SciencePG
Science Publishing Group

Effect of Impact Ionization on the Noise Excess Factor in Solar Photodiodes Based on CuInSe₂ (CIS) of P⁺N Type

Abdoul Aziz Correa[*], **Mamadou Dia, El Hadji Mamadou Keita, Chamsdine Sow, Babacar Mbow**

Laboratory of Semiconductors and Solar Energy, Physics Department, Faculty of Science and Technology, University Cheikh Anta Diop, Dakar, Senegal

Email address:
azizcorrea88@gmail.com (A. A. Correa), drdiamamadou84@gmail.com (M. Dia)
[*]Corresponding author

Abstract: The effects of impact ionization in the space charge zone on the multiplication factor of the carriers, the noise excess factor, and the multiplication voltage (avalanche voltage) are modeled for avalanche photodiodes (APD). Research has shown that photomultiplication of charge carriers and impact ionization allow to improve the quantum efficiency of avalanche photodiodes. However, these phenomena are not without effect on the background noise which tends to disturb the signal of these devices. The aim of this article is therefore to verify the effect of impact ionization on this noise characterized by an noise excess factor. Our work consists, at first, to establish the mathematical expressions linking the characteristic parameters of photomultiplication, impact ionization and noise before carring out simulations on photodiode model based on CuInSe₂ (CIS) of the P⁺N type. In our photocurrent calculation models, we first worked in the absence of electronic ionization, then in the presence of electronic ionization. Our simulation results confirm that ionization by impact in the part of the multiplication layer far from the active surface (the junction) increases the noise excess factor. We were able to note that the effect of impact ionization places strict constraints on the doping level of the carrier multiplication layer in order to minimize noise. However, the noise excess factor should be reduced in the layer (CuInSe₂ (N)) where the electric field and the multiplication factor of the charge carriers are important. We have shown that the gap between the ionization coefficients of the carriers (electrons and holes), reduces the excess noise in the avalanche layer (carrier multiplication layer or space charge area). For a coefficients ionization ratio $k=k_p/k_n=11$, a low value of the noise excess factor of the order of 1.5 is obtained with a multiplication coefficient Mph=2.

Keywords: Noise Excess Factor, Ionization Coefficient, Photomultiplication, Solar Photodiode

1. Introduction

The detector of choice for the communication systems by optical fiber often based on an avalanche photodiode (APD) operating in the near infrared range, because its multiplication factor makes it possible to obtain overall sensitivity of the receiver [1]. The quantum efficiency, frequency response and excessive noise of such devices are therefore a great interest [2]. The ionization coefficients, the multiplication factor and the noise excess factor are determined in the carrier multiplication region. The ionization coefficients kn, for the electrons and kp for the holes, are highly dependent on the reverse electric field. However their report tells us about the quality of the noise. The effect of the extension of the space charge zone on the photocurrent density generated in the absence of reverse polarization voltage $J_{ph}(V=0)$ and on the multiplication factor has been demonstrated by V. W. Gartner [3]. The extension of the space charge zone, allows to multiplicate these photocarriers and causing the noise characterized by a noise excess factor F. We decided to adopt the same theoretical model and to carry out our simulations on solar photodiodes models based on CuInSe₂ (CIS) of P⁺N type to verify the effect of impact ionization on noise in solar junctions and to improve their performance.

2. Theoretical Study

The doping profile is designed so that the multiplication zone is completely exhausted. For this, we will keep high the electric field (10^5V/cm), in order to ensure a rapid drift of the photogenerated carriers towards the edges of the space charge zone.

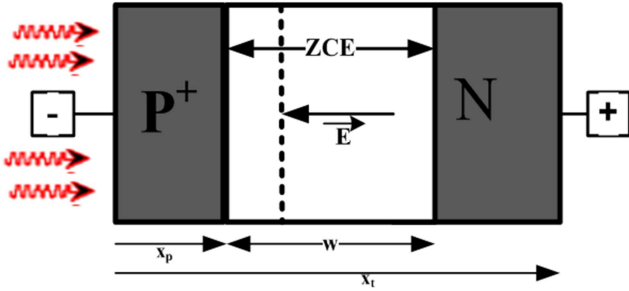After optical excitation, the concentration of free carriers, in the crystal, increases.

Figure 1. *Diagram of a PN junction under reverse polarization and under illumination.*

Depending on their lifetime, the photocarriers move under the influence of the electric field which is due to the concentration gradient of the charge carriers. The nature of the photocurrent will depend on the transport process of the generated photocarriers. In the space charge zone, due to the intense electric field which exists there, all the carriers generated are separated and participate in the conduction, while in the zones doped P⁺ and N, the electric field is zero and the current is essentially due to the diffusion of minority carriers.

2.1. Determination of the Photomultiplication Factor of the Carriers

In order to simulate P⁺N type CuInSe₂ (CIS) ADP models, we assume that the electric field in the space charge zone, far from the junction, is weak. This assumption allows us to ensure that only the part of the active surface contributes to the multiplication factor of the carriers and to the noise excess factor during ionization. The multiplication factor M_{ph} is usually defined as the ratio of the photocurrent density $J_{ph}(V)$ to the voltage V on the photocurrent density $J_{ph}(V=0)$ at V=0V or at a low voltage in front of the avalanche voltage [4].

