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Optimization of the Electrical Characteristics of the Photodiodes based on III-Sb Antimonide by a $Ga_{1-y}Al_y$ Sb Window layer Deposit at the $Ga_{1-x}In_xSb$ Emitter Surface.

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ABSTRACT: *The semiconductor materials GaSb, InSb and their alloys appear thanks to their superior transport properties as good candidates for high frequency applications with very low power consumption. Thus, a special interest in microelectronic applications of this sector has manifested itself in recent years. However, the losses by recombination at the surface of the emitters constitute a brake on the development of devices based on these materials. To provide an answer to these performance losses of photodetectors, our team is working to model devices with a window layer on the surface of the emitters. In this article we seek to optimize the characteristic parameters of photodiodes based on III-Sb antimonides and their alloys. We have defined photodiodes models capable of allowing us to simulate the current-voltage characteristics. The simulations are made on two models of photodiode based on,* $Ga_{1-x}In_xSb$, $Ga_{1-y}Al_ySb$ *used as a window layer and GaSb as a substrate. The results showed that the deposition of window layer on the surface of the emitter, not only makes it possible to reduce the phenomena of recombination on the surface, but mostly to optimize the electrical characteristics, in particular the photocurrent density which goes from* $0,4mA/cm^2$ *at a density of the order of* $0,7mA/cm^2$ *.*

Keywords - *III-Sb Antimonides, Electrical Characteristics, Photodiode, Window Layer.*

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I. INTRODUCTION

To achieve optical interconnections using photonics III-Sb, it is necessary to develop a set of optoelectronic components that will provide the link between the components using an electrical signal. Among these optoelectronic components that provide this optical link, we are interested in photodetectors that convert the optical signal into an electrical signal. We will define models of one-dimensional structures capable of allowing us to appreciate the current-tension characteristics. From the current-tension characteristics obtained by simulation, we will extract the characteristic parameters of the two photodiode models. The two photodiode models are the homojunction model deposited on substrate $\mathbf{Ga_{1-x}In_xSb/Ga_{1-x}In_xSb/GaSb}$ and the homojunction model with window layer deposited on substrate $\mathbf{Ga_{1-y}Al_ySb/Ga_{1-x}In_xSb\ /Ga_{1-x}In_xSb/GaSb}$ with $\mathbf{Ga_{1-y}Al_ySb}$ as window layer. The simulation results are obtained in the wavelength range between 0.8µm and 1.74µm including the two windows [1.3µm and 1.55µm] used in optical fiber telecommunications [1].

II. MODELING

We recall that the analytical modeling is the first approach of the physical simulation. This is the approach, which requires the least amount of computing resources, since it is looking for to approach the phenomenon and /or the structure studied in order to have the simplest possible model. The aim is to define models of one-dimensional structures that allow us to calculate photocurrent densities involving geometric and photoelectric parameters. In order to obtain rapid results and make it possible to study the influence of certain parameters on the functioning of the photodetector devices, an analytical method of calculation on the diffusion phenomena has been developed. In the absence of polarization, the results give analytical solutions that allow to analyze the behavior of electronic components. The adopted method relies notably on electron and hole current equations and continuity equations. Mamadou Dia et al [2] carried out calculations of the current densities on the models that we present in this work. From their calculation results, we were able to continue in order to be able to simulate current-tension characteristics on our photodiode models.

1. Unidimensional Structure Models

1.1 Homojunction model p-n deposited on N-type substrate

In order to simulate a model corresponding to a p-n-N structure deposited on GaSb substrate (Figure1), we assume that the junction is between the first two layers (p-type and n-type) and that the thickness of the substrate is infinitely large compared to other geometrical parameters.

