**International Conference on Space Optics—ICSO 2018**

Chania, Greece

9–12 October 2018

*Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny*

# *InAs/GaSb Type-II superlattice (T2SL) photodetector operating in the very-long wavelength infrared (VLWIR) spectral domain*

*P. Christol*

*R. Alchaar*

*J. -B. Rodriguez*

*L. Höglund*

*et al.*

International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik,
Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 111806N · © 2018 ESA
and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2536158

# InAs/GaSb Type-II Superlattice (T2SL) photodetector operating in the long wavelength infrared (LWIR) spectral domain.

P. Christol[1*], R. Alchaar[1], J.B. Rodriguez[1], L. Höglund[2], S. Naureen[2], R. Marcks von Würtemberg[2], C. Asplund[2], E. Costard[2], A. Rouvié[3], J. Brocal[3], O. Saint-Pé[3]

[1] *IES, Université de Montpellier, CNRS, F- 34000, Montpellier, France*
[2] *IRnova AB, Isafjordsgatan 22 C5, SE-16440 Kista, Sweden*
[3] *Airbus Defence and Space, 31 Rue des Cosmonautes, ZI du Palays, 31402 Toulouse, France*

*Corresponding author e-mail : christol@ies.univ-montp2.fr

## ABSTRACT

In this communication, we report on electrical and electro-optical characterizations of InAs/GaSb Type-II superlattice (T2SL) LWIR photodetector, showing cut-off wavelengths at 11µm at 77K. The devices, made of barrier structures in XBp configuration, were grown by molecular beam epitaxy (MBE) on GaSb substrate. Experimental measurements on samples were made by photoresponse spectra, by capacitance-voltage (C-V) and dark current-voltage (I-V) characteristics performed as a function of temperature.

**Keywords:** infrared detector, barrier structure (XBp), Type-II superlattice (T2SL), InAs/GaSb, LWIR

## 1. INTRODUCTION

Detectors operating in the long wave infrared (LWIR, $8\mu m < \lambda < 12\mu m$) are useful for space applications. Among the suitable IR technologies addressing the LWIR spectral domain, InAs/GaSb Type II Superlattice (T2SL) on GaSb substrate is an attractive photodetector material for high performance cooled IR focal plane array (FPA) because of its potentiality in terms of operability and stability over time with high quantum efficiency and low dark current levels, associated with scalability to large format showing high uniformity.

The barrier photodetector is a minority carrier unipolar device, hybrid between a photovoltaïc and a photoconductive system, with a potential barrier to block the majority carrier transport. The bulk generation-recombination (GR) current, which is the dominant current in a pin photodiode at low temperature, is suppressed by excluding the depleted electric field region from the photon absorbing layer. Consequently, the unipolar barrier detector device is diffusion-current limited whatever the temperature and compared to a pin diode configuration, the dark current is strongly reduced inducing an improvement of the electrical performance at iso-temperature or an enhancement of the operating temperature at iso-performance[1]. Such detector structure, which replaced the regular pin photodiode, is made of n-type or p-type photon absorbing layer, a barrier layer (B) and a contact layer (X) that can be made from either the same, or a different material, to that used for the photon absorbing layer. In the case of InAs/GaSb T2SL lattice-matched to the GaSb substrate, the absorbing zone is p-type leading to a XBp configuration design with electron minority carriers[2].

In this paper, electro-optical (photoresponse) and electrical (I-V dark current-voltage and C-V capacitance-voltage) characterizations of XBp T2SL single pixel detectors operating in the LWIR domain are reported. In particular, the resulting dark current values are compared to the HgCdTe benchmark, known as rule 07[3], and are analyzed in term of lifetime of electron minority carriers by performing current simulations.

