^{10}\,\text{cm} \cdot \text{Hz}^{1/2} \cdot \text{W}^{-1}$ at room temperature and $Si > 0.1$ A/W at $T = 500$ K.

Keywords: medium-wave photodiode, InAs photodiode, InAsSb photodiodes, high-temperature photodiodes, InAsSbP/InAs heterostructure, FSI photodiode.

DOI: 10.61011/SC.2025.06.62055.8070

1. Introduction

Photonic photodetectors operating in the medium-wavelength IR wavelength range ($\lambda = 2.5-6\,\mu$m) are used in many gas analysis and low-temperature pyrometry devices, such as infrared sensors for methane and natural gas, breathalyzers, alcohol interlocks and alcohol detection gates, fire safety sensors and high-speed low-temperature pyrometers. The continued development of these devices is accompanied by a trend towards reducing the size, weight and energy consumption of used photodetectors (minimizing SWaP — Scale, Weight and Power). This generates a request for improvement photodetector performance that would make it possible to abandon systems for their cooling or thermal stabilization. The answer to this request is reflected in the term High-Operating-Temperature Infrared Photodetectors (HOT Photodetectors) [1], used to denote photodetectors operating at temperatures close to or above room temperature [2], as well as for photodetectors that achieve background-limited mode (BLIP mode) at $T \geq 150$ K.

Earlier, we reported on the research and development of photodiodes (PDs) based on the double heterostructure (DH) n-InAsSbP/InAs/p-InAsSbP with radiation input from the upper layer p-InAsSbP grown on n^+-InAs(100) substrates by liquid phase epitaxy (LPE), photosensitive in the spectral range of $\lambda = 2-4\,\mu$m and operating in the temperature range of 200−500 K [3,4]. It was shown in these studies that the detectability $D^* = 1.5 \cdot 10^{10}\,\text{cm} \cdot \text{Hz}^{1/2} \cdot \text{W}^{-1}(300\,\text{K})$ was achieved, which is one of the best results among the published data. However, the photodiodes showed a sharp drop in current sensitivity at temperatures above 300 K (up to $Si = 0.01$ A/W, $T = 500$ K), which limited the prospects for their use in infrared sensors operating without cooling at elevated temperatures.

This work is devoted to the development of photodetectors based on the DH n-InAsSbP/InAs/p-InAsSbP with radiation input through the p-InAsSbP layer operating in wavelength range $\lambda = 2-4\,\mu$m, within which the proposed solutions for the design of the photodetector chip provided a weaker temperature dependence of the PD parameters than before, which made it possible for the PD to operate at $T = 500$ K with the value of $Si > 0.1$ A/W.

2. Experimental results

Epitaxial heterostructures n-InAsSb/InAs/p-InAsSbP were obtained by the LPE method on n^+-InAs(100) substrates and were similar to those described in Refs. [3,4]. Post-growth processes were carried out using standard photolithography methods to obtain single photodiode elements (chips) with radiation input through the wide-band layer p-InAsSbP („FSI“ — front-side illuminated design). The photosensitive area of the chip is $390 \times 390\,\mu$m with thickness about $40\,\mu$m and a gold contact to the substrate n^+-InAs and grid contact to the p-InAsSbP. The chips were mounted on a submount and then on a TO-18 case.

Figure 1 shows the photoluminescence (PL) spectra of epitaxial structures from this work and from this work, from Ref. [5], and for undoped substrate n-InAs ($n = 1 \cdot 10^{16}\,\text{cm}^{-3}$). The PL spectra of heterostructures consist of two bands responsible for recombination in the photosensitive InAs region (with a maximum of about 410 meV) and the wide-band p-InAsSbP layer (with a maximum of 470−490 meV).