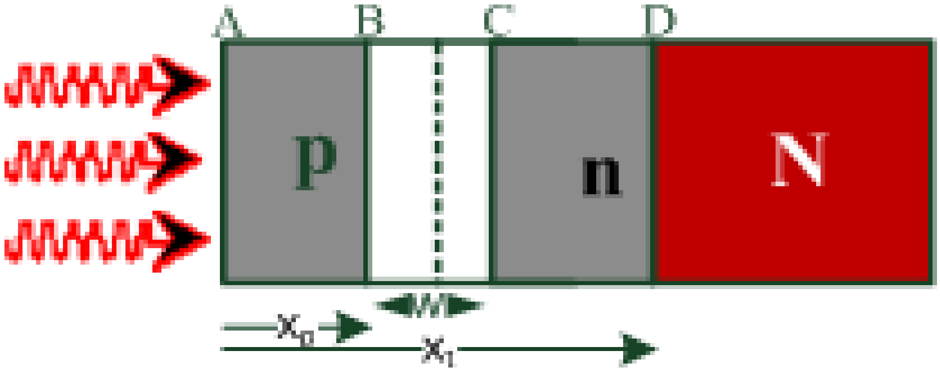

Figure 1: Schema of a homojunction p-n deposited on N-type substrate.

H. Luquet et al [3] used a similar model to calculate the quantum efficiency at the base. The uppercase letters (P and N) and lowercase letters (p and n), model the type of semiconductor, represent respectively the large-gap and the low-gap materials for the same type of doping. Mamadou Dia et al [2] used this model and calculated the photocurrent density resulting from the diffusion of the minority carriers generated in each region. Moreover, it is from their calculation results that we will be able to simulate, the current-voltage characteristic of this photodiode model.

1.2 Homojunction model with P-p-n window layer deposited on N-type substrate

In fact, on the surface of the emitter of a homojunction p-n deposited on substrate we deposit a layer whose gap of the material is greater than that of the emitter (figure 2). Mamadou Dia et al [2] used a similar model and calculated the photocurrent density resulting from the diffusion of the minority carriers generated in each region. Although, it is from their calculation results that we will be able to simulate the current-voltage characteristic of this photodiode model.

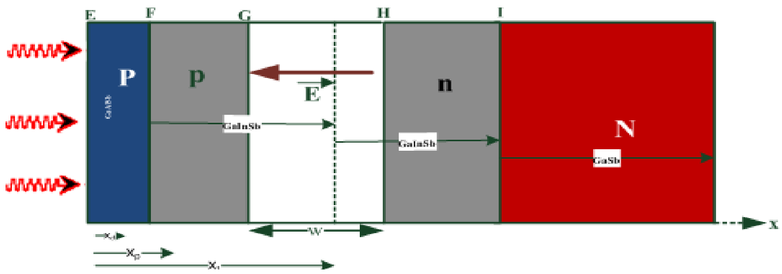

Figure 2: Schema of a homojunction P-p-n deposited on N-type substrate with P-type window layer.

Using a similar model, Mamadou Dia et al [2] obtained an expression of the internal quantum efficiency describing the contribution of the electrons generated in the two frontal layers. From this expression, we deduced the expression of the photocurrent density resulting from the diffusion of the electrons generated in these two layers. This contribution of the frontal layers is described by equation (1).

$$Jn_2 = -\frac{e(1-R)\Phi_0\alpha_2 Ln_2 e^{-(\alpha_1-\alpha_2)x_d}}{\left[(\alpha_2)^2(Ln_2)^2-1\right]}\left[\frac{\left(Ln_2\alpha_2+\frac{Sn_2Ln_2}{Dn_2}\right)e^{-\alpha_2x_d}-e^{-\alpha_2x_p}\left[\sinh\left(\frac{x_p-x_d}{Ln_2}\right)+\frac{Sn_2Ln_2}{Dn_2}\cosh\left(\frac{x_p-x_d}{Ln_2}\right)\right]}{\left[\cosh\left(\frac{x_p-x_d}{Ln_2}\right)+\frac{Sn_2Ln_2}{Dn_2}\sinh\left(\frac{x_p-x_d}{Ln_2}\right)\right]}-Ln_2\alpha_2e^{-\alpha_2x_p}\right]$$

