Infrared Physics & Technology 76 (2016) 542–545

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Brief Report

Low dark current P-*InAsSbP*/n-*InAs*/N-*InAsSbP*/n⁺-*InAs* double heterostructure back-side illuminated photodiodes

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HIGHLIGHTS

- Lowest capacitance of *InAs* heterojunction PD.
- Fast response.
- High detectivity in the 3 μm range.
- BLIP operation at 150 K at 3 μm.
- Flip-chip design.

ARTICLE INFO

Article history:
Received 26 January 2016
Revised 30 March 2016
Accepted 1 April 2016
Available online 13 April 2016

Keywords:
Mid-IR detectors
InAs photodiodes
Infrared sensors
Dark current
Backside illuminated photodiodes
Pyrometry
IR gas sensors

ABSTRACT

P-*InAsSbP*/n-*InAs*/N-*InAsSbP*/n⁺-*InAs* double heterostructure photodiodes with linear impurity distribution in the space charge region have been fabricated and studied. The photodiodes showed good perspectives for use in low temperature pyrometry as low dark current ($8\cdot10^{-6}$ A/cm^2, $V_{bias} = -0.5$ V, 164 K) and background limited infrared photodetector (BLIP) regime starting from 150 K (2π field of view, $D^*_{3.1\,\mu m} = 1.4\cdot10^{12}$ cm Hz$^{1/2}$/W) have been demonstrated.

1. Introduction

There is growing interest to photodiodes (PDs) with peak sensitivity around $\lambda = 3$–4 μm for use in thermal imaging [1], low temperature pyrometry [2,3] and in nondispersive infrared (NDIR) analysis of hydrocarbon gases that have fundamental absorption band near the 3.4 μm wavelength. In combination with light emitting diodes (LEDs) with peak emission at 3.4 μm the above large area PDs can be used for low power consumption gas sensors and portable gas analyzers [4] while small (element) area/capacitance PDs are important for recording of fast thermal processes.

In *InAs* based PDs an inversion layer on the surface of the p-type cap layer give rise to leakage current that may be of the same order that the bulk one in small area PDs [5]. This decreases specific detectivity D^* at low temperatures when bulk current is low [5–8]. That's why several passivation techniques including coating with SU-8 photoresist [6–8] and sulphidation treatment [9] have been already suggested in order to suppress surface leakage and to increase the zero bias resistance area product R_0A. On the other hand several publications outlined that creation of *P-InAsSbP/n-InAs/N-InAsSbP* double heterostructures (DH) increases R_0A product and decreases reverse current at high bias with respect to homo *InAs* and single heterojunctions with no *n-InAs/N-InAsSbP* interface (see e.g. [10]).

At the same time several groups reported on deep recombination centers (traps) that assist tunneling [11] and increase a response time [12] in *InAs* based p–n junctions. The authors of [11] stated that the tunnel leakage current is due mostly to the inclined dislocations. The authors of [12,13] reported on deep

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http://dx.doi.org/10.1016/j.infrared.2016.04.002
1350-4495/

diffusion of *Zn* atoms during the P-*InAsSbP(Zn)* growth onto n-*InAs* with sequential formation of 2–10 μm thick p-*InAs* layer containing electrically active defects [12]. It follows then that to improve the quality of the PDs one have to grow structures with no p-*InAs* layers, e.g. to grow the *P-InAsSbP/n-InAs/N-InAsSbP* DHs with spatial coincidence of p–n junction and heterointerface. Low plasticity of the P-*InAsSbP* quaternary alloy with respect to *InAs* [14] suppresses formation of defects [15] and thus one can expect reduction of leakage current in the P-*InAsSbP* cap layer.

In this paper we present and discuss data on electro-physical and optical characterization of the *P-InAsSbP/n-InAs/N-InAsSbP* DH PDs in the 60–300 K temperature range.

2. Device fabrication and measurements

Wafers were grown at 640–650 °C by the LPE method onto heavily doped n^+-*InAs* (*Sn*) (100) substrates with an electron concentration of $n^+ = (2–3)\cdot 10^{18}$ cm^{-3} and contained three epitaxial layers. They represented 2–3 μm thick wide-gap undoped N-*InAsSbP* ($E_g \approx 0.48$ eV, 77 K) confining layer, 3–4 μm thick n-*InAs* active region and 2–3 μm thick wide-gap P-*InAsSbP* (*Zn*) ($E_g \approx 0.48$ eV, 77 K, $P = (2–5)\cdot 10^{17}$ cm^{-3}) cap layer. In accordance with formalism and band gap parameters suggested in [16] the energy gap discontinuities constituted to $\Delta E_c = 120$ meV and $\Delta E_v = -30$ meV (300 K); the latter form shallow potential wells at an isotype N-*InAsSbP/n-InAs* interface (see Fig. 1). The photoluminescence spectrum of the narrow gap layer measured at 77 K in a reflection mode showed an emission peak at 0.41 eV, which is a common value for the undoped n^0-*InAs;* room temperature electroluminescence peaked at 0.36 eV typical for LEDs with n^0-*InAs* active layer as well. The latter suggests lack of P-*InAsSbP*/p-*InAs* heterojunction in our samples as the above Type II junction usually causes high radiative recombination rate of electron-hole pairs localized at shallow quantum wells at the P-*InAsSbP*/p-*InAs* interface with subsequent electroluminescent peak emission formation at 0.32 eV (300 K) [13]. It is worth mentioning that close proximity of p–n junction and *InAsSbP/InAs* interface has been already confirmed by the Atomic Force Microscopy (AFM) measurements in single P-*InAsSbP*/n-*InAs* heterostructure analogs grown by close procedure [17] and by recent AFM measurements to be published shortly.

