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HOT surface illuminated phoodiodes based on *n*-InAsSbP/InAs/*p*-InAsSbP heterostructures

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Abstract. Photodetectors operating in the mid-infrared (IR) wavelength range (3 – 4 μm) are widely used in gas analysis instruments and low-temperature pyrometry, such as methane and natural gas sensors, alcohol detectors, fire safety sensors, and fast-response pyrometers. This study investigates the causes of the decrease in current sensitivity with rising temperature in surface-illuminated photodiodes (PDs) based on *n*-InAsSbP/InAs/*p*-InAsSbP double heterostructures (DHS), sensitive in the spectral range of $\lambda = 2 - 4$ μm at temperatures of 200–500 K. Proposed design improvements for the PD chip resulted in a weaker temperature dependence of the parameters, enabling reliable operation at 500 K with a current sensitivity of $S_i = 0.1$ A/W.

Keywords: InAsSb solid solution, InAs heterostructures, MWIR photodiode, HOT PD, PD mid infrared, FSI infrared photodiodes, surface illuminated PDs

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Материалы конференции
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Поверхностно освещаемые высокотемпературные фотодиоды на основе гетероструктур *n*-InAsSbP/InAs/*p*-InAsSbP

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Аннотация. Представлены результаты разработки и исследования фотодиодов на основе гетероструктуры *n*-InAsSbP/InAs/*p*-InAsSbP в интервале температур 125 – 500 K. Обсуждаются конструктивные особенности эпитаксиальной структуры и чипа фотоприемника, которые обеспечили значения токовой чувствительности и обнаружительной способности $S_i = 1.6$ А/Вт и $D^* = 1.5\cdot10^{10}$ см·Гц$^{1/2}$·Вт$^{-1}$ при комнатной температуре и $S_i > 0{,}1$ А/Вт при $T = 500$ K.

Ключевые слова: средневолновый фотодиод, фотодиод InAs, фотодиоды InAsSb, высокотемпературные фотодиоды, гетероструктура InAsSbP/InAs, FSI фотодиод

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Introduction

Photodetectors operating in the mid-wave infrared (MWIR) range (λ = 2.5–6 μm) are widely used in gas analysis and low-temperature pyrometry instruments, such as methane and natural gas infrared sensors, breathalyzers, alcohol interlocks, fire safety detectors, and fast-response low-temperature pyrometers. The ongoing development of these devices is accompanied by a trend toward reducing the size, weight, and power consumption of photodetector modules (SWaP minimization – Scale, Weight, and Power). This creates a demand for photodetectors with sufficiently high performance to eliminate the need for cooling or thermal stabilization systems.

This demand has led to the emergence of the term 'high-operating-temperature (HOT) infrared photodetectors' [1], referring to detectors that operate at near-room temperature or above [2], as well as detectors achieving background-limited performance (BLIP mode) at $T \geq 150$ K.

Previously, we reported on the development and investigation of *n*-InAsSbP/InAs/*p*-InAsSbP double heterostructure (DHS) photodiodes with front-side illumination (FSI geometry), grown by liquid-phase epitaxy (LPE) on n^+-InAs (100) substrates. These photodiodes exhibited sensitivity in the spectral range λ = 2–4 μm and operated within a temperature range of 200–500 K [3, 4]. In those studies, a detectivity of $D^* = 1.5 \cdot 10^{10}$ cm·Hz$^{1/2}$·W^{-1} (300 K) was achieved, representing one of the best results among published data. However, the fabricated photodiodes showed a sharp decline in current responsivity at temperatures above 300 K (down to S_i = 0.01 A/W at T = 500 K), limiting their potential for use in uncooled infrared sensors operating at elevated temperatures.

This work focuses on the development of n-InAsSbP/InAs/p-InAsSbP DHS photodetectors with illumination through the *p*-InAsSbP layer, operating in the λ = 2–4 μm range. The proposed chip design modifications result in a weaker temperature dependence of photodiode parameters compared to previous versions, enabling operation at T = 500 K with a responsivity of $S_i > 0.1$ A/W.