## 2. DESIGN OF XBP LWIR T2SL DETECTOR

The LWIR XBp architecture detector on GaSb substrate consists of a 4µm thick 15/7 InAs/GaSb SL (dimension in monolayers (MLs)) slightly p-type active region, chosen to exhibit a cut-off wavelength around 11µm at 77K, an appropriate p-type barrier layer to block majority hole carriers and finally, a highly n-type doped contact layer composed of the 15/7 InAs/GaSb SL and an InAs cap layer. The main difficulty in designing a XBp barrier structure resides in the choice of the barrier layer : high and thick enough to block the hole majority carrier transport while allowing the electron minority to reach the contact. A solution to have a barrier in the valence band is to consider a InAs/GaSb/AlSb/GaSb SL to tailor the hole potential barrier (ΔEv). A ΔEv higher than 250meV is adjusted by difference between the first heavy hole minibands of 15/7 InAs/GaSb SL and the one of InAs/GaSb/AlSb/GaSb SL for which a period 8/1/5/1 has been calculated.

The corresponding XBp band diagram structure calculated under no bias at 77K is shown in Fig. 1a, where the doping of each layer is specified. These have been chosen in order to confine the electric field in the barrier layer and to generate flat band (no depleted region) condition in the absorbing zone. Consequently, the device should be diffusion current limited. A small electron potential barrier (ΔEc) which can penalize the quantum efficiency can be noticed from Fig. 1a. This can be overcome by applying a small reverse bias. The T2SL XBp design is compared with an equivalent T2SL pin photodiode (same doping and thickness layers) which is displayed in Fig. 1b.

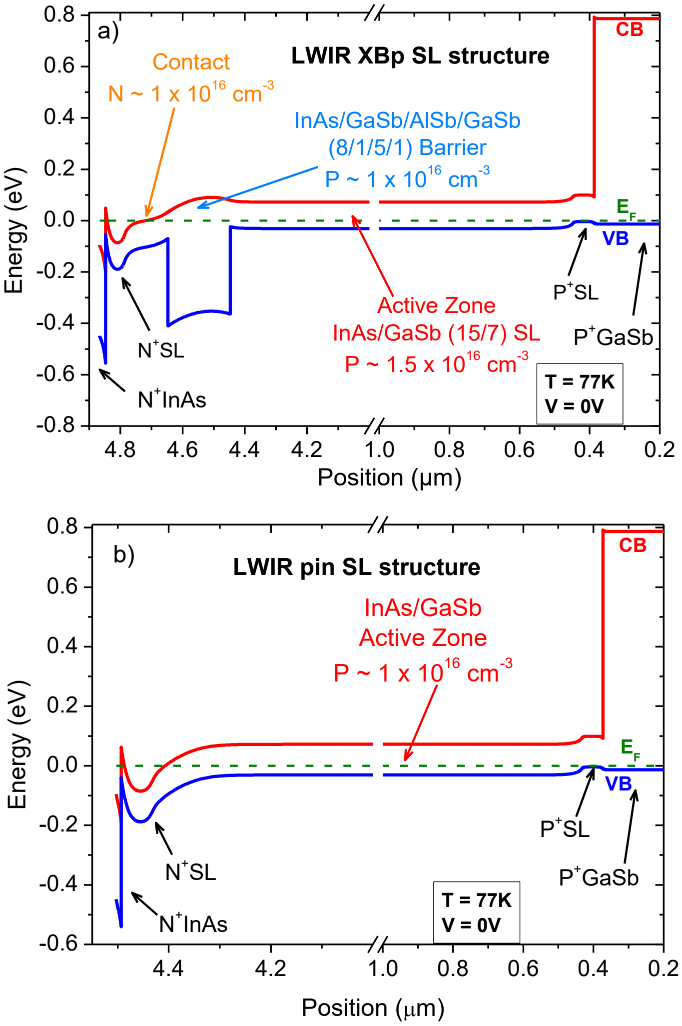

Fig. 1 : Calculated energy band diagram profile at T = 77 K under no bias of the LWIR XBp (a) and pin (b) SL structure.

In the case of pin photodiode, the dark-current under moderate reverse bias is mainly limited by the GR current at low temperature and by the diffusion current at high temperature. In addition, under some conditions of reverse bias and residual doping level, the trap-assisted tunneling (TAT) and the band-to-band tunneling (BTB) can affect the dark current. Same currents are present in a XBp barrier detector but, compared to a pin diode at a given temperature, GR current appears at higher reverse voltage. The dark current of the XBp T2SL structure was calculated using the ATLAS software from SILVACO. ATLAS is a commercially available physically based device TCAD simulator often used for the simulation of the dark current-voltage (J-V) characteristics of IR photodiodes[4].