The PL spectra in this paper are differs from Ref. [5] that allow us to make the following assumptions about the properties of the obtained heterostructures: the photosensitive region is characterized by a lower level of doping with a donor impurity than in Ref. [5]. This is evidenced by

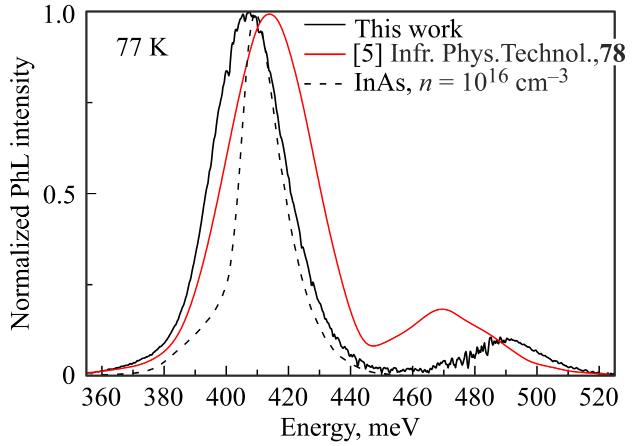

Figure 1. Photoluminescence spectra of the n-InAsSbP/InAs/p-InAsSbP heterostructure from this paper; study in Ref. [5], undoped n-InAs substrate ($n_0 = 1 \cdot 10^{16}\,\mathrm{cm}^{-3}$) at 77 K.

the proximity of the maximum of its PL and the maximum of the PL of the undoped n-InAs; the layer p-InAsSbP is characterized by a higher value of the band gap. These properties of the heterostructure allow us to expect a decrease in the values of dark currents, which will be confirmed by the data presented below (Figure 4).

Figure 2 shows the current sensitivity spectra in the temperature range 125–300 K (a), 300–500 K and data from [4] at $T = 500$ K (b). The photosensitivity spectra in the low temperature region (Figure 2, a) have a shape with a pronounced maximum, which we associate with multipass absorption of radiation in the photosensitive region when it is reflected from the mirror contact to the substrate (cathode). This effect leads to an increase in current sensitivity in the optical transparency region of the substrate, and its effect decreases with increasing temperature due to a decrease in the optical transmission of the substrate.

As the temperature increases (Figure 2, b), the current sensitivity decreases, which is partly due to a decrease of the collection efficiency of photogenerated carriers when the dark resistance of the p–n junction is close to the values of the series resistance between the depleted region and anode contact. This also explains the relatively low current sensitivity of the PD based on an identical structure with a point anode contact, shown in Figures 2, b and 3, a [3,4].

Figure 3, a shows the temperature dependences of the current sensitivity of an PD with a photosensitive InAs region both in the geometry „FSI“ and with radiation input through a substrate (BSI — back side illuminated) [3,5]. The weakest temperature dependence is observed in BSI geometry samples, which have the smallest chip thickness and, as a result, the lowest absorption in the substrate, as well as a grid anode contact, which minimizes the decrease in the efficiency of collecting photogenerated media. A comparison with the data from Ref. [3,4] let us suggest that the current sensitivity decrease due to this effect occurs at temperatures > 400 K.

Figure 3, b shows the temperature dependences of the $R_0 \cdot A$ product (R_0 — dark resistance, A — sensitive area) of the above-mentioned PD. All of them are characterized by an exponential dependence of the product $R_0 \cdot A$ with an activation energy close to the value of the band gap of the photosensitive region (n-InAs), which indicates a diffusion mechanism of current flow in $T = 175$–500 K At elevated temperatures the differences that occur can be

