

# High-performance InP/InGaAs heterojunction bipolar phototransistors for optoelectronic applications

Jihane Ouchrif, Abdennaceur Baghdad, Aïcha Sahel, Abdelmajid Badri

Laboratory of Electronics, Energy, Automation and Information Processing (LEEA&TI), Department of Electrical Engineering, Faculty of Sciences and Techniques, Hassan II University of Casablanca, Mohammedia, Morocco

## Article Info

### Article history:

Received Nov 1, 2022

Revised Jun 4, 2023

Accepted Jun 17, 2023

### Keywords:

Bipolar phototransistor

InP/InGaAs heterojunction

Optical fiber

Telecommunication systems

Optoelectronic applications

Responsivity

TCAD-Silvaco

## ABSTRACT

Phototransistors are attractive devices for applications in optical fiber telecommunication systems. They are used for the detection of optical signals and the amplification of these signals. This paper presents an investigation of how the technological parameters of indium phosphide (InP)/indium gallium arsenide (InGaAs) heterojunction bipolar phototransistor can impact its responsivity at two wavelengths, 1310 nm and 1550 nm. Based on the results of this investigation, we proposed optimized structures for the studied phototransistor. In this work, we used the software technology computer aided-design (TCAD)-Silvaco to simulate the physical and the electrical behavior of the different structures. The proposed optimized phototransistors can be used for various optoelectronic applications.

This is an open access article under the [CC BY-SA](https://creativecommons.org/licenses/by-sa/4.0/) license.



## Corresponding Author:

Jihane Ouchrif

Laboratory of Electronics, Energy, Automation and Information Processing (LEEA&TI)

Department of Electrical Engineering, Faculty of Sciences and Techniques

Hassan II University of Casablanca

Mohammedia, Morocco

Email: ouchrif.jihane1@gmail.com

## 1. INTRODUCTION

Semiconductor devices are indispensable for communication and information systems, they are more requests for various applications. III-V semiconductor materials are used in the fabrication of electronic devices owing to their transport properties. They have a direct band gap, and their electronic mobility is high. They have exceptional speed characteristics, furthermore they enable the operation of electronic devices at high frequencies [1].

Indium phosphide (InP) and indium gallium arsenide (InGaAs) are semiconductor materials of the III-V family of semiconductors. InP-InGaAs HBTs have proved to be excellent electronic devices, they are characterized by high electrical performances of speed and superior frequency [2], [3], and excellent current handling capability [4]. The heterojunction bipolar phototransistor (HPT) has almost the same epitaxial layer as the HBT, but the exclusive difference is in the electrode structure which allows illumination at the top of the device structure [5], [6]. The optical signal is absorbed in the base-collector region, and the signal is amplified by the intrinsic gain of the transistor [7], [8].

Different research works on HPT were performed for several decades [9]–[11]. HPTs are considered promising alternatives to devices such as metal-semiconductor-metal (MSM), the PIN and avalanche photodiodes [12], [13]. Furthermore, HPTs are more advantageous for highly sensitive infrared photodetection and imaging over the PIN and the avalanche photodiode (APD) due to their excellent characteristics of high gains without differences in high potentials and without excess noise [14]–[16]. In addition, the operation of HPTs can be done at a low bias voltage, and with a low gain sensitivity to the bias voltages [17]. There are

several applications where photodetectors based on InP are requested and used, such as biomedical field, optical communication systems, environment and also firms of chemistry for near infrared (NIR) light detection [18].

The objective of this work is to investigate the impact of technological parameters on the electrical performances of the InP/InGaAs HPT in terms of the responsivity at the wavelengths 1310 nm and 1550 nm. This investigation will help us to propose some optimized devices with different values of responsivities. These devices can be used in various optoelectronic applications.

## 2. INDIUM PHOSPHIDE/INDIUM GALLIUM ARSENIDE HPT MODELLING

In this work, we designed the InP/InGaAs HPT, which is mainly based on the HBT structure studied in papers [2], [19]–[21]. It is basically composed of two III-V semiconductor materials made from two alloys, a binary alloy for InP, and InGaAs. The topology of HBT structure has been adapted to receive light. Regarding the modifications made in HBT structure, a base contact has been removed, and the emitter contact has been reduced. The type of illumination is from above.

As detailed in Table 1 and shown in Figure 1, the epitaxial layer structure of the InP/InGaAs HPT comprises a cap layer, an emitter 1 layer, an emitter 2 layer, a spacer layer, a base layer, a collector layer, a sub-collector layer and a buffer layer. For the fabrication of this device, there are different techniques used for the growth of epitaxial layers such as metal organic chemical vapor deposition (MOCVD), and molecular jet epitaxy (MBE) technique [22].

Figure 1 shows the device structure of the InP/InGaAs HPT that respects the order of the epitaxial layers of the Table 1. It is an NPN heterojunction bipolar phototransistor; the ohmic contacts are made of the material gold. In the top view, the optical window as illustrated is the space between the base and the emitter. The illuminated surface is equal to  $4 \times 4 \mu\text{m}^2$ . The illumination is considered vertical to the HPT optical window. To design the device structure, we have carefully layered and meshed the InP/InGaAs HPT using the device editor DevEdit which allows the creation of the device structure.

Table 1. Layer structure for lattice-matched InP/In<sub>0.47</sub>Ga<sub>0.53</sub>HPT

Layer	Material	Doping ( $\text{cm}^{-3}$ )	Thickness (nm)
Cap	In <sub>0.47</sub> Ga <sub>0.53</sub> As	$n=1 \times 10^{19}$	135
Emitter 1	In <sub>0.47</sub> Ga <sub>0.53</sub> As	$n=1 \times 10^{17}$	135
Emitter 2	InP	$n=1 \times 10^{17}$	40
Spacer	In <sub>0.47</sub> Ga <sub>0.53</sub> As	-	5
Base	In <sub>0.47</sub> Ga <sub>0.53</sub> As	$p=1.5 \times 10^{19}$	65
Collector	In <sub>0.47</sub> Ga <sub>0.53</sub> As	$n=1 \times 10^{16}$	630
Sub-collector	In <sub>0.47</sub> Ga <sub>0.53</sub> As	$n=1 \times 10^{19}$	500
Buffer	In <sub>0.47</sub> Ga <sub>0.53</sub> As	-	10
Substrate	Semi-insulating InP		