The advantage of the barrier device is demonstrated in Fig. 2, which compares the calculated current-voltage characteristics at 77K obtained for the XBp and standard pin LWIR SL diodes. At low reverse bias, the pin diode is GR current limited with a dark current level at – 50 mV of $5.7 \times 10^{-3}$ A/cm$^2$. It can be seen that the BTB contribution appears quickly started from 120 mV reverse bias. On the other hand, the XBp device is, as expected, diffusion current limited at low reverse bias until -0.3V, showing a dark current density at -50mV of $3.7 \times 10^{-4}$ A/cm$^2$, which is more than one decade lower than the corresponding pin diode.

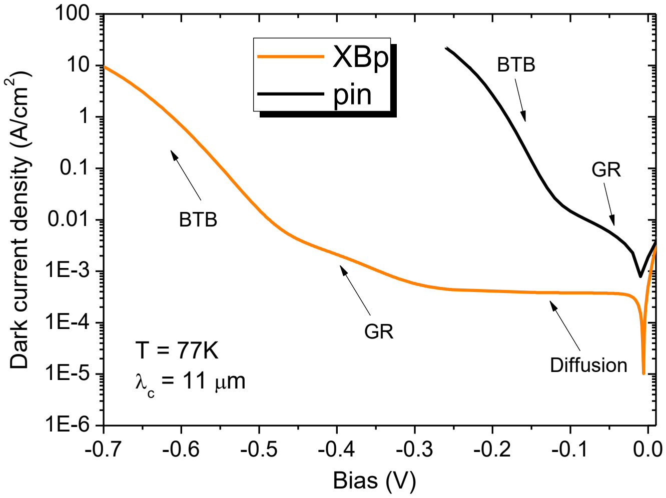

Fig. 2 : Simulated dark current density at 77K of LWIR T2SL detector : XBp and pin designs

## 3. FABRICATION AND CHARACTERIZATION OF XBP LWIR T2SL DETECTOR

The XBp structures previously designed but with an T2SL active layer of 3µm thick have been realized by molecular beam epitaxy (MBE) on GaSb substrate. From epitaxial SL material, LWIR single pixel photodiodes and photodiode arrays (PDA) were fabricated using standard III/V processing procedures. For single pixel photodiodes, photolithography was used with a mask set containing circular diodes and photodiodes with several diameters, from 60µm up to 310µm, while stepper lithography was used to define the pixels in the PDA fabrication. For both single pixels and PDAs, pixels were formed by a combination of dry and wet etching[5] and passivated using a dielectric passivation[6]. Top and bottom contact metal were made and for PDAs, indium bumps were evaporated onto the pixels before dicing. The arrays were then hybridized to fan-out chips (Silicon chip with surface metallic pattern identical to a read out integrated circuit (ROIC)), underfill was deposited and finally the GaSb substrate was fully removed.

Finally, the samples (single pixels and PDAs) were wire-bounded to a dedicated PLCC and loaded into a cryostat in order to perform both electrical and electro-optical characterizations at temperatures ranging from 20 to 200K.

### 3.1 Photoresponse spectra

Fig. 3 reports the calibrated photoresponse spectra, and then the external quantum efficiency (QE), of the XBp detector, recorded at various temperature (from 40K to 80K). The optical characterization was done at -0.15V applied bias voltage, under front-side illumination without any anti-reflection coating having been applied to the photodetector. At 80K, the device shows a 50% cut-off wavelength of 11µm, which corresponds with the chosen 15/7 period of the InAs/GaSb SL structure. For the device with 3µm thick absorption region, the QE is 30-35% in the 8-12µm LWIR domain.