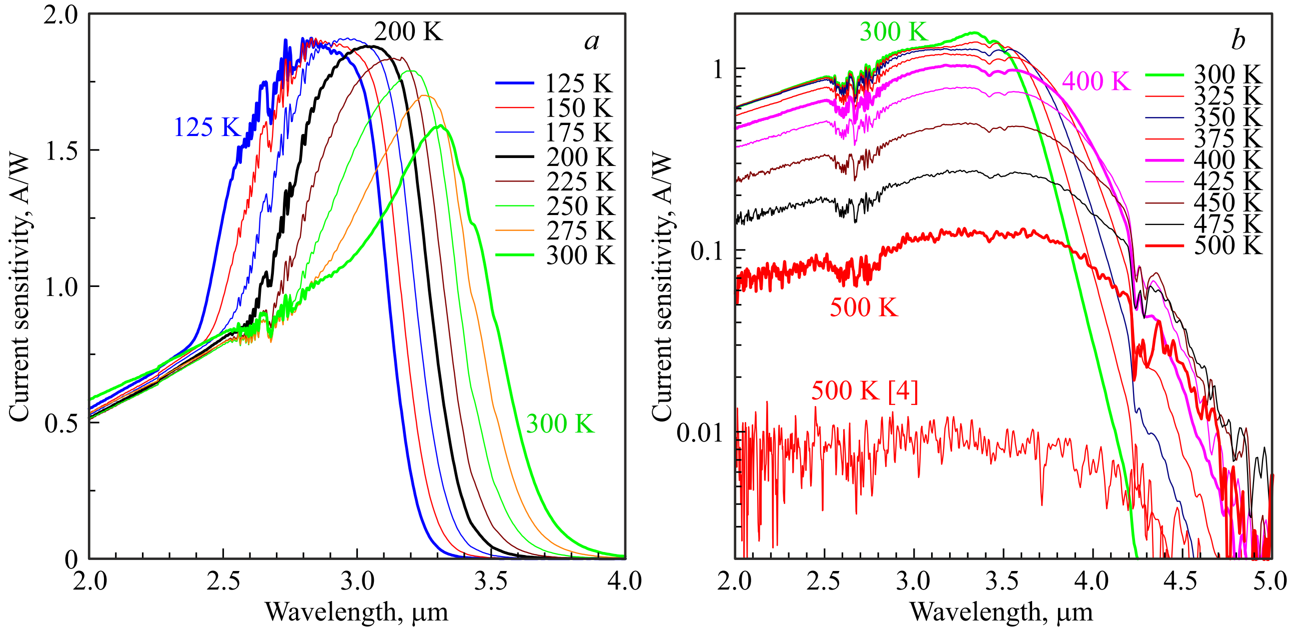

Figure 2. Current sensitivity spectra of PD in the temperature range of 125–300 K (a), 300–500 K and samples [4] at $T = 500$ K (b).

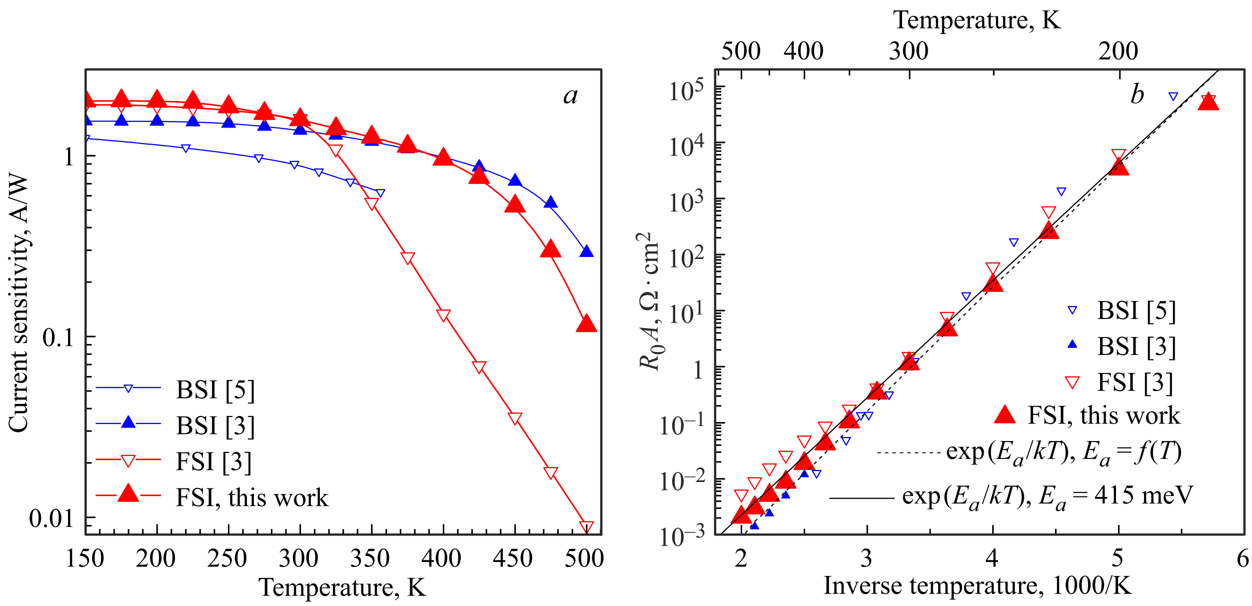

Figure 3. Temperature dependences of current sensitivity at maximum S_i (*a*) and products $R_0 \cdot A$ (*b*) of photodiodes with photosensitive InAs region with radiation input through the substrate (BSI) and through the epitaxial layer (FSI).