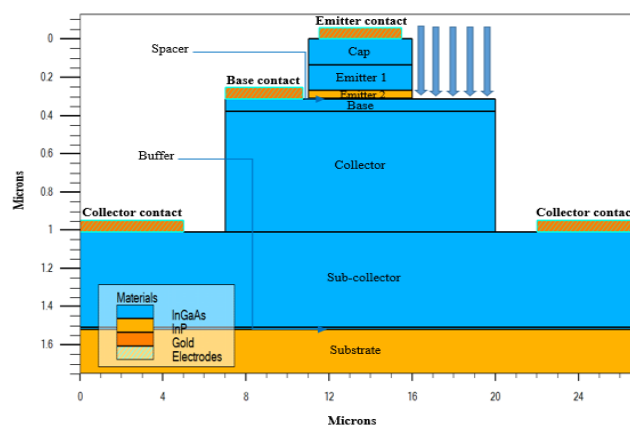


Figure 1. Schematic device structure of the InP/In<sub>0.47</sub>Ga<sub>0.53</sub>HPT

### 2.1. Physical and numerical modelling of InP/InGaAs HPT

ATLAS is a device simulator. It helps users predict the electrical behavior of any electronic device. It has been integrated into the simulation program for the physical and numerical modelling of HPT.

### 2.1.1. Physical modelling

The physical modelling of electronic devices allows to take into consideration the physical phenomena and mechanisms occurring within these devices. After designing the HPT device structure, we added in the simulation some physical models integrated into the simulator. Among these physical models, we cite the carrier statistical model (BGN), the recombination model (SRH), the Selberherr's model of the impact of ionization (IMPACT SELB), the band-to-band model (BBT.STD), the optical recombination model (OPTR), the parallel electric field dependence model (FLDMOB), and the fermi-dirac model (FERMI).

### 2.1.2. Numerical modelling

Semiconductor equations were solved employing the newton method. Among these equations, the carrier continuity equations, the Poisson's equation, the drift and the diffusion equations for both the electrons and the holes. These equations allow calculating currents, potentials and charge carriers, more details can be found elsewhere [21].

## 3. RESULTS AND DISCUSSION

This study is carried out at room temperature  $T=300$  K, for the two wavelengths 1310 nm and 1550 nm. The photodiode mode is taken for at  $V_{ce}=0$  V and  $V_{be}=0$  V. The phototransistor mode is considered for the bias conditions at  $V_{ce}=1.6$  V and  $V_{be}=0.86$  V.

### 3.1. HPT responsivity

#### 3.1.1. Responsivity definition

The responsivity  $R(\lambda)$  is defined as the ratio of photo-generated current to the input optical power and is expressed as (1) [5], [23]:

$$R(\lambda) = \frac{\lambda I_C(\lambda)}{hc\Phi_0(1-R_f)} \quad (1)$$

where  $h$  is planks constant,  $c$  is the velocity of light,  $\Phi_0$  is total incident flux density and  $R_f$  is the Fresnel reflection coefficient. The flux-dependent collector current ( $I_C$ ) is the sum of individual current contributions in the base, sub-collector and B-C depletion regions [23].

The phototransistor is working in two modes, photodiode mode and phototransistor mode; we are more interested in the phototransistor mode. The figures below present the simulation results of the studied InP/InGaAs HPT. We simulated the collector current as a function of light intensity, after that we extracted the responsivity in phototransistor mode  $R_{HPT}$ . For the applied light intensity, it is from 0 to  $100 \text{ W/cm}^2$ . All the results for responsivity are taken for the phototransistor mode, more precisely for  $V_{ce}=1.6$  V and  $V_{be}=0.86$  V. We investigated the impact of technological parameters on the responsivity of the studied HPT.

#### 3.1.2. Responsivity of the studied HPT at $\lambda=1310$ nm and $\lambda=1550$ nm

Figure 2 and Figure 3 present the evolution of the collector current (A) as a function of the light intensity ( $\text{W/cm}^2$ ) respectively at  $\lambda=1310$  nm and  $\lambda=1550$  nm. The light intensity is from 0 to  $100 \text{ W/cm}^2$ . It is clearly noticed a linear evolution, the collector current increases gradually with the increase of the applied light intensity. The responsivity  $R_{HPT}$  is approximately equal to  $3.2 \text{ A/W}$  at  $\lambda=1310$  nm, and it is around  $2.7 \text{ A/W}$  at  $\lambda=1550$  nm.

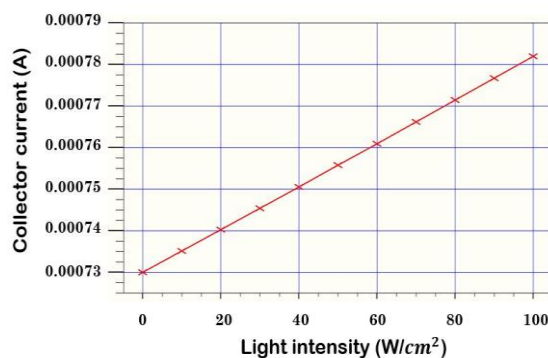


Figure 2. Collector current as a function of light intensity at  $\lambda=1310$  nm and  $V_{ce}=1.6$  V

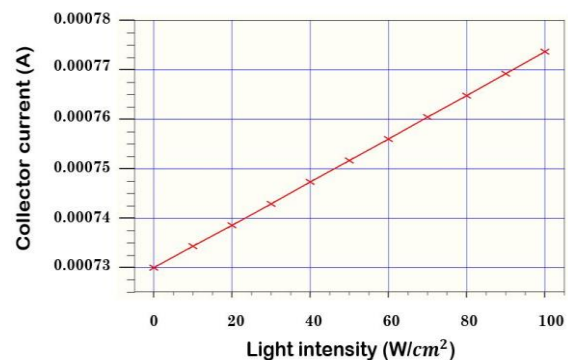


Figure 3. Collector current as a function of light intensity at  $\lambda=1550$  nm and  $V_{ce}=1.6$  V

We have investigated the impact of technological parameters of the studied phototransistor on its responsivity in the phototransistor mode. This investigation was performed at room temperature  $T=300$  K respectively for the wavelength  $\lambda=1310$  nm and  $\lambda=1550$  nm. The evaluated technological parameters are the base width, the base doping, and the collector doping.