Standard optical photolithography and wet chemical etching processes developed by Ioffe Institute together with IoffeLED, Ltd. have been implemented to obtain two types of rectangular PD chips with circular mesa ($d_1^m = 90$ μm and $d_2^m = 260$ μm) as high as 15 μm. Broad reflective Ag-based anode onto the P-*InAsSbP* cap layer and *Cr–Au–Ni–Au* cathode onto the n^+-*InAs* substrate material were formed by evaporation in vacuum; together with Au wires they provided electrical connection to external circuits. Backside illumination (BSI) through a 110 μm thick substrate without shadowing by electrical contacts has been organized. PD chips were mounted into TO-18 cases; no special passivation technique has been implemented.

Current–voltage (*I–V*) characteristics were measured in the range of $I = 10^{-14}–10^{-3}$ A under dark or illuminated conditions at the CW mode using sub-femtoampere SourceMeter Keithley 6430 equipped with a remote preamplifier. $1/R_o$ (the derivative of the experimental *I–V* dependence near $V = 0$) was obtained via direct measurements at $|V_{bias}| < 5$ mV. The sample was mounted in the Closed Cycle Refrigerator CCS-450 DLTS (Janis). Optical source with $\lambda = 3$ μm was a light emitting diode LED30Sr (IoffeLED, Ltd.) with an immersion lens. Capacitance–voltage (*C–V*) characteristics were measured with E4980A LCR meter (KEYSIGHT Technologies) in the modulation frequency range of $f = 0.1–2000$ kHz.

Current sensitivity at maximum ($S_{\lambda max}$) was estimated with a Black Body model at 573 K using the sample with 260 μm wide circular mesa that provided minimal uncertainty in the incoming radiation flux. Relative S_λ spectra were measured with Globar as a light source.

3. Results and discussion

Fig. 2 presents typical temperature dependent *I–V* characteristics. Values of the current below $5\cdot 10^{-14}$ A are obviously uncertain because of noise. Low temperature reverse bias (RB) *I–V* characteristics at $|V_{bias}| > 0.4$ V most likely indicate leakage current but not an avalanche multiplication. This conclusion is supported by the fact that the 60 K photocurrent induced by the LED30Sr illumination was almost independent on V_{bias} indicating low avalanche multiplication probability for holes in n-*InAs*. The latter agrees with the recent evaluation of low value of the hole ionization coefficient in *InAs* [6–8].

The 296 K I^{FB}–*V* data as well as data for some other temperatures deviated from exponent at high currents probably due to series resistance impact. The ideality factor β derived from the modified Shockley formula ($I = I_o[\exp(eV/\beta kT) - 1]$) fitting had negligible dependence on temperature and was close to unity (see insert in Fig. 2) suggesting diffusion current domination in the whole 80–296 K temperature range.

Fig. 3 shows temperature variation of the R_oA product measured at $|V_{bias}| < 0.005$ V ($115 < T < 300$ K) and that simulated as $R_0A = A\beta kT/eI_o$ (FB fit, $T < 115$ K). Fig. 3 presents also the simulated detectivity $D^*_{\lambda max}$ values evaluated for thermal noise domination ($D^*_{\lambda max} = S_{\lambda max}\sqrt{R_oA/4kT}$, $S_{\lambda max}$ –current sensitivity at maximum). It follows from the Arrhenius plot in Fig. 3 that the activation energy of the temperature dependence of the R_oA product ($E = 0.25$ eV) is quite close to the *InAs* energy gap value. It is worth

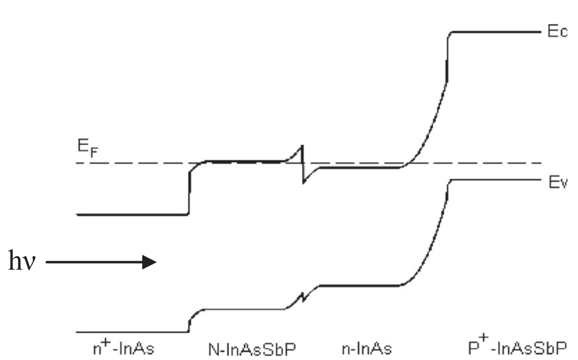

Fig. 1. Energy band-gap schematic of the P-*InAsSbP*/n-*InAs*/N-*InAsSbP*/n^+-*InAs* DH.

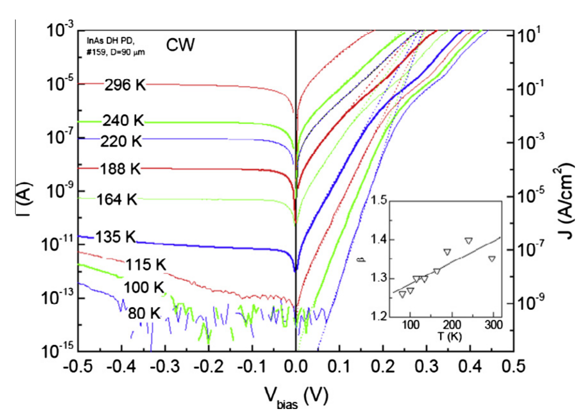

Fig. 2. Temperature-dependent semilog *I–V* characteristics of *InAs* DH diode with $d = 90$ μm. In the insert – ideality factor (β) vs temperature.