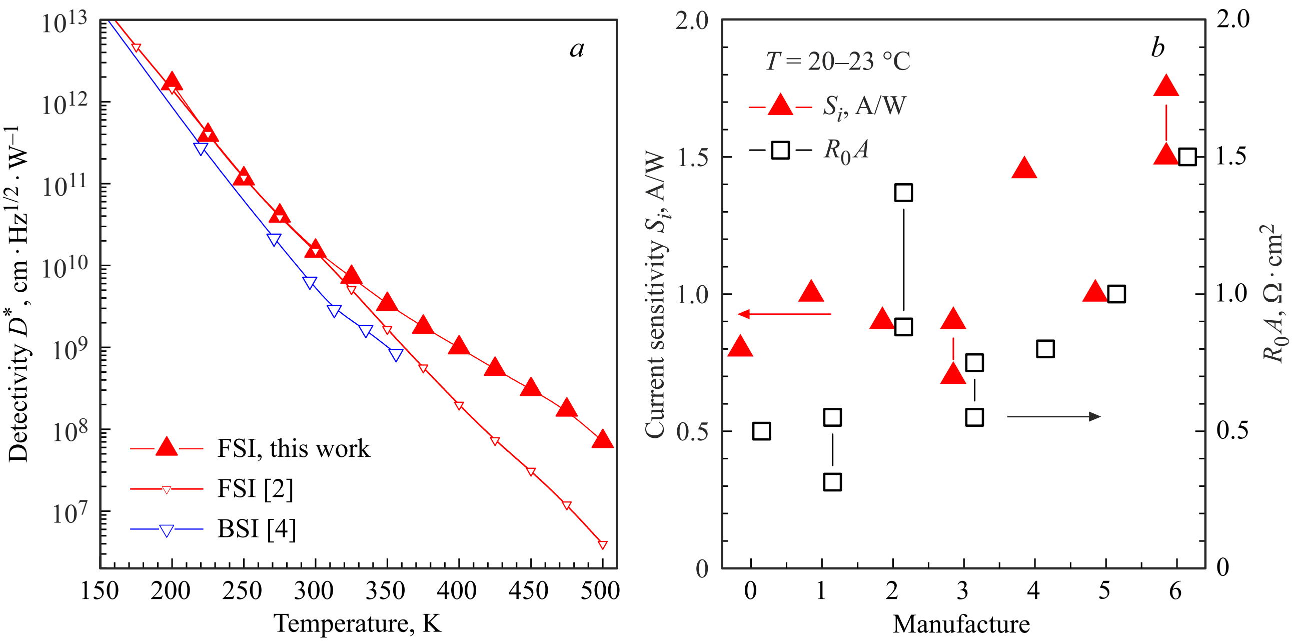

Figure 4. Temperature dependences of the detection ability in comparison with the results of previous studies (*a*); comparison of the current sensitivity values obtained and the product of $R_0 \cdot A$ with analogues (*b*), numbers on the axis *X* correspond to the developer numbers from the table.

explained by the effect of „current crowding" to the area under contact with point and grid contacts [6]. This confirms the previously made assumption about the reason for the decrease in the current sensitivity of the FSI photodiodes with an increase in temperature.

Figure 4, *a* shows the temperature dependences of the detectivity D^* together with the results of our previous studies.

So, we have got the increase in detectivity due to the increase in dark resistance by way of epitaxial structure properties (compared with the Ref. [5]) and the increase in current sensitivity in the chip with a grid anode contact (compared with the Ref. [3,4]).