A. Impact of technological parameters on responsivity in phototransistor mode at  $\lambda=1310$  nm

1) Impact of base width

Based on Figure 4, the collector current (A) increases with the application of light intensity ( $W/cm^2$ ). We noticed that the collector current increases with the reduction of the base width  $W_b$ . Figure 5 shows the responsivity  $R_{HPT}(A/W)$  of the HPT that varies according to the base width  $W_b$  for the wavelength  $\lambda=1310$  nm. We observed that the responsivity had an increasing trend with the decrease in the base width. Therefore, the decreased values of base width allowed obtaining high values of the responsivity of the HPT, the intrinsic current gain of a transistor increases when we reduce the base width [20]. The base width has the same important impact for the intrinsic current gain and the responsivity.

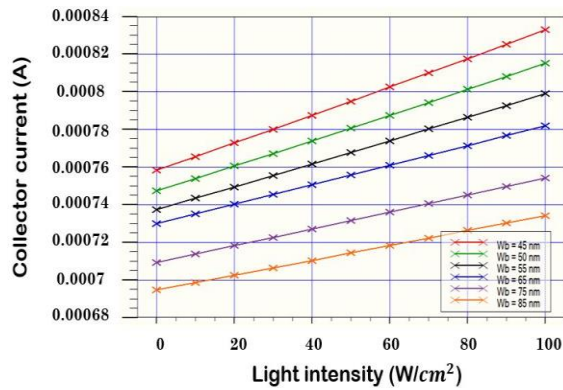


Figure 4. Collector current as a function of light intensity for different base width  $W_b$  at  $\lambda=1310$  nm and  $V_{ce}=1.6$  V

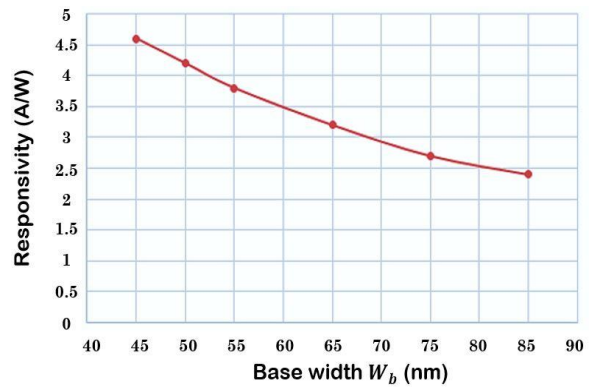


Figure 5. Responsivity as a function of base width  $W_b$  at  $\lambda=1310$  nm and  $V_{ce}=1.6$  V

2) Impact of base doping

Figure 6 presents the evolution of the collector current (A) as a function of the light intensity ( $W/cm^2$ ) for different base doping  $N_b$  at  $\lambda=1310$  nm. According to Figure 7, we find that when the base doping  $N_b$  is reduced, the responsivity  $R_{HPT}(A/W)$  increases gradually and reaches a large value for  $N_b = 1 \times 10^{18} cm^{-3}$ . The base doping  $N_b$  has a significant impact on the responsivity of the studied phototransistor.

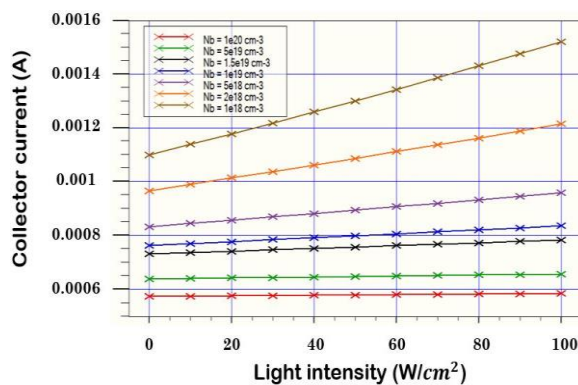


Figure 6. Collector current as a function of light intensity for different base doping  $N_b$  at  $\lambda=1310$  nm and  $V_{ce}=1.6$  V

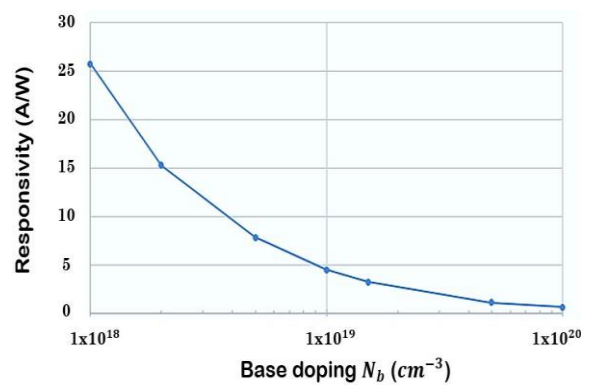


Figure 7. Responsivity as a function of base doping  $N_b$  at  $\lambda=1310$  nm and  $V_{ce}=1.6$  V

### 3) Impact of collector doping

According to Figure 8, the collector current  $I_C$  increases with the increasing of applied light intensity ( $W/cm^2$ ) at  $\lambda=1310$  nm. The investigated values of collector doping are between  $1 \times 10^{14} cm^{-3}$  and  $1 \times 10^{17} cm^{-3}$ . Based on Figure 9, we noticed from the examined values that the responsivity  $R_{HPT}(A/W)$  increases slowly and its value is constant for some values of  $N_C$ . Collector doping has a small impact on HPT responsivity compared to other technological parameters.