Results and discussion

The *n*-InAsSbP/InAs/*p*-InAsSbP heterostructures investigated in this work were grown by LPE on n^+-InAs (100) substrates, following a methodology analogous to that described in references [3, 4]. Post-growth processing employed standard photolithographic techniques to fabricate single-element photodiode chips utilizing FSI through the wide-bandgap *p*-InAsSbP layer. The resulting chips featured a photosensitive area of 390×390 μm with a thickness of approximately 40 μm. Ohmic contacts were implemented as follows: a solid contact to the n^+-InAs substrate and a branched contact to the *p*-InAsSbP layer. Final device packaging was performed using TO-18 housings with intermediate subcarrier board mounting.

Photoluminescence (PL) characterization at 77 K (Fig. 1) revealed distinct spectral features when comparing the studied heterostructures with reference samples from [5] and undoped *n*-InAs substrates ($n = 1 \cdot 10^{16}$ cm^{-3}). The PL spectra exhibited two characteristic bands: a lower-energy emission at ~410 meV corresponding to the InAs photosensitive region, and a higher-energy band at 470–490 meV originating from the *p*-InAsSbP layer. Comparative analysis with prior work [5] suggests two significant structural differences: reduced donor doping concentration in the InAs photosensitive region, as evidenced by spectral alignment with undoped InAs, and increased bandgap in the *p*-InAsSbP layer. These modifications are anticipated to yield improved dark current characteristics, as subsequently confirmed by the experimental data presented in Fig. 4.

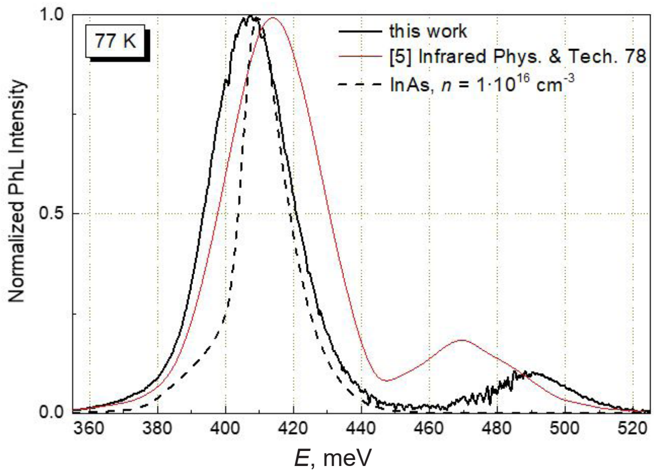

Fig. 1. Photoluminescence spectra of the *n*-InAsSbP/InAs/*p*-InAsSbP heterostructure from this work, reference [5], and undoped *n*-InAs substrate ($n_0 = 1\cdot10^{16}$ cm^{-3}) at 77 K

Temperature-dependent spectral responsivity measurements (Fig. 2) demonstrated distinct behavior across different thermal regimes. In the 125-300 K range (Fig. 2, *a*), the responsivity spectra displayed a pronounced maximum attributed to multipass optical absorption within the photosensitive region, enhanced by reflection from the mirror-like substrate contact. This effect diminished at elevated temperatures due to reduced substrate transparency. The responsivity degradation observed above 300 K (Fig. 2, *b*) correlates with decreasing charge collection efficiency as the *p*–*n* junction's dark resistance approaches the series resistance between the depletion region and anode contact [6]. This mechanism similarly explains the comparatively lower responsivity of point-contact photodiodes reported in references [3, 4].