Figure 4, *b* and the table shows a comparison of the current sensitivity and the $R_0 \cdot A$ product with the nearest analogues: photodiodes with photosensitive region from

Comparison with analogues

Developer	S_i, current Sensitivity, A/W	Product $R_0 \cdot A$, $\Omega \cdot cm^2$	Detection ability D^*, $cm \cdot Hz^{1/2} \cdot W^{-1}$
0. Vigo System SA (Poland)	0.8	0.5	$7 \cdot 10^9$
1. Hamamatsu (Japan)	1	0.31–0.55	$(3-4.5) \cdot 10^9$
2. Laser Components (Germany)	0.9	0.88–1.37	$1 \cdot 10^{10}$
3. Vigo System SA (Poland)	0.7–0.9	0.55–0.75	$(5-7) \cdot 10^9$
4. Sample from Ref. [7] (China)	1.45	0.8	$1.6 \cdot 10^{10}$ $1 \cdot 10^{10}$ (of the specified S_i and $R_0 \cdot A$)
5. Sample from Ref. [8] (Ioffe Physical-Technical Institute)	1	1	$8 \cdot 10^9$
6. This paper (Ioffe Physical-Technical Institute)	1.5–1.75	1.5	$1.5 \cdot 10^{10}$

InAs (developers „1–6“) and an HgCdTe-based photosensitive region for the same spectral region (developer „0“). The comparison shows the prospects of using the *n*-InAsSb/InAs/*p*-InAsSbP heterostructure to create an PD with a branched anode for the spectral range 2–4 μm.

3. Conclusion

So, we reports the photoelectric properties of FSI photodiodes based on the DH *n*-InAs/*n*-InAsSbP/InAs/*p*-InAsSbP with a grid anode contact in the temperature range of 125–500 K. As the results of proposed epitaxial structure properties and chip design the detectivity as high as $D^* = 1.5 \cdot 10^{10}\,cm \cdot Hz^{1/2} \cdot W^{-1}$ and the current sensitivity $Si = 1.6$ A/W at room temperature and $Si > 0.1$ A/W at $T = 500$ K was obtained.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] J. Piotrowski, A. Rogalski. *High-Operating-Temperature Infrared Photodetectors* (SPIE Press, Bellingham, WA, USA, 2007).
[2] G.Yu. Sotnikova, S.A. Alexandrov, G.A. Gavrilov. Uspekhi prikl. fiziki, **10** (4), 389 (2022). (in Russian). DOI: 10.51368/2307-4469-2022-10-4-389-403
[3] M.A. Remenniy, A.A. Klimov, R.E. Kunkov, T.S. Luhmyrina, B.A. Matveev, A.A. Usikova. Tez. dokl. XXVII Mezhdunar. nauchno-tekhnicheskoy konf. po fotoelektronike i priboram nochnogo videniya (M., 2024), p. 76. (in Russian).
[4] A.A. Klimov, R.E. Kunkov, T.S. Lukhmyrina, B.A. Matveev, M.A. Remenniy. Tez. dokl. conf. FizikA SPb (Sankt-Peterburg, 2024) p. 188.
[5] P.N. Brunkov, N.D. Il'inskaya, S.A. Karandashev, A.A. Lavrov, B.A. Matveev, M.A. Remennyi, N.M. Stus', A.A. Usikova. Infr. Phys. Technol., **78**, 249 (2016). https://doi.org/10.1016/j.infrared.2016.08.013
[6] N.D. Ilyinskaya, A.L. Zakheim, S.A. Karandashev, B.A. Matveev, V.I. Ratushny, M.A. Remenniy, A.Yu. Rybalchenko, N.M. Stus, A.E. Chernyakov. FTP, **46** (5), 708 (2012). (in Russian).
[7] Hongyu Lin, Hao Xie, Yan Sun, Shuhong Hu, Ning Dai. J. Cryst. Growth, **617**, 127293 (2023). https://doi.org/10.1016/j.jcrysgro.2023.127293
[8] P.N. Brunkov, N.D. Il'inskaya, S.A. Karandashev, N.M. Latnikova, A.A. Lavrov, B.A. Matveev, A.S. Petrov, M.A. Remennyi, E.N. Sevostyanov, N.M. Stus. Semiconductors, **48** (10), 1359 (2014). DOI: 10.1134/S1063782614100066

Translated by A.Akhtyamov