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Very-Long-Wavelength Infrared Range Type-II Superlattice InAs/InAsSb GaAs/Immersed Photodetectors for High-Operating-Temperature Conditions [†]

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Abstract: Recently, there has been significant interest in type-II superlattice (T2SL) infrared detectors based on both InAs/GaSb and InAs/InAsSb material systems, and fully operating devices have been presented in the mid- (MWIR) and long-wavelength (LWIR) infrared ranges. In addition, theoretical simulations and experimental reports show high-performance T2SL devices in the very-long-wavelength infrared range (VLWIR) (cutoff wavelength, $\lambda_c \geq 12$ µm). Devices in this wavelength range are essential for space-based applications. In VLWIR, the existing detectors with satisfactory performance are extrinsic silicon detectors operating under heavy, bulky and short-lifetime multistage cryocoolers. These disadvantages are mainly critical for space applications, and thus, developing a device exhibiting a higher operating temperature (HOT) is of high priority. We report on a photoconductive T2SL InAs/InAsSb detector with $\lambda_c > 18$ µm (limited by a GaAs substrate) and high-operating-temperature (HOT) conditions (T = 210–240 K) grown on thick semi-insulating GaA substrates by molecular beam epitaxy (MBE).

Keywords: VLWIR; T2SLs; InAs/InAsSb; HOT

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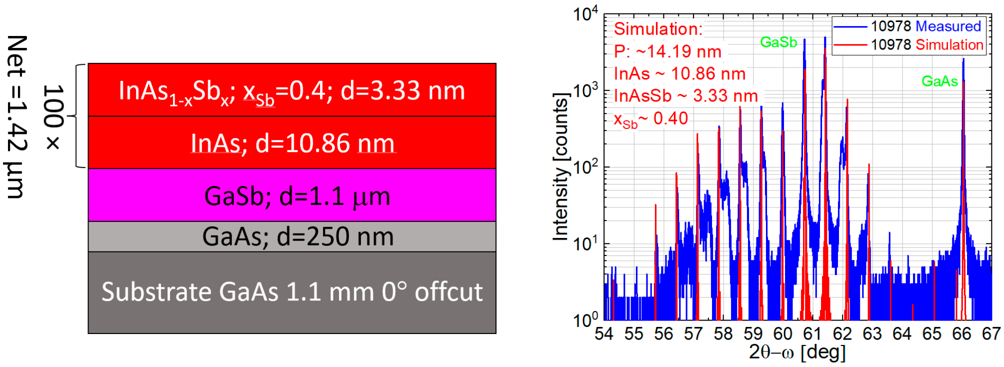
1. Introduction

Lately, there has been considerable interest in type-II superlattice (T2SL) infrared detectors based on InAs/GaSb and "Ga-free" InAs/InAsSb material systems, and fully operating devices competing with HgCdTe have been presented in the mid- (MWIR) and long-wavelength (LWIR) infrared ranges [1,2]. In addition, theoretical simulations and experimental reports proves that T2SLs devices show high performance in the very-long-wavelength infrared range (VLWIR) (cutoff wavelength, $\lambda_c \geq 12$ µm) [3–5]. VLWIR systems are essential for space applications such as pollution awareness and astronomy [6]. In VLWIR, the existing detectors with satisfactory uniformity and quantum efficiency (QE) are extrinsic silicon detectors operating under heavy, bulky and short-lifetime multistage cryocooler conditions [7,8]. These disadvantages are primarily significant for space applications, and thus, detectors exhibiting higher operating temperatures (HOTs, reached by 2–3-stage thermoelectric (TE) cooling) are in high demand. In comparison to extrinsic silicon devices, T2SL devices are based on interband optical transitions allowing them to operate at much higher temperatures. What is more, theoretical simulations and measured results prove that T2SL InAs/InAsSb detectors exhibit a comparable absorption coefficient to HgCdTe, and hence, the development of detectors with high QE is feasible [9]. This is why we report on a photoconductive T2SL InAs/InAsSb detector with a cutoff wavelength of $\lambda_c > 18$ µm (limited by GaAs substrate transmission) operating at T = 210–240 K, grown on a 1.1 µm GaSb buffer and a 0.25 µm GaAs smoothing layer on a 1.1 mm thick, semi-insulating GaAs substrate (intended to be converted into an immersion lens), by molecular beam epitaxy (MBE). The VLWIR range was reached by growing T2SL InAs/InAsSb detectors in a period (P) of ~ 14.2 nm (InAs: ~10.86 nm and InAsSb: ~3.33 nm, x_{Sb}: ~0.4). A net with an active layer thickness of ~1.42 µm was grown. Theoretical simulations suggest that the analyzed T2SLs should reach λ_c ~ 28 µm (300 K, E_g: ~0.044 eV).

