



Influence of the p-type doping on the radiometric performances of MWIR InAs/GaSb superlattice photodiodes



E. Giard^{a,*}, I. Ribet-Mohamed^a, M. Delmas^{b,c}, J.B. Rodriguez^{b,c}, P. Christol^{b,c}

^a ONERA, Chemin de la Hunière, 91761 Palaiseau, France

^b Univ. Montpellier, IES, UMR 5214, F-34000 Montpellier, France

^c CNRS, IES, UMR 5214, F-34000 Montpellier, France

HIGHLIGHTS

- T2SL photodiodes were grown with different designs and active zone thicknesses.
- InAs-rich design was proposed to both reduce the dark current and increase the QE.
- We study the influence of the active zone thickness on the QE spectrum.
- We examine the influence of the p-type doping on the QE spectrum.
- We study the influence of the SL design on the QE spectrum.

ARTICLE INFO

Article history:

Received 21 July 2014

Available online 7 August 2014

Keywords:

InAs/GaSb superlattice

Photodiode

Quantum efficiency

ABSTRACT

In this paper, quantum efficiency (QE) measurements performed on type-II InAs/GaSb superlattice (T2SL) photodiodes operating in the mid-wavelength infrared domain, are reported. Several comparisons were made in order to determine the SL structure showing optimum radiometric performances: same InAs-rich SL structure with different active zone thicknesses (from 0.5 μm to 4 μm) and different active zone doping (n-type versus p-type), same 1 μm thick p-type active zone doping with different SL designs (InAs-rich versus GaSb-rich and symmetric SL structures). Best result was obtained for the p-type doped InAs-rich SL photodiode, with a 4 μm active zone thickness, showing a QE that reaches 61% at $\lambda = 2 \mu\text{m}$ and 0 V bias voltage.

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1. Introduction

Type II InAs/GaSb superlattices (T2SL) were introduced in the early 70s by Esaki and Tsu [1]. T2SL mid-wavelength infrared (MWIR) pin photodiodes were first studied by Yang and Bennet [2]. Since then, significant improvements were obtained on SL detectors as show demonstrations of high-performance MWIR focal plane arrays (FPA) [3–7]. These performances were obtained with devices designed with barriers [8–10] to reduce the generation recombination dark current. Another way to enhance performances is to reduce the Shockley–Read–Hall (SRH) recombination mechanism in order to increase the carrier lifetimes. Most T2SL devices exhibit shorter carrier lifetime than InAs/InAsSb superlattices [11]. But InAs/InAsSb superlattices have not yet reached the same

performance than T2SL in terms of quantum efficiency (QE) and dark current [12].

Therefore to combine the long carrier lifetime of the InAs/InAsSb superlattice and the good QE of the T2SL, an InAs-rich T2SL was proposed [13]: this superlattice exhibits an InAs to GaSb thickness ratio close to $R = 2$. Good performances in terms of dark current were already reported [13–15] but a recent study tends to prove a problem of minority carrier collection with this design [16] leading to non-optimal performances in terms of QE.

In this paper, we report on quantum efficiency of MWIR SL photodiodes with active zone made of asymmetric period composed of 7 InAs monolayers (MLs)/4 GaSb MLs (7/4 SL structure), showing cut-off wavelength at 5 μm (77 K). We study the influence of a p-type doping in the active zone in order to correct the non-optimal collection of the minority carriers. Then we study the influence of the InAs to GaSb thickness ratio on the radiometric performances of MWIR InAs/GaSb superlattice photodiodes.

* Corresponding author. Tel.: +33 180 386 334.

E-mail address: edouard.giard@onera.fr (E. Giard).

2. Samples

The InAs/GaSb SL structure for the MWIR domain was grown on p-type GaSb substrate by Molecular Beam Epitaxy. The growth procedure, the epitaxy characterization and the device processing were already reported [14]. The structure is described in Fig. 1: it consists of a 200 nm Be-doped (p+ type doping $\sim 1 \times 10^{18} \text{ cm}^{-3}$) GaSb buffer layer, a 60 nm Be-doped (p+ type doping $\sim 1 \times 10^{18} \text{ cm}^{-3}$) SL layer, an InAs/GaSb SL active zone, a 60 nm Te-doped (n+ type doping $\sim 1 \times 10^{18} \text{ cm}^{-3}$) SL layer, and a 20 nm Te-doped (n+ type doping $\sim 1 \times 10^{18} \text{ cm}^{-3}$) InAs cap layer. Different samples are presented in this paper: the first samples (A, B, C) have an InAs-rich design with active layer thickness varying from 500 nm (155 periods) to 4 μm (1240 periods). The asymmetric period of this non-intentionally doped (nid) active zone is composed of 7 InAs monolayers (MLs)/4 GaSb MLs (7/4 SL structure). Then the second set of samples contains two InAs-rich (7/4 SL structure) samples (D, E) with active layer thickness of 500 nm and 4 μm respectively. But, unlike the first set of samples, the active zone of these samples is Be-doped (p type doping $\sim 1 \times 10^{15} \text{ cm}^{-3}$). The two last samples exhibit an active layer thickness equal to 1 μm with two different designs: sample F is a GaSb-rich (10/19) SL structure and sample B a symmetric (10/10) SL structure. These samples are listed in Table 1.