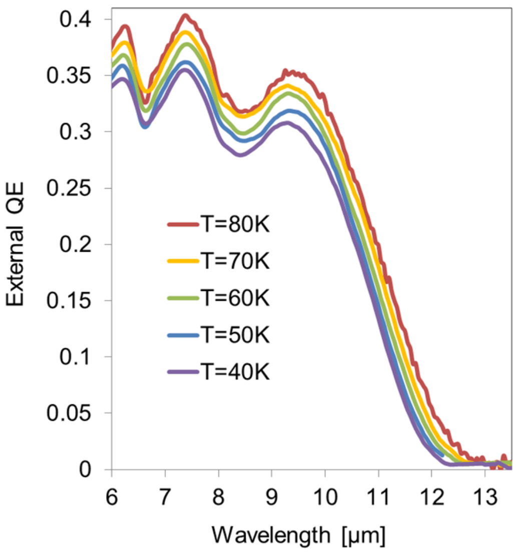

*Fig.3 : External quantum efficiency (QE) of the XBp LWIR T2SL detector at -0.15V applied bias voltage in front-side illumination configuration without any anti-reflection coating*

### 3.2 Capacitance Voltage (C-V) measurements

C-V characteristics at a frequency f = 1MHz were performed on T2SL XBp devices with different mesa sizes. Fig. 4a reports an example of measurement made at 80K for two different mesa detectors of the same test chip with diameters equal to 210µm (A2) and 310µm (A1). From linear parts of C-V spectrum, we can extract the reduced carrier concentrations $N_{dop}$ in the absorbing T2SL region and barrier layer (Fig. 4b) by using the following expression :

$$N_{dop} = \frac{2}{q\varepsilon_S\varepsilon_0 \frac{\partial\left(\left(\frac{A}{C}\right)^2\right)}{\partial V}}$$

where A is the device area, C is the measured capacitance, q is the electron charge, V the applied bias and the relative permittivity $\varepsilon_S$ of the T2SL layer is taken equal to 15.2 $\varepsilon_0$. A background carrier concentrations equal to $1\text{x}10^{16}\text{cm}^{-3}$ and $1.5\text{x}10^{16}\text{cm}^{-3}$ are deduced from the slopes, in agreement with the targeted values (Fig. 1a).

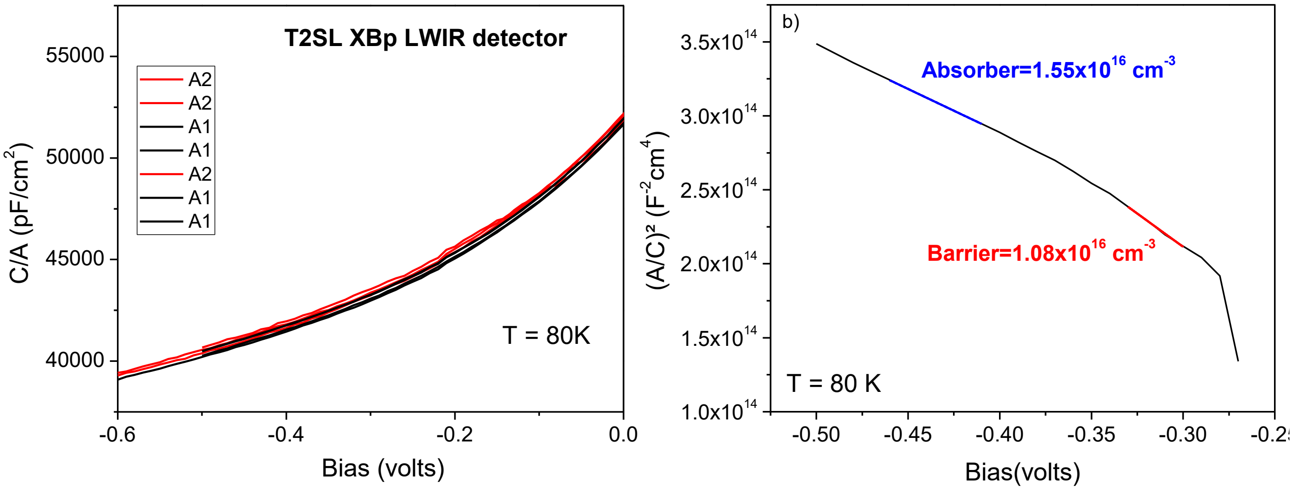

Fig. 4 : Capacitance per unit area (C/A) for the T2SL LWIR XBp detector at 80K (a) and extraction of carrier concentrations in the absorber and barrier layers (b)