$$-\frac{e(1-R)\Phi_0\alpha_1Ln_1}{\left[(\alpha_1)^2(Ln_1)^2-1\right]}\left[\frac{Ln_1\alpha_1+\frac{Sn_1Ln_1}{Dn_1}-e^{-\alpha_1x_d}\left[\sinh\left(\frac{x_d}{Ln_1}\right)+\frac{Sn_1Ln_1}{Dn_1}\cosh\left(\frac{x_d}{Ln_1}\right)\right]}{\left[\cosh\left(\frac{x_d}{Ln_1}\right)+\frac{Sn_1Ln_1}{Dn_1}\sinh\left(\frac{x_d}{Ln_1}\right)\right]\left[\cosh\left(\frac{x_p-x_d}{Ln_2}\right)+\frac{Sn_2Ln_2}{Dn_2}\sinh\left(\frac{x_p-x_d}{Ln_2}\right)\right]}-\frac{Ln_1\alpha_1e^{-\alpha_1x_d}}{\left[\cosh\left(\frac{x_p-x_d}{Ln_2}\right)+\frac{Sn_2Ln_2}{Dn_2}\sinh\left(\frac{x_p-x_d}{Ln_2}\right)\right]}\right] \quad (1)$$

In this equation, we have two terms. The first term describes the contribution of the electrons generated in the emitter and the second describes the contribution of the electrons generated in the window layer;
e is the elementary charge of a charge carrier, R is the reflection coefficient and Φ_0 is the flux density of the incident photons.

2. Electrical modeling of a photodiode under illumination

The understanding of the physical configuration of the elements of a photodiode is necessary to model an electric circuit of a photodiode under illumination. Indeed, to calculate the actually current delivered on a load R_{ch} of the external circuit, we must take into account most of the phenomena that govern the operation of a photodiode under illumination. For this, we introduce in the ideal photodiode model (Figure 3) two resistances, one in series R_s and the other in derivation R_{sh}. The model obtained is represented by the electric diagram of figure 3. This model is the most current one and is used by many authors to obtain values of certain parameters of the characteristic of a photodiode by methods of approximations [4].

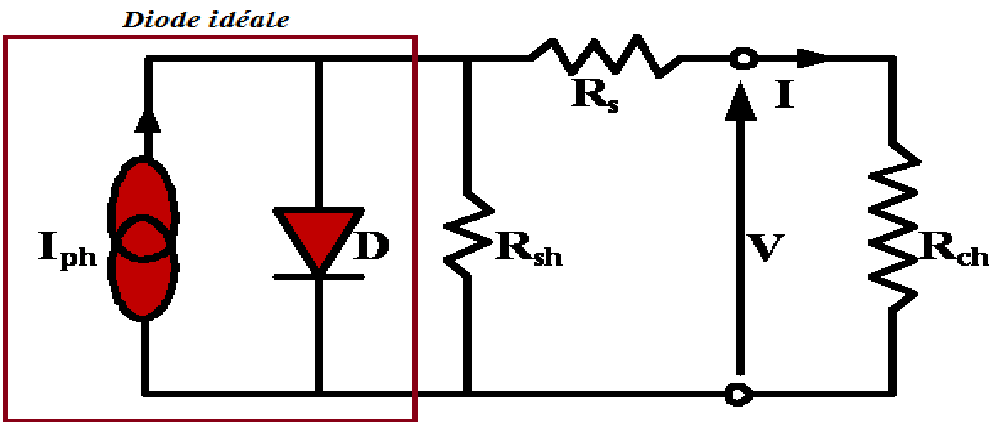

Figure 3: Electrical schema of a photodiode under illumination.

