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Letter

Mid-wave T2SLs InAs/GaSb single pixel PIN detector with GaAs immersion lens for HOT condition

Piotr Martyniuk [a,*], Djalal Benyahia [a], Andrzej Kowalewski [a], Łukasz Kubiszyn [b], Dawid Stępień [a], Waldemar Gawron [a], Antoni Rogalski [a]

[a] Institute of Applied Physics, Military University of Technology, 2 Kaliskiego St., 00-908 Warsaw, Poland
[b] Vigo System S.A., 129/133 Poznańska Str., 05-850 Ożarów Mazowiecki, Poland

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ABSTRACT

In this paper we report on high operating temperature mid-wave infrared detector based on type-II superlattice InAs/GaSb mesa PIN architecture with 50% cut-off wavelength ~5.2 μm at 230 K. The 1.1 mm thick GaAs substrate was converted into immersion lens to limit an influence of the defects occurring during growth on GaAs substrate and to increase detectivity, $\sim 2 \times 10^{10}$ cm Hz$^{1/2}$/W at 230 K, under reverse bias 100 mV and $\sim 4 \times 10^{9}$ cm Hz$^{1/2}$/W at 300 K, under 500 mV. Presented results are better than PIN architectures with the same and lower cut-off wavelength grown on GaAs without immersion lens and grown on GaSb substrates.

1. Introduction

In the competition for which material system will be chosen for the future single pixel detectors, the type-II InAs/GaSb superlattice (T2SLs) has recently shown significant improvement and proven itself a viable alternative to the state of the art mercury cadmium telluride (MCT) suitable for mid-wave infrared (MWIR) range [1–3]. T2SLs have demonstrated their flexibility in controlling the electronic band structure as well as creating sophisticated designs, which enabled achieving performance levels comparable to that of MCT [4,5]. In addition, inherent T2SLs InAs/GaSb material properties related to the reduced Auger generation-recombination (GR) rates, higher effective masses in comparison to MCT material system are considered to be the very first step in theoretical improvement of the performance at higher operating temperature (HOT) condition [6]. In addition, further increase of the specific detectivity could be reached by GaAs immersion lens formation, where detector's optical and electrical areas ratio is increased by $\sim n^4$ of the GaAs substrate's refractive index contributing to $\sim n^2$ increase in detectivity [7]. This approach requires relatively thick GaAs substrates (~1.1 mm).

The paper presents performance of the T2SLs InAs/GaSb based PIN, mesa MWIR detector operated under HOT condition with 50% cut-off wavelength 5.2 μm at 230 K. The ~1.1 mm thick GaAs substrate was converted into immersion lens to increase performance, reaching peak detectivity $\sim 2 \times 10^{10}$ cm Hz$^{1/2}$/W at 230 K, under reverse bias 200 mV and $\sim 4 \times 10^{9}$ cm Hz$^{1/2}$/W at 300 K, under 500 mV. Presented results are better than PIN architectures with the same and lower cut-off wavelength grown on GaAs without immersion lens and grown on GaSb substrates.

2. Sample structure

The wafers presented in this work were grown by solid-source molecular beam epitaxy (MBE) VG-80 system in Center for High Technology Materials (CHTM), University of New Mexico (UNM) on epi-ready (100) GaAs substrates, while device fabrication process was performed at Military University of Technology (MUT) and Vigo System S.A.

The GaAs (~1.1 mm) substrate was converted into immersion lens by micropolishing technique. The analyzed MWIR T2SLs InAs/GaSb PIN detector is presented in Fig. 1, where SEM image of the GaAs immersion lens with diameter 1.66 mm (a), MWIR T2SLs PIN detector structure with GaAs substrate (b), and fully operating device before housing with four-stage thermoelectrical cooler (c) are shown. Detector's electrical area is $\sim 100 \times 100$ μm^2.

* Corresponding author.
E-mail address: piotr.martyniuk@wat.edu.pl (P. Martyniuk).

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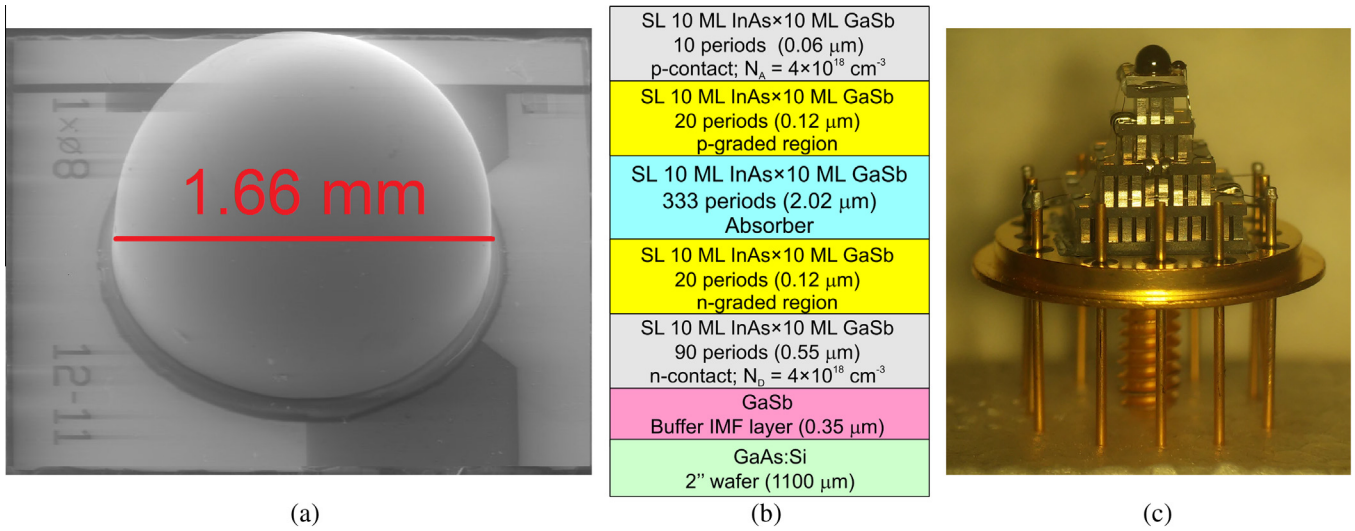

Fig. 1. SEM image of the GaAs immersion lens (a); MWIR T2SLs PIN detector structure with GaAs substrate (b); fully operating device before housing with four-stage thermoelectrical cooler (c).