Comparative analysis of FSI and back-side illuminated (BSI) geometries (Fig. 3, *a*) revealed superior temperature stability in BSI devices, attributable to their reduced substrate thickness and implementation of solid anode contacts that minimize current crowding effects. The observed behavior suggests that FSI devices in the current study experience noticeable current crowding above 400 K. Temperature-dependent $R_0 \cdot A$ product analysis (Fig. 3, *b*) confirmed diffusion-dominated transport mechanisms across the 175–500 K range, with activation energies approximating the InAs bandgap. Deviations at higher temperatures correlate with current crowding phenomena in devices employing non-solid anode contacts, further supporting the proposed responsivity degradation mechanism.

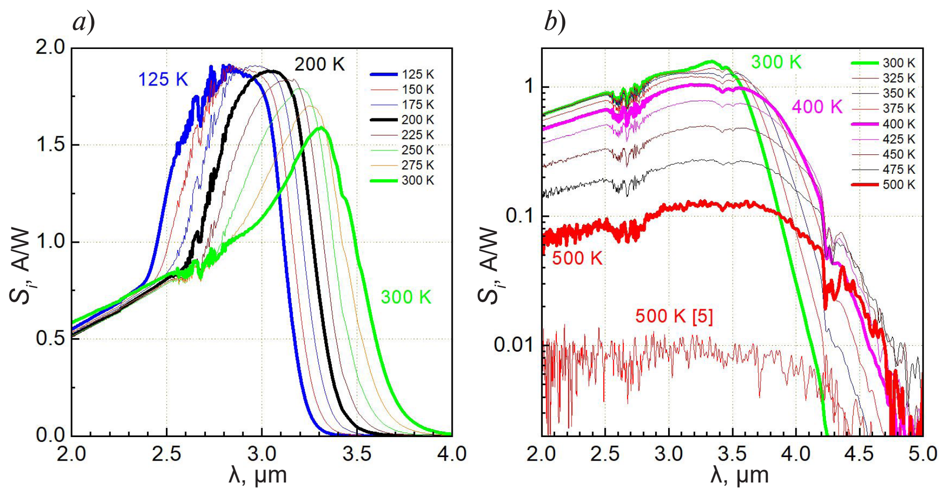

Fig. 2. Spectral responsivity of photodiodes at temperatures of 125–300 K (*a*), 300–500 K (*b*), and reference sample [4] at $T = 500$ K (*b*)

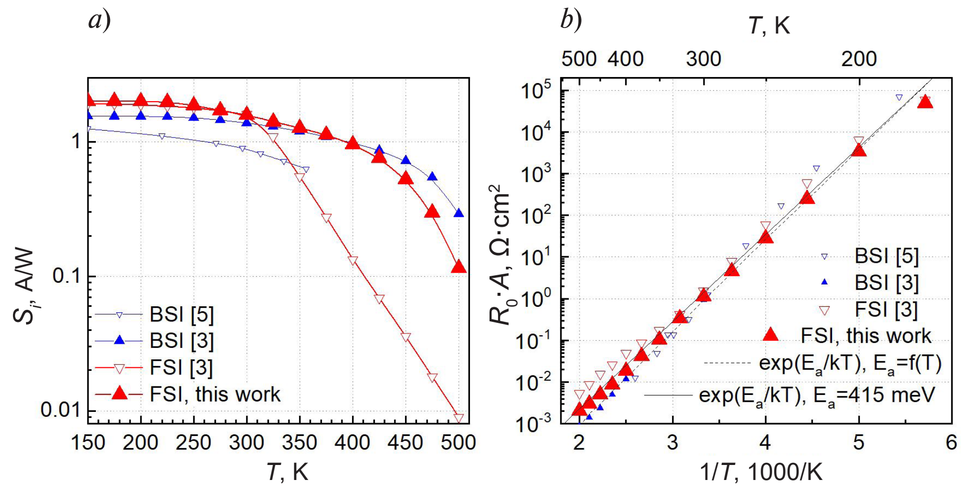

Fig. 3. Temperature dependences of peak responsivity S_i (*a*) and $R_0{\cdot}A$ product (*b*) for photodiodes with InAs photosensitive region in back-side illuminated (BSI) and front-side illuminated (FSI) configurations