The electrical circuit of a photodiode under illumination is thus composed of a current source Iph, a diode in parallel D, a resistance R_s in series and a resistance R_{sh} in parallel.
The current source models the photogenerated current during absorption of incident photons.
The current losses related to the generation/recombination phenomena in the base and in the emitter are modeled by the diode D in parallel.
The resistance R_{sh} in parallel represents the leakage currents that exist in the structure. These leakage currents can take place along the periphery of the photodiode surface and through the emitter. These leakage currents become significant when the p-n junction is placed near to the surface [5]. The value of this resistance should be as high as possible. A good quality photodiode has a shunt resistance greater than $10^4\Omega$ [6].
The resistive losses in the semiconductor material and the contact resistances at the metal/semiconductor interfaces are modeled by the resistance R_s in series. It is possible to minimize the influence of this resistance on

the current delivered by the photodiode by optimizing the metal/semiconductor contacts and by decreasing the resistivity of the semiconductor material. For a good quality photodiode, R_s must be less than 1Ω [7].
Thus the characteristic current-tension equation of a photodiode under illumination is given by equation (2) [8]:

$$I = I_{ph} - Is.\left\{ \exp\left[\frac{q}{KT} \times (V + I.R_s) \right] - 1 \right\} - \frac{V + I.R_s}{R_{sh}} \quad (2)$$

This equation describes the static behavior of a photodiode under illumination. The first term of this expression models the photocurrent generated by absorption of incident photons, the second term represents the current losses related to the generation/recombination phenomena in the base and in the emitter and the third term describes the leakage currents that exist in the structure and the current losses by Joule effect through the resistance R_s in series.
I: the current delivered by the solar cell under illumination.
V: the voltage at the terminal of the load resistor Rch of the external circuit.
I_{ph}: Photocurrent generated by photon absorption.
R_s: The series resistance
R_{sh}: Shunt resistance or parallel resistance
Is: corresponds to the current of saturation which is the current of the minority carriers of the junction D.

III. SIMULATION OF THE PHOTOCURRENT-PHOTOTENSION $J_{ph} - V_{ph}$ CHARACTERISTIC OF A PHOTODIODE UNDER ILLUMINATION BASED ON $III - Sb$ ANTIMONIDES.

The use of the simulation tools has made it possible to better predict the behavior and performance of photodetector devices. The current-tension characteristic is a very important criterion of appreciation.

1. Characteristic photocurrent density-phototension of a $Ga_{1-x}In_xSb/Ga_{1-x}In_xSb/GaSb$ homojunction and a $Ga_{1-y}Al_ySb/Ga_{1-x}In_xSb/Ga_{1-x}In_xSb/GaSb$ homojunction with window layer.

A comparison of the current-voltage characteristic of the two models is obtained by simulation. The figure 4 shows the Jph-Vph characteristics of a **$Ga_{1-x}In_xSb_p/Ga_{1-x}In_xSb_n/GaSb$** homojunction and of a **$Ga_{1-y}Al_ySb_P/Ga_{1-x}In_xSb_p/Ga_{1-x}In_xSb_n/GaSb$** homojunction deposited on a GaSb substrate with **$Ga_{1-y}Al_ySb_P$** as a window layer (the indices P, p and n indicate the materials doping type and the capital letter indicates that the material has of greater gap).
The analysis of the photocurrent-phototension density characteristic shows that the characteristic of photodiode model with window layer is significantly higher than that of the classic photodiode model deposited on substrate. Note that regardless of the photodiode model considered, the Jph-Vph characteristic shows three areas of operation of the photodiode based on III-Sb antimonides and their alloys (Figure 4).