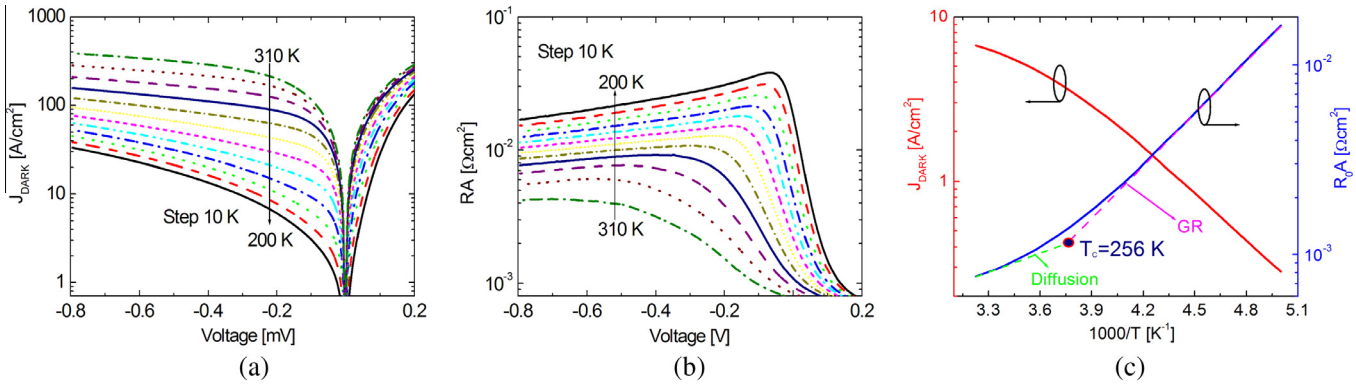

Fig. 2. Dark current density (a); differential resistance area product (b) versus applied voltage for selected temperatures 200–310 K; differential resistance area product at zero bias versus voltage and dark current versus reciprocal temperature (c) for PIN T2SLs InAs/GaSb detector with $100 \times 100\ \mu m^2$ area.

The detector structure consists of two 10 monolayer (ML) InAs × 10 ML GaSb:Te n-type doped ($4 \times 10^{18}\ cm^{-3}$) contact layers with thickness 0.55 μm (90 periods) and 60 nm (10 periods) respectively. Between contact layers the n-type (20 periods – 0.12 μm) and p-type (20 periods – 0.12 μm) doping graded regions and finally the non-intentionally doped absorber (333 periods – 2 μm) were grown. The interfacial misfit dislocation (IMF) array and GaSb (0.35 μm) buffer layer were introduced to accommodate the 7.8% lattice mismatch [8]. The total device thickness was estimated ~3.2 μm.

3. Results

Dark current density voltage (J_{DARK}-V) characteristics and differential resistance area product (RA) were measured and calculated for temperature ranging from 200 to 310 K with increments 10 K and are shown in Fig. 2(a) and (b), respectively. At 200 K and $V = 200$ mV, the dark current density was ~5 A/cm^2, corresponding to $RA \sim 0.03\ \Omega cm^2$. At 300 K and the same applied voltage, J_{DARK} was ~200 A/cm^2 with $RA \sim 0.003\ \Omega cm^2$. The shape of the R_0A product versus $1/T$ curve in Fig. 2(c) and the modeled values indicate that the dark current is dominated by two mechanisms in two different temperature regimes. From 310 to 256 K (where 256 K is a crossover temperature, T_C), the device performance is limited by the diffusion current. Below crossover temperature, the device is limited by the GR mechanism.

The $\lambda_{50\%\ cut\text{-}off} \sim 5.2$ μm wavelength at 230 K of analyzed devices was obtained from spectral response measurements using a Fourier IR spectrometer and is presented in Fig. 3(a) and (b) respectively. As the temperature increases from 195 K to 300 K the 50% cut-off wavelength of the device shifts from 5 μm to 5.6 μm. Band gap energy (E_g) of the T2SLs InAs/GaSb (10 ML InAs × 10 ML GaSb) was estimated from spectral response characteristics versus temperature at $V = 100$ mV according to Varshni formula: $E_g(T) = 0.288 - 3 \times 10^{-4}T^2/(T + 90)$ [9]. At 300 K and unbiased structure, the quantum efficiency (QE) was equal to 20% for $\lambda_{PEAK} = 4.5$ μm, while corresponding responsivity, (R_i) ~0.5 A/W. Above 100 mV, R_i (QE) remains constant ~3.15 A/W (~89%) for $T = 230$ K.

The specific detectivity was estimated using the relation $D^* = n^2 R_i \sqrt{A/i_n^2}$ where R_i is a measured responsivity, n is GaAs refractive index, A is electrical area of the detector and $i_n = \sqrt{(4k_BT/RA + 2qJ_{DARK})A}$ is a noise current (thermal Johnson–Nyquist and electrical shot noise contribution) where RA is the dynamic resistance area product, J_{DARK} is the dark current density, and k_B is the Boltzmann constant. D^* for structures with GaAs immersion lens versus wavelength and selected voltages