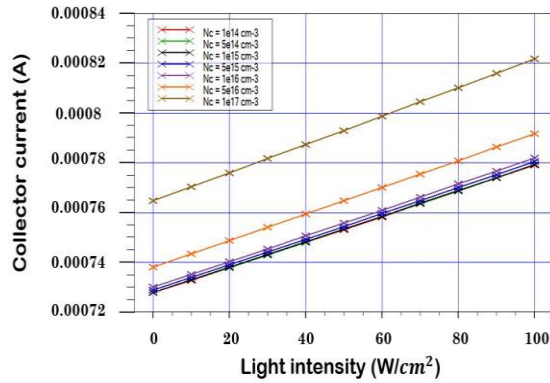


Figure 8. Collector current as a function of light intensity for different collector doping  $N_C$  at  $\lambda=1310$  nm and  $V_{ce}=1.6$  V

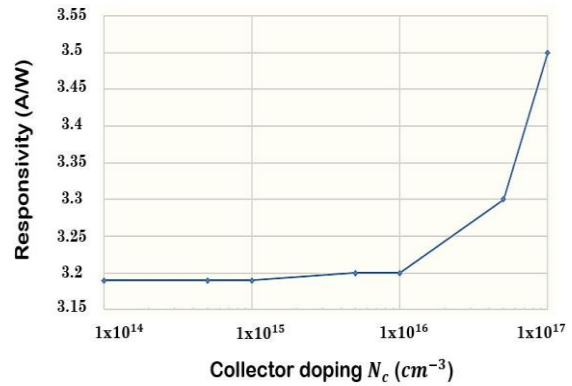


Figure 9. Responsivity as a function of collector doping  $N_C$  at  $\lambda=1310$  nm and  $V_{ce}=1.6$  V

## B. Impact of technological parameters on responsivity in phototransistor mode at $\lambda=1550$ nm

### 1) Impact of base width

Figure 10 presents the curve of collector current  $I_C$  as a function of the light intensity for different values of base width  $W_b$  between 45 nm and 85 nm. According to Figure 11, it is observed that the responsivity  $R_{HPT}(A/W)$  decreases with the increasing of the base width  $W_b$  at the wavelength 1550 nm. The base width as a technological parameter has an impact on the responsivity of this studied photodetector.

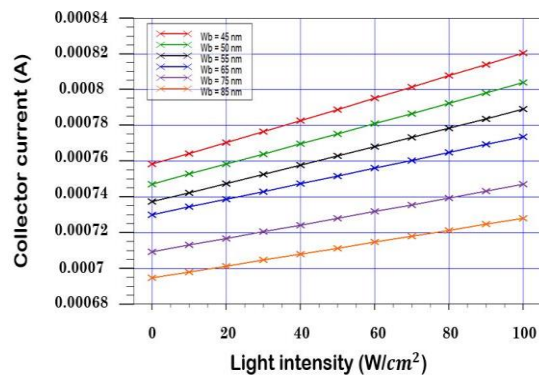


Figure 10. Collector current as a function of light intensity for different base width  $W_b$  at  $\lambda=1550$  nm and  $V_{ce}=1.6$  V

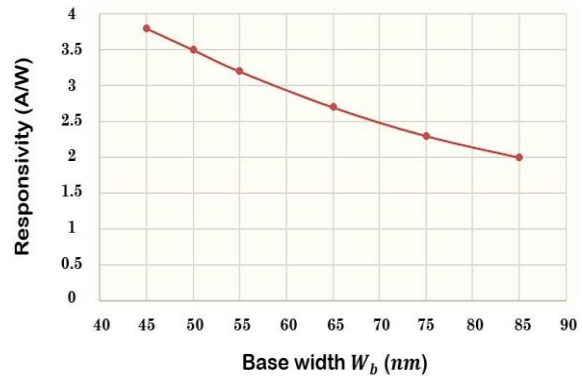


Figure 11. Responsivity as a function of base width  $W_b$  at  $\lambda=1550$  nm and  $V_{ce}=1.6$  V

### 2) Impact of base doping

Figure 12 presents the evolution of the collector current as a function of the light intensity ( $W/cm^2$ ) for different base dopings  $N_b$  at  $\lambda=1550$  nm. Based on Figure 13, we find that the responsivity  $R_{HPT}(A/W)$  increases when the base doping  $N_b$  is reduced. The base doping  $N_b$  corresponding to  $1 \times 10^{18} cm^{-3}$  gives the highest responsivity among the investigated base dopings ranging from  $1 \times 10^{18} cm^{-3}$  up to  $1 \times 10^{20} cm^{-3}$ . Therefore, the base doping  $N_b$  has a considerable impact on the responsivity of the phototransistor.

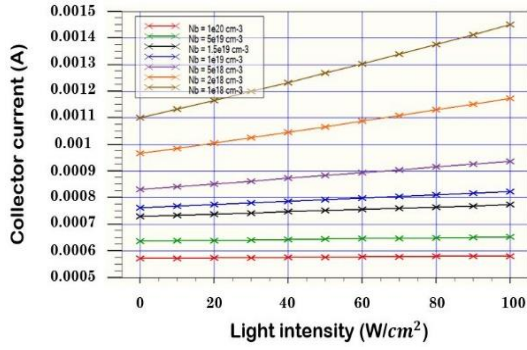


Figure 12. Collector current as a function of light intensity for different base doping  $N_b$  at  $\lambda=1550$  nm and  $V_{ce}=1.6$  V

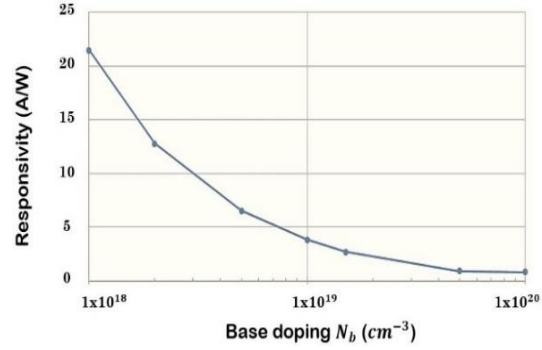


Figure 13. Responsivity as a function of base doping  $N_b$  at  $\lambda=1550$  nm and  $V_{ce}=1.6$  V

3) Impact of collector doping

According to Figure 14, the collector current  $I_C$  increases with the increasing of the applied light intensity ( $W/cm^2$ ) at  $\lambda=1550$  nm. The investigated values of collector doping range from  $1 \times 10^{14} cm^{-3}$  to  $1 \times 10^{17} cm^{-3}$ . Based on Figure 15, we noticed that responsivity  $R_{HPT}$  as a function of collector doping  $N_c$  varies in a very light way. The responsivity increases slightly.