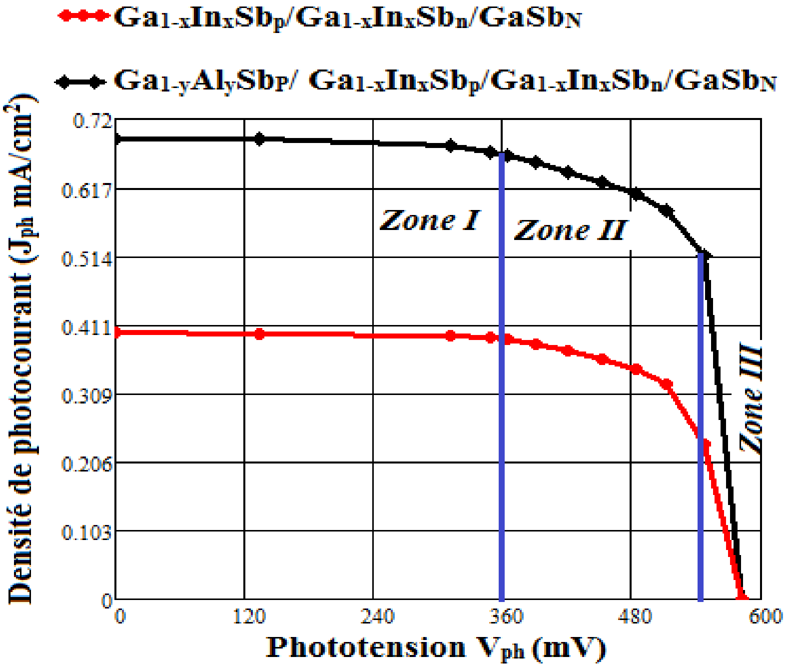

Figure 4: photocurrent-phototension density characteristic of two photodiode models under illumination

Zone I, where the photocurrent density is practically constant while the phototension increases. For this region, the photodiode functions as a current generator. This maximum photocurrent density corresponds to the short circuit current Icc of the photodiode.
Zone II, corresponding to the bend of the characteristic, the intermediate zone between the two zones, represents the preferred region for the operation of the photodiode. It is in this zone where it is possible to determine the optimum operating point, characterized by a maximum power density P_{max} of coordinates (J_{max}; V_{max}).
Zone III is distinguished by a variation in photocurrent density for almost constant phototension. In this region, the photodiode behaves like a tension generator. The maximum phototension noted in this region corresponds to an open-circuit voltage V_{oc} of the photodiode.
These three operating zones justify most of the characteristics that appear on the electrical circuit of a photodiode under illumination and that it is pratically impossible to obtain an ideal operation of the photodiode regardless of its design.

2. Determination of the Electrical Characteristics of the two Photodiode Models under Illumination.

The characteristic parameters of the photodiodes, extracted from the photocurrent-phototension density characteristics, make it possible to compare different photodiodes under the same illumination conditions. The main parameters are the open circuit voltage V_{oc}, the short circuit current density J_{sc}, the maximum power density P_{max}, the fill factor FF and the conversion efficiency η_{conv}. Figure.5 shows the photocurrent-phototension density characteristic of a $Ga_{1-x}In_xSb_p/Ga_{1-x}In_xSb_n$ /$GaSb_N$ homojunction and that of a $Ga_{1-y}Al_ySb_P$ /$Ga_{1-x}In_xSb_p$/ $Ga_{1-x}In_xSb_n$ /$GaSb_N$ homojunction with $Ga_{1-y}Al_ySb_P$ as a window layer.
From the photocurrent-phototension density characteristics of each model, we extracted the characteristic parameters of each of the two photodiodes models.