2. Detector Structure

The T2SL InAs/InAsSb wafer was deposited by a RIBER Compact 21-DZ MBE on 2″ semi-insulating 1.1 mm GaAs (001) substrates. The IMF GaSb buffer layer (1.1 µm) was deposited at 500 °C on a thin 250 nm GaAs smoothing layer. A detailed description of the buffer growth and substrate processing procedure was presented by Benyahia et al. [10]. Before T2SL deposition, the GaAs substrate was cooled down to 425 °C under Sb flux. The T2SLs growth rate was assumed to be at the level of ~0.52 µm/h. T2SLa deposition was accompanied by short As or As + Sb soaking fluxes to reduce the composition variation at the interfaces.

The absorber consisted of 100 P with a 1.42 µm net thickness. The VLWIR ($\lambda_c > 18$ µm) was obtained by growing 10.86 nm InAs and 3.33 nm InAsSb ($x_{Sb} = 0.4$). Assuming no strain in both InAs and InAsSb, the cutoff wavelength was estimated at the level of ~28 µm (300 K). Intentional doping was not used during the growth process. The thickness of both the InAs and InAsSb layers was estimated by continuum elastic theory as presented by Polly et al. [11]. The T2SL VLWIR structure is presented in Figure 1a in detail, while Figure 1b presents the XRXRD of 100 P, with the simulation confirming the assumed growth nominal structural parameters of the T2SL InAs/InAsSb detectors to include thickness and x_{Sb} composition (P: ~14.19 nm, InAs: ~10.86 nm, InAsSb: ~3.33 nm, x_{Sb}: ~0.4). The FWHM of the 0th-order peak (2Θ-ω) was estimated at the level of ~155 arcsec for the analyzed VLWIR. The detector was mounted on a TO-8 stage, housed with a ZnSe (λ_c ~ 22 µm) window.



(**a**) (**b**)

Figure 1. The $\lambda_c > 18$ µm T2SL InAs/InAsSb (absorber thickness: 1.42 µm) sample schematic cross section (**a**) and HRXRD spectrum with T2SL simulation results (**b**).

3. Results and Discussion

Figure 2 presents the noise for the analyzed detector measured using a low-noise preamplifier and signal analyzer for V = 0.5 V and T = 210–240 K (f = 1–100 kHz). The noise VLWIR device at 20 kHz (T = 210–240 K) stays within ~2.47×10^{-10}–3.2×10^{-10} A/Hz$^{1/2}$. The Johnson noise was estimated by the relation $I_J^2 = \frac{4kT}{R_d}$, where R_d is the detector resistance and k is the Boltzmann constant. The Johnson noise of the analyzed VLWIR detector when T = 210–240 K was assessed within the range of ~1.89–2.34×10^{-11} A/Hz$^{1/2}$.

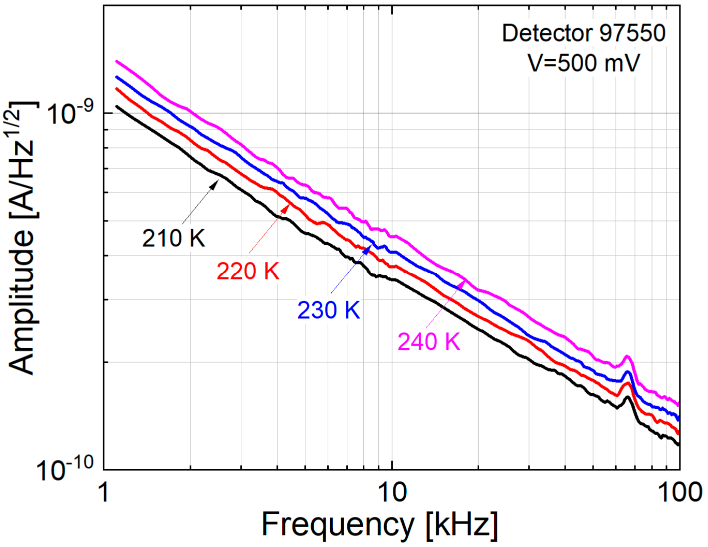
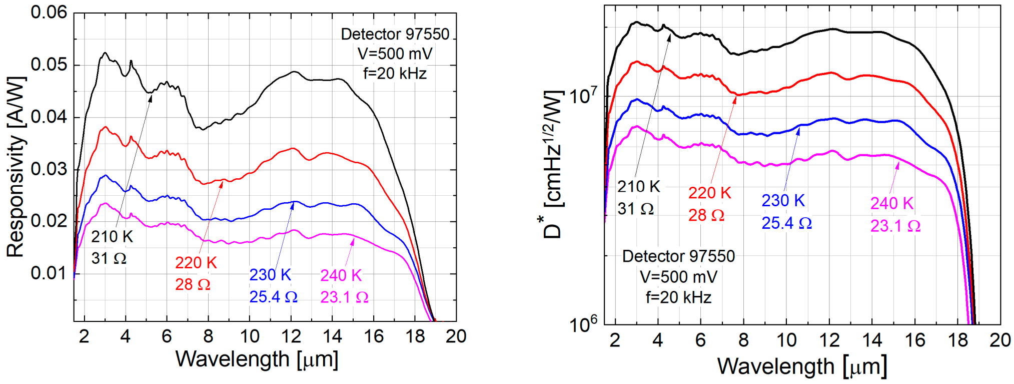