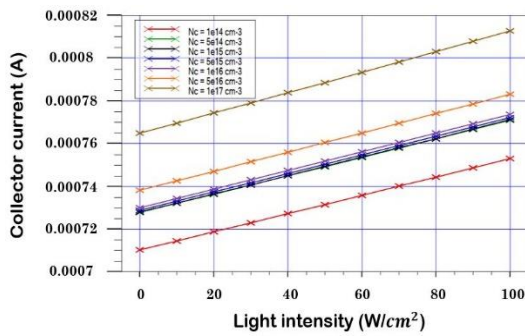


Figure 14. Collector current as a function of light intensity for different collector doping  $N_c$  at  $\lambda=1550$  nm and  $V_{ce}=1.6$  V

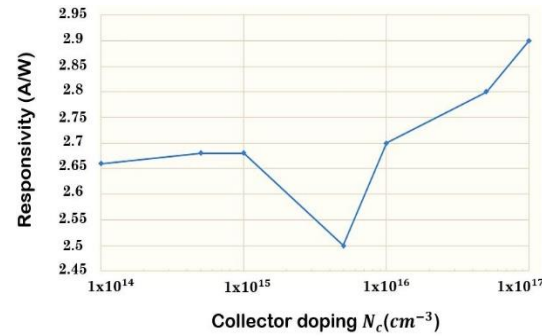


Figure 15. Responsivity as a function of collector doping  $N_c$  at  $\lambda=1550$  nm and  $V_{ce}=1.6$  V

3.1.3. Proposition of optimized structures

Based on the study of the impact of technological parameters on the responsivity of the phototransistor HPT InP/InGaAs. We proposed four new optimized topologies as shown in Table 2. These topologies can be used as photodetectors in optoelectronic applications. The Figures 16-23 present the simulation results of responsivity for the new optimized topologies of the InP/InGaAs HPT for  $\lambda=1310$  nm and  $\lambda=1550$  nm.

Table 2. Proposed optimized topologies HPTs

Changed parameters	Studied structure	Optimized structure A	Optimized structure B	Optimized structure C	Optimized structure D
Base width $W_b$ (nm)	65	50	50	50	50
Base doping $N_b$ ( $cm^{-3}$ )	$1.5 \times 10^{19}$	$1 \times 10^{19}$	$5 \times 10^{18}$	$2 \times 10^{18}$	$1 \times 10^{18}$
Collector doping $N_c$ ( $cm^{-3}$ )	$1 \times 10^{16}$	$1 \times 10^{17}$	$1 \times 10^{17}$	$1 \times 10^{17}$	$1 \times 10^{17}$

A. Responsivity of the optimized structure A

Figures 16 and 17 present the evolution of the collector current  $I_C$  as a function of the light intensity in phototransistor mode at  $V_{ce}=1.6$  V respectively for  $\lambda=1310$  nm and  $\lambda=1550$  nm. The collector current  $I_C$  increases with the increasing of the applied light intensity ( $W/cm^2$ ) which range between 0 to  $100 W/cm^2$ . The responsivity  $R_{HPT}$  (A/W) of the optimized structure A is around 7 A/W for  $\lambda=1310$  nm, and it is around 3.8 A/W for  $\lambda=1550$  nm.

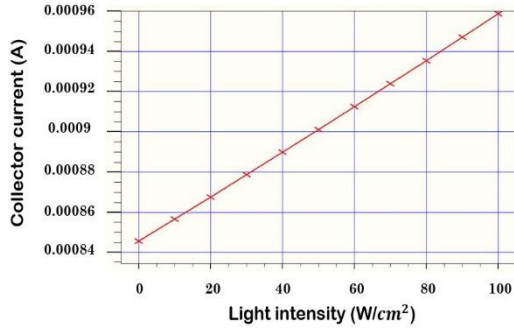


Figure 16. Collector current as a function of light intensity at  $\lambda=1310$  nm and  $V_{ce}=1.6$  V

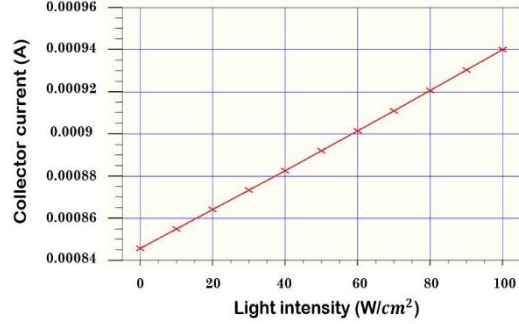


Figure 17. Collector current as a function of light intensity at  $\lambda=1550$  nm and  $V_{ce}=1.6$  V

B. Responsivity of the optimized structure B

As shown in Figures 18 and 19, the collector current  $I_C$  varies as a function of the light intensity in phototransistor mode at  $V_{ce}=1.6$  V respectively for  $\lambda=1310$  nm and  $\lambda=1550$  nm. We applied light intensity ( $W/cm^2$ ) ranging from 0 to  $100 W/cm^2$ . We noticed that the collector current  $I_C$  is increasing with the increase of the light intensity ( $W/cm^2$ ). The responsivity  $R_{HPT}(A/W)$  of the optimized structure B is around 13.1 A/W for  $\lambda=1310$  nm, and it is around 10.9 A/W for  $\lambda=1550$  nm.

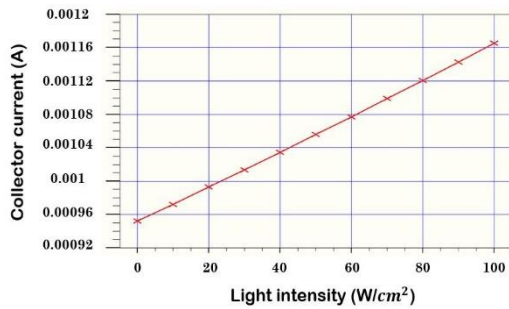


Figure 18. Collector current as a function of light intensity at  $\lambda=1310$  nm and  $V_{ce}=1.6$  V

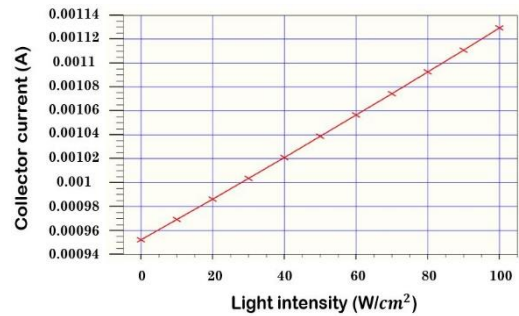


Figure 19. Collector current as a function of light intensity at  $\lambda=1550$  nm and  $V_{ce}=1.6$  V

C. Responsivity of the optimized structure C

From Figures 20 and 21, the collector current varies according to the light intensity in phototransistor mode at  $V_{ce}=1.6$  V respectively for  $\lambda=1310$  nm and  $\lambda=1550$  nm. The collector current increases gradually with increasing application of light intensities ranging from 0 to  $100 W/cm^2$ . The responsivity  $R_{HPT}(A/W)$  of the optimized structure C is around 29.3 A/W for  $\lambda=1310$  nm, and it is around 24.3 A/W for  $\lambda=1550$  nm.