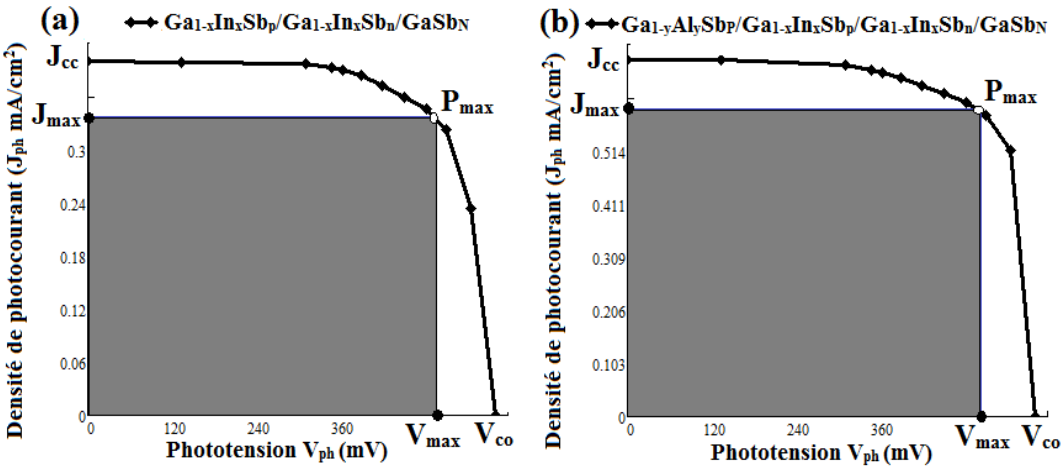

Figure 5: Jph-Vph characteristics of a $Ga_{1-x}In_xSb_p/Ga_{1-x}In_xSb_n$ homojunction and of a $Ga_{1-y}Al_ySb_P/Ga_{1-x}In_xSb_p/Ga_{1-x}In_xSb_n$ homojunction deposited on a GaSb substrate with $Ga_{1-y}Al_ySb_P$ as a window layer

Open circuit voltage V_{oc}: it is the maximum tension that can generate a photodiode under constant illumination, without any receiver at its terminals. In practice, this tension is measured using a voltmeter that is placed in parallel across the photodiode. In general, this open circuit voltage is of the order of 700mV. In the case of our two models, we obtain practically the same tension in open circuit V_{oc} = 583mV. However, the analysis of Jph-Vph characteristics shows us that for voltages higher than the respective Vco of the two models of photodiode under illumination, neither of the two photodiodes delivers current and cannot power any receiver. Therefore, it is under a tension lower than the open circuit voltage that a photodiode will be used, so that it outputs a tension and a current to power a receiver.
Photocurrent density of short circuit J_{sc}: It corresponds to the current density that flows through a junction under illumination without tension application. This photocurrent density depends inter alia on the mobility of the carriers and the wavelength of the radiation, therefore, on the absorption spectrum of the semiconductor material. The characteristic of the classical homojunction model gives a short-circuit photocurrent density J_{sc}=0,4mA/cm^2, while that of a homojunction with a window layer provides a density of the order of 0,7mA/cm^2. We assist to a clear improvement of this parameter, for the $Ga_{1-y}Al_ySb_P/Ga_{1-x}In_xSb_p/Ga_{1-x}In_xSb_n$ /$GaSb_N$ model compared to the classical homojunction model.
Maximum power point MPP: this is the point of optimal use of a photodiode. This point consists in supplying a load under a maximum tension and at a maximum current. Indeed, according to the formula P = IV, for the

power to be maximum, it is necessary that the photodiode operates under the conditions where the product I*V is maximum. These conditions correspond to an ideal point of charge of the photodiode or point of maximum power. This point P_{max} has coordinates V_{max} and I_{max} (Figure 5). The photocurrent-phototension density characteristic of each of the two photodiode models under illumination gives a maximum power density P_{max}=167µW/cm^2 for the classical homojunction (figure. 5a) and a maximum power density P max = 300 µW / cm^2 for the homojunction with window layer (Figure 5b). It is realized that the optimized photodiode produces almost twice as much power as the classic photodiode model deposited on substrate. The analysis of the current-tension characteristic shows that for tensions higher than a maximum tension V_{max}, there is a decrease in the photocurrent density. This decrease related to the recombination phenomena is modeled by the shunt resistance Rsh. In the case where the photocurrent density is greater than J_{max}, it is the dissipation losses (joule effect) which appear. These losses are modeled by the series resistance and are at the origin of the sharp decrease in the phototension observed at the photocurrent-phototension density characteristic (figure. 5). The maximum power density characterized by the maximum photocurrent density and the maximum phototension remains a determining parameter for optimal use of a photodiode.