### 3.3 Dark current density Voltage (J-V) measurements

Electrical measurements (J-V characteristics) performed in dark conditions (0° field of view) for different operating temperatures (from 20K to 160K) were measured using a Keithley 6517A electrometer to both apply the bias voltage and read the current delivered by the device. J-V curves are reported in Fig. 5. Al low temperature, experimental set-up (probe station) is sensible to photonic current until T = 70K. At this temperature, the dark current presents a diffusion behavior at low reverse bias until 0.4V before to be limited by G-R current. At 80K, dark current density as low as $4x10^{-4}A/cm^2$ at a reverse bias of -50 mV was measured, in total agreement with the one calculated in Fig. 2. This value is among the lowest dark current reported for XBp SL LWIR detectors having a cut-off wavelength at 11µm at 80K. However, at this wavelength and temperature, this dark current value remains more than one decade higher the well-known HgCdTe benchmark (rule 07[3]).

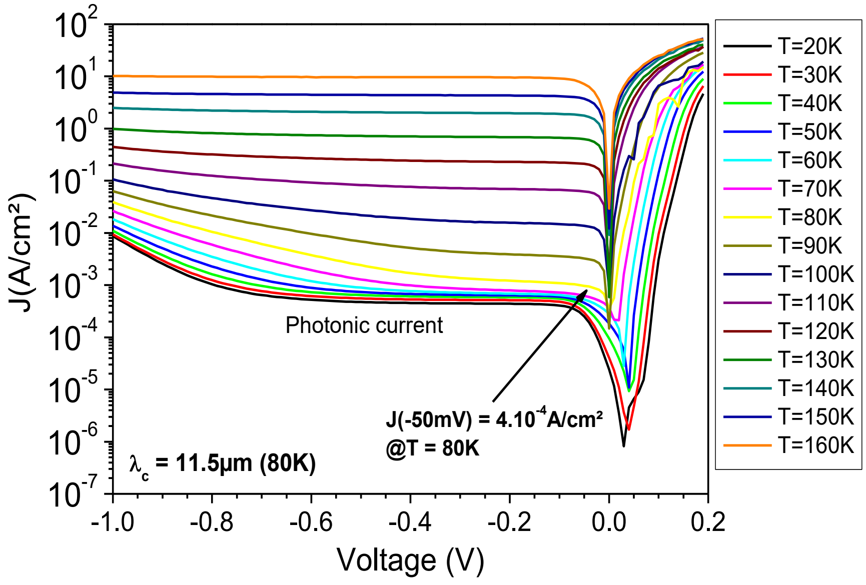

Fig. 5 : Dark current density–voltage characteristics of the XBp detector
for different operating temperature from 20 to 160K.

Dark J-V curves at different temperatures were then simulated where the minority carrier lifetime was adjusted to fit the measurements (Fig. 6a).