All these samples exhibit photoluminescence emission and cut-off wavelength around 5 μm at 77 K. From epitaxial SL material, circular mesa photodiodes were fabricated using standard photolithography. The devices were placed in a LN_2 bath cryostat ready to perform photoelectrical measurements at 77 K. All measurements presented below were performed with a front side illumination (through the InAs cap layer) on 160 μm diameter photodiodes.

3. Influence of the active zone thickness on the QE spectrum for InAs-rich T2SL pin photodiodes

To investigate an eventual non-optimal collection of the minority carriers suspected [16] in the InAs-rich SL structure, we decided to measure QE spectra of several InAs-rich samples with different active zone thicknesses (AZT). Fig. 2 presents the QE spectra of three InAs-rich samples with different nid AZT: 500 nm (sample A), 1 μm (sample B) and 4 μm (sample C). The QE spectra were measured at 77 K and 0 V bias voltage.

Each QE spectrum was measured in two steps. First the relative photoresponse was measured using a FTIR spectrometer and then the absolute QE was calibrated using a SR200 blackbody [16].

The following comments can be made in Fig. 2: at 0 V bias voltage, the QE between $\lambda = 4.5 \mu\text{m}$ and $\lambda = 5 \mu\text{m}$ does not depend on the thickness of the active layer. However, at 0 V bias voltage for shorter wavelengths, the thinner the active zone is, the higher the QE is. In the inset of Fig. 2 are plotted the experimental QE of

cap InAs $n^+ = 1.10^{18} \text{ cm}^{-3}$ (20nm)
n^+ (Te) SL (60nm)
active zone SL n.i.d
p^+ (Be) SL (60nm)
GaSb $p^+ = 1.10^{18} \text{ cm}^{-3}$ (200nm)
GaSb (p) substrate (2")

Fig. 1. Schematic view of the SL structure on p-type GaSb substrate.

the same samples at $\lambda = 4.5 \mu\text{m}$ versus the electric field, calculated as the ratio between the bias voltage and the active zone thickness. The QE of the thinnest active zone presents no bias voltage dependence. The QE of the 1 μm thick active zone increases with the reverse bias voltage until $-10,000 \text{ V/cm}$ ($U_{\text{bias}} = -1 \text{ V}$), and is constant for high reverse bias voltages. The QE of the thickest active zone increases linearly also with the reverse bias voltage. This reverse bias dependence of the QE could be the signature of a non-optimal minority carrier collection. Indeed, the nid region of the InAs-rich SL structures is expected to be n-type residual at 77 K, therefore the minority carriers are the holes. The real P–N junction is between the active layer and the p+ -doped SL layer, “far” from the illuminated side which is the InAs cap layer. The space charge region (SCR) width was calculated with the Poisson’s equations equal to 451 nm for 0 V bias voltage. The 500 nm thick active zone is quite completely depleted at 0 V whereas the 1 μm thick active zone and the 4 μm thick active zone are not. Therefore, the bias dependence of the QE (see the inset of Fig. 2) and the low QE values at 0 V bias voltage for short wavelengths and thick structures (see Fig. 2) can be explained by a short hole diffusion length. The hole diffusion length is necessarily shorter than 500 nm because the 1 μm thick active zone is not completely depleted at 0 V and the QE of this device increases linearly until $-10,000 \text{ V/cm}$.

4. Influence of the p-type doping on the QE spectrum of InAs-rich T2SL photodiodes

To optimize the minority carrier collection, we decided to dope the active zone with Beryllium (p-type doping $\sim 5 \times 10^{15} \text{ cm}^{-3}$). Be-doping was already used to increase the performances of InAs-rich structure but only in the long-wavelength infrared (LWIR) domain [17]. In the Be-doped active zone, the minority carriers are the electrons, unlike in the nid active zone in which the minority carriers are the holes (n-type residual doping). Because the electron mobility is higher than the hole mobility, the electron diffusion length is expected to be longer than the hole diffusion length.

Fig. 3 presents the QE spectrum of sample D at 0 V bias voltage and 77 K operating temperature. Sample D has a p-doped active zone and its active zone thickness is equal to 4 μm . Sample D was compared to sample C which has the same active zone thickness and the same 7/4 design but its active zone is nid. The QE of p doped active zone is higher than the QE of the nid active zone in the entire spectrum. The QE reaches 61% at $\lambda = 2 \mu\text{m}$. In the p doped active zone, nearly all photo-generated carriers are collected, whereas, in the nid active zone, carriers which are photo-generated far from the SCR are not collected. The inset of Fig. 3 presents the experimental QE of samples C and D at $\lambda = 4.5 \mu\text{m}$ versus the bias voltage. For reverse bias voltages higher than -0.4 V , the QE of sample D is nearly constant. It means that the electron diffusion length is long enough to collect nearly all minority carriers. But it also means that the electron diffusion length is shorter than 4 μm because between 0 V and -0.4 V the QE increases with the reverse bias voltage.

5. Influence of the SL design on the QE spectrum of T2SL photodiodes

To study the influence of the InAs to GaSb thickness ratio on the radiometric performances of MWIR InAs/GaSb superlattice photodiodes, two other samples were grown with different designs: sample F exhibits a GaSb-rich design (10/19 SL structure) and sample G exhibits a symmetric design (10/10 SL structure). These two samples have a 1 μm thick active layer. Therefore we can compare

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