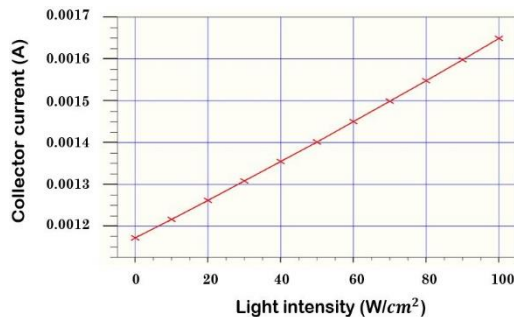


Figure 20. Collector current as a function of light intensity at  $\lambda=1310$  nm and  $V_{ce}=1.6$  V

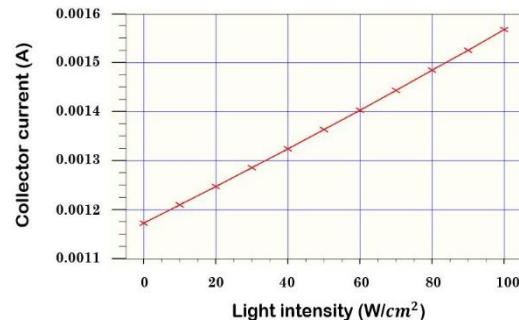


Figure 21. Collector current as a function of light intensity at  $\lambda=1550$  nm and  $V_{ce}=1.6$  V

D. Responsivity of the optimized structure D

According to Figures 22 and 23, the collector current evolves in a linear way with the application of the light intensity in phototransistor mode at  $V_{ce}=1.6$  V respectively for  $\lambda=1310$  nm and  $\lambda=1550$  nm. The light intensity varies from 0 to  $100$   $W/cm^2$ . The responsivity  $R_{HPT}(A/W)$  of the optimized structure D is equal to  $57.8$  A/W for  $\lambda=1310$  nm, and it is of the order of  $48.1$  A/W for  $\lambda=1550$  nm.

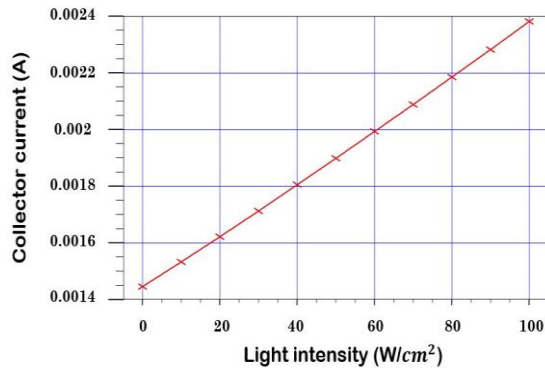


Figure 22. Collector current as a function of light intensity at  $\lambda=1310$  nm and  $V_{ce}=1.6$  V

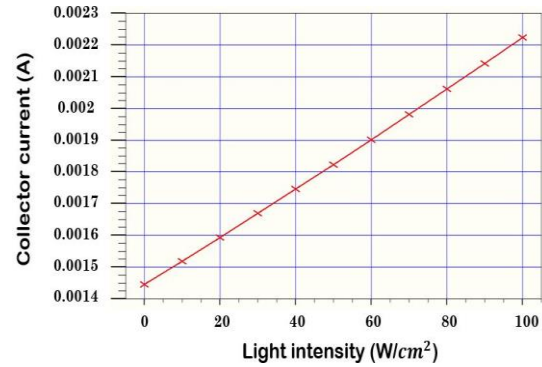


Figure 23. Collector current as a function of light intensity at  $\lambda=1550$  nm and  $V_{ce}=1.6$  V

3.1.4. Comparison with other research works

Table 3 presents the comparison between our results and some other research works, we were able to design photodetector topologies based on HPT InP/InGaAs. We obtained promising results in terms of responsivity which is a performance parameter allowing the characterization of photodetectors. These optimized structures can be used for digital fiber and microwave telecommunications applications.

Table 3. Comparison with other research results on InP/InGaAs HPTs

Reference	$R_{HPT}(\lambda=1.31 \mu m)$	$R_{HPT}(\lambda=1.55 \mu m)$
Jeong <i>et al.</i> [24]	-	5
Our work before optimization	3.2	2.7
Optimized structure A	7	3.8
Optimized structure B	13.1	10.9
Optimized structure C	29.3	24.3
Optimized structure D	57.8	48.1
Ouchrif <i>et al.</i> [25]	10	8.4
Khan <i>et al.</i> [5]	11	8.7
HPT without optical waveguide [26]	-	4
HPT with integrated optical waveguide [26]	-	29

4. CONCLUSION

In this present work, we investigated the impact of technological parameters on responsivity of InP/InGaAs HPT. Our results are mainly based on this investigation, and our objective is to design optimized structures using technology computer aided-design (TCAD)-Silvaco at the two wavelengths  $\lambda=1310$  nm and  $\lambda=1550$  nm. We proposed four structures. The optimized structure A has a responsivity of  $7$  A/W for  $\lambda=1310$  nm and  $3.8$  A/W for  $\lambda=1550$  nm. The optimized structure B has a responsivity of  $13.1$  A/W for  $\lambda=1310$  nm and  $10.9$  A/W for  $\lambda=1550$  nm. The optimized structure C has a responsivity of  $29.3$  A/W for  $\lambda=1310$  nm and  $24.3$  A/W for  $\lambda=1550$  nm. The optimized structure D has a responsivity of  $57.8$  A/W for  $\lambda=1310$  nm and  $48.1$  A/W for  $\lambda=1550$  nm. The proposed phototransistors were compared with other research works. These optimized structures can be integrated as photodetectors in different optoelectronic applications.