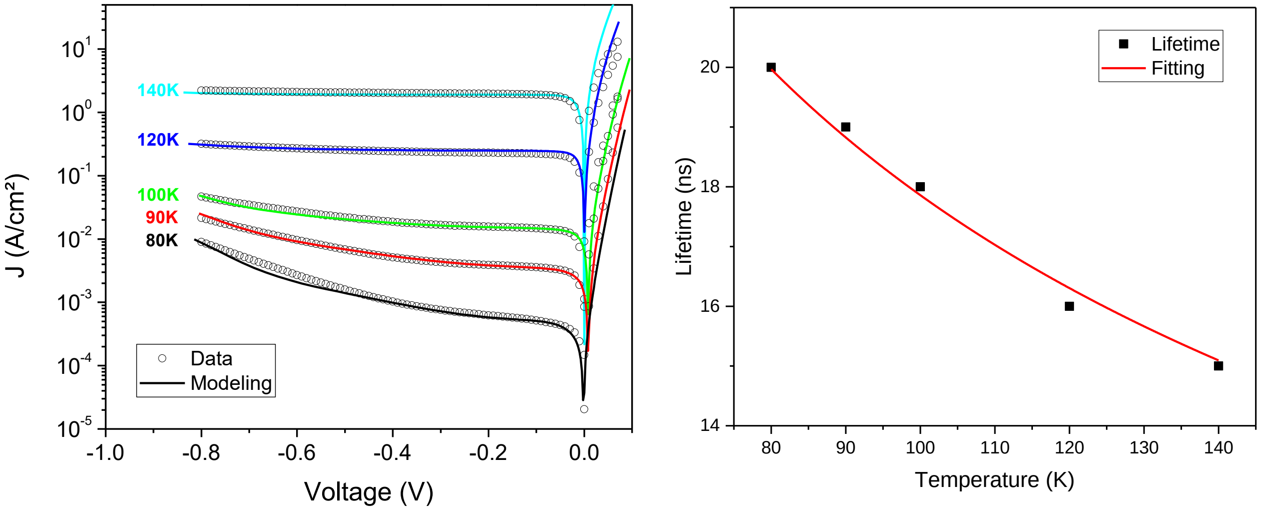

Fig. 6 : Experimental (open circles) and simulated J-V curves (line) at different temperatures (a)
Simulated lifetime as a function of temperature (square) and the adjusted $T^{-1/2}$ law (solid line) (b).

Values between 20 ns and 15 ns are obtained in the 80 to 140 K temperature range (Fig. 6b). The variation of the lifetime follows a $T^{-1/2}$ law, which is the signature that SRH (Shockley-Read-Hall) generation is the physical mechanism limiting the lifetime as already experimentally observed on LWIR InAs/GaSb T2SL[7].

## 4. SUMMARY

In this paper, results from the development of LWIR InAs/GaSb XBp T2SL photodiodes and detector arrays with cut-off wavelengths of 11µm have been presented. Low turn on bias (V = -0.15V) quantum efficiencies on the order of 30 % have been obtained with 3 µm thick absorbers (without AR-coating). With thick absorber layer and with AR coating, quantum efficiencies higher than 60% in the LWIR spectral range is expected. Dark current density as low as $4 \times 10^{-4}$ $A/cm^2$ for 11µm cut-off is measured, one decade higher than the corresponding MCT reference value.

These performance levels in combination with the radiometric stability over time observed for T2SL FPAs[8] make this technology an attractive alternative to the current state of the art technologies.

## 5. ACKNOWLEDGEMENTS

This work was partially funded by the French “Investment for the Future” program (EquipEx EXTRA, ANR 11-EQPX-0016) and ESA contract n° 4000116260/16/NL/BJ.

## REFERENCES

[1] Klipstein, P.C., "XBn and XBp infrared detectors", *J. Cryst. Growth* **425**, 351-356 (2015).

[2] Delmas, M., Rossignol, R., Rodriguez, J.B., Christol, P., "Design of InAs/GaSb superlattice infrared barrier detectors", *Super. Micro.* **104,** 402-414 (2017).

[3] Rhiger, D.R., "Performance comparison of Long-Wavelength Infrared Type II superlattice devices with HgCdTe", *J. Electron Mater.* **40**, 1815-1822 (2011).

[4] Delmas, M., Rodriguez, J.B., Christol, P., "Electrical modeling of InAs/GaSb superlattice mid-wavelength infrared pin photodiode to analyze experimental dark current characteristics", *J. Appl. Phys.* **116,** 113101-7 (2014)

[5] Chaghi, R., Cervera, C., Aït-Kaci, H., Grech, P., Rodriguez, J.B., Christol, P., "Wet etching and chemical polishing of InAs / GaSb superlattice photodiodes", Semicond. Sci. Technol. 24, 065010-6 (2009).

[6] Martijn, H., Asplund, C., Marcks von Würtemberg, R. and Malm, H.,"High performance MWIR type-II superlattice detectors", Infrared Technology and Applications XXXIX, Proc. of SPIE Vol. 8704, 87040Z (2013).

[7] Connelly, B.C., Metcalfe, G.D., Shen, H., Wraback, M., "Direct minority carrier lifetime measurements and recombination mechanisms in long-wave infrared type II superlattices using time-resolved photo-luminescence" Appl. Phys. Lett. 97, 251117-4 (2010).

[8] Nghiem, J., Giard, E., Delmas, M., Rodriguez, J.B., Christol, P., Caes, M., Martijn, H., Costard, E., Ribet-Mohamed, I., "Radiometric characterization of type-II InAs/GaSb superlattice (t2sl) midwave infrared photodetectors and focal plane arrays", International Conference on Space Optics - ICSO 2016, **10562**, 105623Y (2017)