Fill Factor FF: This is an important parameter that is used, from the photocurrent-phototension density characteristic, to qualify the quality of the photodiode. This factor represents the ratio between the maximum power P_{max} that can deliver a photodiode and the power formed by the rectangle J_{sc}-V_{oc}. The usable power of a photodiode will be greater if the value of the form factor is greater. The form factor name (fill factor) derives from the graphical representation. It is defined by the relation given by equation (3) [9].

$$FF = \frac{P_{max}}{V_{co} \times J_{cc}} = \frac{J_{max} \times V_{max}}{J_{cc} \times V_{co}} \qquad (3)$$

The photocurrent-phototension density characteristic of $Ga_{1-x}In_xSb_p$/ $Ga_{1-x}In_xSb_n$ /$GaSb_N$ gives a fill factor FF = 0.72 and that of the photodiode model with window layer gives a fill factor FF = 0.74. We find that the model, with window layer, has better conversion efficiency. Moreover, even in the ideal case, the fill factor cannot exceed 0.89 [10] because of the exponential term of the Boltzmann equations governing the current-tension equations. Indeed, the fill factor FF is a characteristic parameter that depends on the design of the photodiode, the quality of the p-n junction, the material used, the resistivity of the metal contacts, etc. [11].

Conversion efficiency η_{conv} : it is an essential parameter for characterizing a photodiode. The only knowledge of the value of this parameter allows us to appreciate the performance of the device. It is obtained from the electrical parameters extracted from the current-tension characteristics. The conversion efficiency is defined, as the ratio between the maximum power density, P_{max} delivered by the cell, and the incident light power density, P_{in}. This parameter is given by the equation (4) [12]:

$$\eta_{conv} = \frac{P_{max}}{P_{in}} = \frac{V_{max} \times J_{max}}{P_{in}} = FF \cdot \frac{V_{co} \times J_{cc}}{P_{in}} \qquad (4)$$

For a luminous power density of 600µW/cm^2, the classic cell model ($Ga_{1-x}In_xSb_p$/$Ga_{1-x}In_xSb_n$/$GaSb_N$) gives conversion efficiency of the order of 27.8%, whereas the homojunction model with a window layer ($Ga_{1-y}Al_ySb_P$/$Ga_{1-x}In_xSb_p$/$Ga_{1-x}In_xSb_n$/$GaSb_N$) allows to achieve an optimal efficiency of 50%. The presence of the window layer, of greater gap, on the emitter surface has thus made it possible to optimize the conversion efficiency of the conventional photodiode. Given the expression of this parameter, it is possible to improve it by increasing the fill factor FF, the short-circuit photocurrent density J_{sc}, or the open-circuit voltage V_{oc}.

The results are summarized in table 1.

Tableau1 : *Characteristic parameters of the two models of photodiodes ($Ga_{1-x}In_xSb_p$/$Ga_{1-x}In_xSb_n$ / $GaSb_N$ et $Ga_{1-y}Al_ySb_P$/$Ga_{1-X}In_XSb_p$/$Ga_{1-x}In_xSb_n$/$GaSb_N$) under illumination.*

Characteristic parameters	V_{oc}	J_{sc}	V_{max}	J_{max}	P_{max}	FF
$Ga_{1-x}In_xSb_p$/$Ga_{1-x}In_xSb_n$ /$GaSb_N$	583mV	0,4mA/cm^2	498mV	0,336mA/cm^2	167µW/cm^2	0,72
$Ga_{1-y}Al_ySb_P$/$Ga_{1-x}In_xSb_p$/$Ga_{1-x}In_xSb_n$/$GaSb_N$	583mV	0,7mA/cm^2	500mV	0,6mA/cm^2	300µW/cm^2	0,74