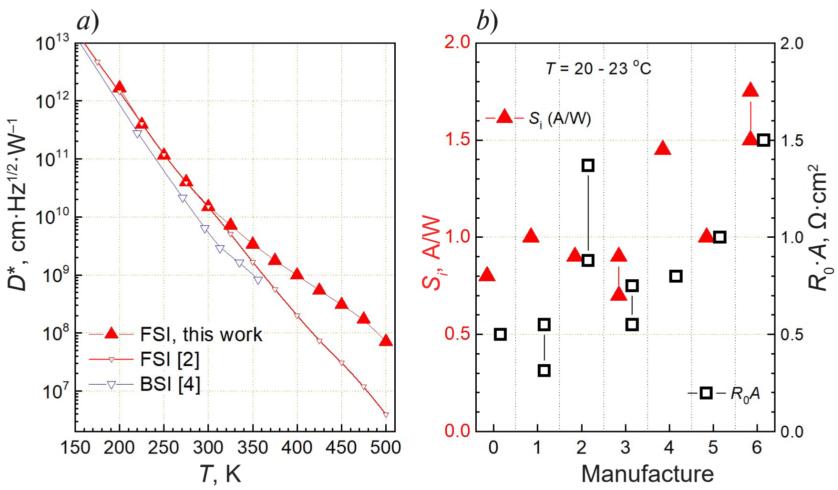

Fig. 4. Temperature-dependent detectivity compared with prior works (*a*); benchmarking of responsivity and $R_0{\cdot}A$ values against alternative technologies (*b*). Numbers on the *X*-axis correspond to developers listed in Table

Table

Performance comparison with alternative technologies

Manufacturer	S_i, current sensitivity, A/W	$R_0{\cdot}A$, Ω·cm²	Detectivity D^*, cm·Hz$^{1/2}$·W^{-1}
0. Vigo System SA	0.8	0.5	$7{\cdot}10^9$
1. Hamamatsu	1	0.314–0.55	(3–4.5) 10^9
2. Laser Components	0.9	0.88–1.37	$1{\cdot}10^{10}$
3. Vigo System SA	0.7–0.9	0.55–0.75	(5–7)$\cdot 10^9$
4. Reference sample from [7]	1.45	0.8	$1.6{\cdot}10^{10}$, $1{\cdot}10^{10}$ (From value S_i and $R_0{\cdot}A$)
5. Reference sample from [8]	1	1	$8{\cdot}10^9$
6. This work	1.5–1.75	1.5	$1.5{\cdot}10^{10}$

The enhanced detectivity (D^*) demonstrated in Fig. 4, *a* stems from two key improvements: (1) increased dark resistance through epitaxial structure optimization relative to Ref. [5], and (2) improved responsivity in branched-anode devices compared to prior designs [3]. Benchmarking against state-of-the-art alternatives (Fig. 4, *b*, Table) confirms the competitive performance of the developed *n*-InAsSbP/InAs/*p*-InAsSbP photodiodes, particularly when compared to both InAs-based and HgCdTe detectors operating in the 2–4 μm spectral range. These results substantiate the potential of branched-anode architectures for uncooled mid-wave infrared photodetection applications.

Conclusion

The photoelectric properties of experimental FSI photodiode samples fabricated from *n*-InAs/*n*-InAsSbP/n-InAs/*p*-InAsSbP double heterostructures with branched anode contacts were investigated over the temperature range of 125–500 K. Through optimized epitaxial structure design and chip architecture, the devices demonstrated remarkable performance characteristics, achieving a current responsivity of S_i = 1.6 A/W and specific detectivity of $D^* = 1.5\cdot10^{10}$ cm·Hz$^{1/2}$·W^{-1} at room temperature. Notably, the photodiodes maintained a responsivity exceeding $S_i > 0.1$ A/W even at elevated temperatures up to 500 K.

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