ACKNOWLEDGEMENTS

We gratefully thank L'Oréal and UNESCO for the financial support and encouragement of our scientific research. Thanks to the award the "2020 L'Oréal-UNESCO Young Talents Maghreb For Women in Science", this work is published.







## REFERENCES





- [1] T. G. Sanchez, J. E. V. Perez, P. M. G. Conde, and D. P. Collantes, "Electron transport in InP under high electric field conditions," *Semiconductor Science and Technology*, vol. 7, no. 1, pp. 31–36, Jan. 1992, doi: 10.1088/0268-1242/7/1/006.
- [2] T. Tauqeer, J. Sexton, F. Amir, and M. Missous, "Two-dimensional physical and numerical modelling of InP-based heterojunction bipolar transistors," in *IEEE International Conference on Advanced Semiconductor Devices and Microsystems*, Oct. 2008, pp. 271–274, doi: 10.1109/ASDAM.2008.4743335.
- [3] D. Yu *et al.*, "Ultra high-speed 0.25- $\mu\text{m}$  emitter InP-InGaAs SHBTs with  $f(\text{max})$  of 687 GHz," in *IEEE International Electron Devices Meeting, USA*, Dec. 2004, pp. 557–560, doi: 10.1109/IEDM.2004.1419219.
- [4] J.-I. Song, K. B. Chough, C. Palmstrom, B. P. V. der Gaag, and W.-P. Hong, "Carbon-doped base InP/InGaAs HBTs with  $f_{\text{sub T}} = 200$  GHz," in *52nd Annual Device Research Conference*, Jun. 1994, pp. 97–98, doi: 10.1109/DRC.1994.1009431.
- [5] H. A. Khan, A. A. Rezaadeh, S. Sohaib, and T. Tauqeer, "Detailed analysis on the spectral response of InP/InGaAs HPTs for optoelectronic applications," *IEEE Journal of Quantum Electronics*, vol. 48, no. 5, pp. 576–580, May 2012, doi: 10.1109/JQE.2012.2187176.
- [6] N. Chennafi, C. Rumelhard, C. Gonzalez, and J. Thuret, "Modelling the photoresponse characteristics of InP/InGaAs heterojunction phototransistor with different incident directions of beam light," presented at the *Gallium Arsenide Applications Symposium. GAAS 1998, Amsterdam, The Netherlands*, Oct. 1998, doi: 10.6092/unibo/amsacta/1616.
- [7] J. P. Helme, P. A. Houston, and C. H. Tan, "Large-signal charge control modeling of photoreceivers for applications up to 40 Gb/s," *IEEE Journal of Quantum Electronics*, vol. 45, no. 7, pp. 833–839, Jul. 2009, doi: 10.1109/JQE.2009.2013127.
- [8] H. Kamitsuna, "Ultra-wideband monolithic photoreceivers using HBT-compatible HPTs with novel base circuits, and simultaneously integrated with an HBT amplifier," *Journal of Lightwave Technology*, vol. 13, no. 12, pp. 2301–2307, Dec. 1995, doi: 10.1109/50.475567.
- [9] J. Campbell, A. Dentai, C. Burrus, and J. Ferguson, "InP/InGaAs heterojunction phototransistors," *IEEE Journal of Quantum Electronics*, vol. 17, no. 2, pp. 264–269, Feb. 1981, doi: 10.1109/JQE.1981.1071072.
- [10] L. Wang *et al.*, "A new phototransistor with uni-travelling-carrier and optically gradual coupling properties," *Opto-Electronics Review*, vol. 17, no. 3, pp. 242–246, Sep. 2009, doi: 10.2478/s11772-008-0064-6.
- [11] J. Kim, W. B. Johnson, S. Kanakaraju, and C. H. Lee, "Lateral InP/InGaAs double heterojunction phototransistor over a trenced interdigitated finger structure," *Solid-State Electronics*, vol. 51, no. 7, pp. 1023–1028, Jul. 2007, doi: 10.1016/j.sse.2007.05.010.
- [12] B. Ściana, M. Panek, A. Borczuch, and M. Tłaczala, "Simulations of AlGaAs/GaAs heterojunction phototransistors," *Central European Journal of Physics*, vol. 9, no. 4, pp. 1114–1121, Aug. 2011, doi: 10.2478/s11534-011-0023-6.
- [13] M. N. Abedin, T. F. Refaat, O. V. Sulima, and U. N. Singh, "AlGaAsSb-InGaAsSb HPTs with high optical gain and wide dynamic range," *IEEE Transactions on Electron Devices*, vol. 51, no. 12, pp. 2013–2018, Dec. 2004, doi: 10.1109/TEDE.2004.838328.
- [14] S. W. Choi, S. Furue, N. Hayama, K. Nishida, and M. Ogura, "Gain-enhanced InGaAs-InP heterojunction phototransistor with Zn-doped mesa sidewall," *IEEE Photonics Technology Letters*, vol. 21, no. 17, pp. 1187–1189, Sep. 2009, doi: 10.1109/LPT.2009.2023367.
- [15] R. Basu, V. Chakraborty, B. Mukhopadhyay, and P. K. Basu, "Predicted performance of Ge/GeSn hetero-phototransistors on Si substrate at 1.55  $\mu\text{m}$ ," in *IEEE International Conference on Microwave and Photonics (ICMAP)*, Dec. 2013, pp. 1–5, doi: 10.1109/ICMAP.2013.6733553.
- [16] J. Chen and M. Zhu, "Performance optimization of Pnp InGaAs/InP heterojunction phototransistors," *Applied Physics A*, vol. 122, no. 12, p. 1034, Nov. 2016, doi: 10.1007/s00339-016-0565-y.
- [17] V. Fathipour, I. H. Nia, A. Bonakdar, and H. Mohseni, "On the sensitivity of electron-injection detectors at low light level," *IEEE Photonics Journal*, vol. 8, no. 3, pp. 1–7, Jun. 2016, doi: 10.1109/JPHOT.2016.2558508.
- [18] Y. C. Jo *et al.*, "Design and optical characterization of passive pixel with sensitivity-improved InGaAs/InP phototransistors considering light-dependent shunt resistance for near infrared imaging applications," *Japanese Journal of Applied Physics*, vol. 46, no. 9S, pp. 6222–6226, Sep. 2007, doi: 10.1143/JJAP.46.6222.
- [19] J. Sexton and M. Missous, "Annealing experiments on InP/InGaAs single and double HBTs grown by molecular beam epitaxy," in *The 10th IEEE International Symposium on Electron Devices for Microwave and Optoelectronic Applications*, Nov. 2002, pp. 300–305, doi: 10.1109/EDMO.2002.1174975.
- [20] J. Ouchrif, A. Baghdad, A. Sahel, A. Badri, and A. Ballouk, "Investigation of the static current gain for InP/InGaAs single heterojunction bipolar transistor," *Indonesian Journal of Electrical Engineering and Computer Science (IJECS)*, vol. 13, no. 3, pp. 1345–1354, Mar. 2019, doi: 10.11591/ijeecs.v13.i3.pp1345-1354.
- [21] J. Ouchrif, A. Baghdad, A. Sahel, A. Badri, and A. Ballouk, "How does technological parameters impact the static current gain of InP-based single heterojunction bipolar transistor?," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 9, no. 5, pp. 3432–3440, Oct. 2019, doi: 10.11591/ijece.v9i5.pp3432-3440.
- [22] J. Sexton, T. Tauqeer, M. Mohiuddin, and M. Missous, "GHz class low-power flash ADC for broadband communications," in *2008 International Conference on Advanced Semiconductor Devices and Microsystems*, Oct. 2008, pp. 235–238, doi: 10.1109/ASDAM.2008.4743326.
- [23] H. A. Khan and A. A. Rezaadeh, "Analytical modeling of the spectral response of heterojunction phototransistors," *IEEE Electron Device Letters*, vol. 30, no. 11, pp. 1158–1160, Nov. 2009, doi: 10.1109/LED.2009.2030376.
- [24] T. W. Jeong, K. Iiyama, and S. Takamiya, "Two terminal InP/InGaAs heterojunction phototransistor with lateral photodiode as sensing section," in *International Conference on Indium Phosphide and Related Materials, 2005*, May 2005, pp. 250–253, doi: 10.1109/ICIPRM.2005.1517470.
- [25] J. Ouchrif, A. Baghdad, A. Sahel, and A. Badri, "Study of responsivity for InP/InGaAs heterojunction bipolar phototransistor intended for optoelectronic applications," presented at the *8th Virtual International Conference on Science, Technology and Management in Energy*, Serbia, Belgrade, Dec. 2022, pp. 155–159.
- [26] P. A. Houston, J. Helme, W. K. Ng, and C. H. Tan, "InP/InGaAs heterojunction phototransistors for optoelectronic receivers," in *2004 IEEE International Conference on Semiconductor Electronics*, Dec. 2004, p. A 1-A 5, doi: 10.1109/SMELEC.2004.1620821.