Figure 2. The noise spectra for the analyzed VLWIR single-pixel immersed photoconductor for V = 0.5 V and T = 210–240 K (f = 1–100 kHz).

The responsivity was measured by FTIR with reference to the calibrated photodetector. The current responsivity versus wavelength is presented in Figure 3a, where R_i = 0.041–0.016 A/W (@16 µm) when T = 210–240 K. The device resistance was measured within the range of 31–23.1 Ω.



(**a**) (**b**)

Figure 3. T2SLs InAs/InAsSb VLWIR device's R_i (**a**) and D^* (**b**) for V = 0.5 V and T = 210–240 K.

The specific detectivity was assessed by the equation $D^* = R_i/\sqrt{I_n^2/A_o\Delta f}$, where R_i is the measured responsivity, A_o is the optical area and I_n is the net noise current. Detectivity versus wavelength is shown in Figure 3b, where D^* = 1.7 × 10^7–4.9 × 10^6 cmHz$^{1/2}$/W for (@16 µm) is estimated. Razeghi et al. reported on VLWIR T2SL InAs/GaSb-based photodiodes with cutoff wavelengths of ~19 µm and ~32 µm exhibiting detectivity of ~3.71 × 10^{10} cmHz$^{1/2}$/W at 50 K and ~1.05 × 10^{10} cmHz$^{1/2}$/W at 34 K, respectively [12]. In addition, Table 1 presents a performance comparison between T2SL InAs/InAsSb- and HgCdTe-based 2-, 3- and 4-stage TE immersed photoconductors (PCIs) [13].

Table 1. D^* comparison of the T2SL InAs/InAsSb and HgCdTe PCIs for selected temperatures (195, 210, 230, 300 K) and operating wavelengths (10.6, 13, 14, 16 μm) for 20 kHz.

Detector	Material	T (K)	λ (μm)	D^* (cmHz$^{1/2}$/W)
PCI	T2SLs InAs/InAsSb	210	10.6	~1.8×10^7
			13	~1.9×10^7
			14	~1.9×10^7
			16	~1.6×10^7
		230	10.6	~7.4×10^6
			13	~7.6×10^6
			14	~7.8×10^6
			16	~6.9×10^6
	HgCdTe	195	10.6	$\geq 3.0 \times 10^9$
			13	$\geq 1.0 \times 10^9$
			14	$\geq 3.0 \times 10^8$
		210	10.6	$\geq 2.5 \times 10^9$
			13	$\geq 4.5 \times 10^8$
		230	10.6	$\geq 1.0 \times 10^9$
			13	$\geq 2.3 \times 10^8$
		300	10.6	$\geq 8 \times 10^7$

4. Conclusions

The VLWIR detectors showed that a proper device architecture and immersion lens allow them to compete with HgCdTe TE cooled detectors. The theoretical simulations suggest that presented device reaches a cutoff wavelength of ~28 μm (300 K) with $D^* = 1.7 \times 10^7$–4.9×10^6 cmHz$^{1/2}$/W for (@16 μm) when T = 210–240 K.

Author Contributions: Conceptualization, P.M. and W.G.; methodology, P.M. and K.M. (Krystian Michalczewski); validation, P.M., W.G. and K.M. (Krystian Michalczewski); formal analysis, K.M. (Kacper Matuszelański) and Ł.K.; investigation, K.M. (Kacper Matuszelański) and Ł.K.; resources, K.M. (Kacper Matuszelański); data curation, K.M. (Kacper Matuszelański), Ł.K. and P.M.; writing—original draft preparation, P.M.; writing—review and editing, K.M. (Krystian Michalczewski) and Ł.K.; visualization, P.M.; supervision, P.M.; project administration, P.M.; funding acquisition, P.M. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: Authors Kacper Matuszelański, Krystian Michalczewski, Łukasz Kubiszyn, Waldemar Gawron are employed by the company VIGO PHOTONICS S.A. The remaining author declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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