IV. CONCLUSION

In this paper we used the results of Mamadou Dia et al calculations based on the same models to simulate the current-voltage characteristics of two under illumination photodiode models. The models studied are a p-n homojunction model deposited on substrate and a homojunction model with a window layer deposited on substrate. The simulation of these photodiode models based on III-Sb antimonides and their alloys allowed us to show that the presence of the window layer makes it possible to optimize the characteristic parameters of the photodiodes, in particular the short-circuit photocurrent density which goes from 0,4mA/cm^2 at a density of the order of 0,7mA/cm^2. This model with window layer **($Ga_{1-y}Al_ySb/Ga_{1-x}In_xSb/Ga_{1-x}In_xSb/GaSb$)**, because of the good complementarity of the gaps of the materials, is therefore a credible alternative for classical photodetector devices for better use in the near infrared, precisely in the wavelength range between 0, 8µm and 1.74µm, including the two windows [1.3µm and 1.55µm] used in fiber optic telecommunications. Beyond improving the performance of photodiodes, this article will contribute to a better understanding of the physical phenomena that govern the photodiodes' operation.

REFERENCES

[1] Remi Beneyton, Sur l'incorporation du tallium dans une matrice III-V : préparation de GaTiAs et InTiAs par EJM ». Thèse de Doctorat, Ecole Centrale de Lyon, 16 Novembre 2004.

[2] M. Dia, B. Mbow, E. M. Keita, A. A. Correa, M. L. Sow. Theoritical Study of the Spectral Response in Near Infrared of III-V Photodetectors Based on Al, Ga, In and Sb: The Window Layer Effect. International Journal of Materials Science and Applications. Vol6, N°1, pp 45-53 (2017).

[3] H. Luquet , M. Pérotin, L. Gouskov, C. Llinares, H. Archidi, M. Lahbibi, M. Karim, and B. Mbow. Ionisation Coefficients in $Ga_{0,96}Al_{0,04}Sb$. J. Appl. Phys. 68 (8), (15 Octobre 1990).

[4] W.C. Benmoussa, S. Amara, et A. Zerga. Etude Comparative des Modèles de la Caractéristique Courant-Tension d'une Cellule Solaire au Silicium Monocristallin. Revue des Energies Renouvelables ICRESD-07 Tlemcen (2007).

[5] J.E. Sutherland and J. R. Hauser. A Computer Analysis of Heterojunction and Graded Composition Solar Cell. IEEE. Trans. Electron. Dev, ED-24 Vol 4, pp 363-372, (1997).

[6] A. Mc Eyoy, T. Markvart and L. Castaner., Pratical Handbook of Photovoltaics Fundamentals and Applications (Second Edition). Elsevier Ltd, (2012) INSB: 978-0-12-3859334-1.

[7] H. Matieu, Physique des Sémiconducteurs et des Composants Electroniques, (4ème Edition, Masson Paris 1998).

[8] I. Mekkaoui Alaoui, Etude Comparative des Méthodes de Détermination des Paramètres de Caractérisation I(V) des Photopiles Solaires, Thèse de Doctorat 3ème Cycle, Université de Montpellier, (1984).

[9] Abderrezek Mahfoud, Modélisation des Cellules Solaires Tandem à Couches Minces et à Haut Rendement, Thèse de Doctorat, Université de Sétif 1, (18 Février 2015).

[10] M. A. Green. J. Zhao, A. Wang, S. R. Wenham. Very High Efficient Silicon Solar Cell. Science and Technology. IEEE, Transactions on Electron Devices, Vol.46 N°10, pp 1940-1947, (1999).

[11] A. Kaminski, Etude des Etapes Technologiques Critiques dans la Production des Cellules Solaires en Silicium Monocristallin , Thèse de Doctorat, EEA Lyon, INSA Lyon, p 165, (1997).

[12] Roshanak Radbeh, Réalisation et Caractérisation des Cellules Solaires Organiques à Couche Composites Polymères Incluant des Nanotubes de Carbones, Thèse de Doctorat, Université de Limoges, (1er Décembre 2008).