## BIOGRAPHIES OF AUTHORS







**Jihane Ouchrif**     holds a Ph.D. degree in Electrical Engineering and Telecommunications in 2020 from the Faculty of Sciences and Techniques of Mohammedia, Hassan II University of Casablanca. She obtained an engineering degree in 2012 in Mechatronics from The National School of Applied Sciences of Tetouan. Her research areas are optoelectronics, semiconductor physics and devices. She worked as a technical engineer in Moroccan companies. She did scientific research in the EEA and TI Laboratory where she works on the design, the modeling and the simulation of different transistors in order to improve their electrical performances for applications in fiber-optic telecommunication systems, and she was under the supervision of Pr. A. Baghdad. She worked as a lecturer in electrical Engineering in the Faculty of Sciences and Techniques of Mohammedia. She won L'Oreal-UNESCO 'For Women in Science' Award for Maghreb in 2020. She also worked on the deposition of oxide thin films for catalytic applications during her postdoctoral internship at LOASL Laboratory, in the Faculty of Physics of Iași, in the Alexandru Ioan Cuza University in Romania, and she was under the supervision of Pr. Silviu Gurlui. She participated in national and international congresses. She can be contacted at email: ouchrif.jihane1@gmail.com.







**Abdennaceur Baghdad**     is a holder of a Ph.D. in Electronics in 1992 at the University of Lille in France. He is a University Professor at Faculty of Sciences and Techniques of Mohammedia, Hassan II University of Casablanca, Morocco. He teaches the electronics, Hyper frequencies, antenna and telecommunications. He is a member of the laboratory EEA and TI (Electronics, Energy, Automatic and Information Processing). The research works of A. Baghdad concerns the communication and information technology (electronic systems and telecommunication). He supervises doctoral theses and he is a co-author of several national and international publications. He was a member of steering committees of several international congresses in the same field of research. He can be contacted at email: nasser\_baghdad@yahoo.fr.



**Aïcha Sahel**     is a holder of a Ph.D. in Electronics and Image Processing in 1996 at the University of Poitiers in France. She works as a University Professor at the Faculty of Sciences and Techniques of Mohammedia, Hassan II University of Casablanca, Morocco. She teaches the electronics, the signal processing, the image processing and Telecommunication. She is a member of the laboratory EEA and TI (Electronics, Energy, Automatic and Information Processing). The research works of A. Sahel concern the communication and information technology (electronic systems, signal/image processing and telecommunication). She co-supervises doctoral theses and she is a co-author of several national and international publications. She is a member in financed research projects. She was a member of steering committees of several international congresses in the same field of research. She can be contacted at email: sahel\_ai@yahoo.fr.



**Abdelmajid Badri**     is a holder of a Ph.D. in Electronics and Image Processing in 1992 at the University of Poitiers in France. In 1996, he obtained the diploma of the authorization to manage Researches in the University of Poitiers in France on the image processing. He is a University Professor in the Faculty of Sciences and Techniques of Mohammedia, Hassan II University of Casablanca, Morocco. He teaches the electronics, the signal processing, the image processing and telecommunication. He is a member of the laboratory EEA and TI (Electronics, Energy, Automatic and Information Processing) which he managed since 1996. The research works of A. Badri concerns the communication and the information technology (electronic systems, signal/image processing and telecommunication). He is qualified by CNU-France in 61th section: informatics engineering, automatic and signal processing. He managed several doctoral theses. He is a co-author of several national and international publications. He is responsible for several research projects financed by the ministry or by the industrials. He was member of different committees of programs of international conferences and president of several international congresses in the same research field. He is a member and co-responsible in several scientific associations of the same research field. He can be contacted at email: abdelmajid\_badri@yahoo.fr.