Its expression is given by [5]: $M_{ph} = \dfrac{J_{ph}(V \neq 0)}{J_{ph}(V = 0)}$

M_{ph} describes the multiplication of minority carriers contributing to the increase of the current generated by the photodiode under reverse polarization. $J_{ph}(V)$ is the total photocurrent density photogenerated at a given reverse polarization voltage V and $J_{ph}(V=0)$ represente the total photocurrent density photogenerated in the absence of applied reverse polarization voltage.

The calculations of photocurrent densities under reverse polarization and in the absence of polarization are carried out respectively by Mamadou Dia [6] and Abdoul Aziz Correa et al [5]. From their results, we were able to deduce the expressions of the photomultiplication factors of the carriers generated in each zone. We then define the photomultiplication factor of the electrons by M_n, that of the holes by M_p and that of the carriers generated in the space charge area by M_{zce} and their expression are given by:

$$\begin{cases} M_n = \dfrac{J_n(V \neq 0)}{J_n(V = 0)} \\[2mm] M_p = \dfrac{J_p(V \neq 0)}{J_p(V = 0)} \\[2mm] M_{zce} = \dfrac{J_{zce}(V \neq 0)}{J_{zce}(V = 0)} \end{cases}$$

J_n describes the contribution of the electrons generated in the emitter, J_p describes the contribution of the holes generated in the base while J_{zce} describes that of the carriers generated in the space charge zone.

We then draw the expression of the multiplication factor of the carriers.

So: $M_{ph} = \dfrac{M_n J_n(V=0) + M_p J_P(V=0) + M_{zce} J_{zce}(V=0)}{J_n(V=0) + J_P(V=0) + J_{zce}(V=0)}$

M_{ph} is the total multiplication factor, M_p is the hole multiplication factor, M_n is the electron multiplication factor, M_{zce} is the carrier multiplication factor in the space charge zone and J_n, J_p et J_{zce} are respectively, the photocurrent density in the emitter, in the base, and in the space charge zone.

For a P⁺N junction, under reverse polarization, the multiplication of the carriers practically takes place in the space charge zone, where the electric field is the most important. The number of electrons or holes participating in the photocurrent therefore increases with the thickness of the space charge zone. The current density $J_{ph}(V)$ resulting from the displacement of the minority carriers is the sum of the components $M_n J_n(V=0)$, $M_{zce} J_{zce}(V=0)$ and $M_p J_p(V=0)$.

In the case of pure frontal injection (λ=0.423μm, λ=0.556μm and λ=0.751μm) we have $M_{ph} = M_n$; in the case of mixed injection (λ=1.037μm, λ=1.141μm) we obtain $M_{ph} = M_{zce}$; similarly in the case of pure injection of the base (λ=1.233μm) $M_{ph} = M_p$ [7].

This situation therefore makes it possible to carry out simplifications according to the wavelength range studied. From the expressions of the photomultiplication factors of the carriers, we will determine the ionization coefficients by proceeding with simplifications and by adopting the appropriate calculation models.

2.2. Determination of Ionization Coefficients of Electrons and Holes

In our study, we use under reverse polarization on our P$^+$N junction model based on CuInSe$_2$ (CIS). The carriers responsible for the photocurrent are the minority carriers, the electrons in the emitter and the holes in the base.

From the assumptions and simplifications, we will deduce the ionization coefficients K_n and K_p from the expression of the multiplication factor of the carriers.

We assume that the junction is abrupt and that the variation of the electric field established in the space charge zone is linear. Thus, if the electric field varies in a simple way in the space charge zone, the simplified expression of M_{ph} makes it possible to deduce K_n et K_p [7] which are the ionization coefficients of electrons and holes respectively. Stillman et al [8] described this method in detail and gave the simplified expression of K_n et K_p as a function of M_p and M_n for a constant electric field (PIN junction) and for linearly varying electric fields (abrupt pn junction).

Thus, after simplification, the expressions of the ionization coefficients as a function of the applied electric field E are given by [9]:

$$\begin{cases} K_p(E) = \dfrac{E}{M_p M_n} \times \dfrac{dM_p}{dV} \\ K_n(E) = E[\dfrac{1}{M_n} \times \dfrac{dM_n}{dV} + (\dfrac{1}{M_n}-1) \times \dfrac{1}{M_p} \dfrac{dM_p}{dV}] \end{cases}$$

We note that the values of the ionization coefficients cannot be directly determined for two reasons:

The first is that for wavelengths on the order of 0.751 μm, the multiplication is too low.

The second is that the variation of the multiplication factor of the carriers is very small, therefore, the derivative $\dfrac{dM_p}{dV}$ remains imprecise.

However the ionization coefficients can be written in the form:

$$\begin{cases} K_p(E) = A_p \exp(-\dfrac{B_p}{E}) \\ K_n(E) = A_n \exp(-\dfrac{B_n}{E}) \end{cases}$$

After linearization of the expressions of the ionization coefficients we obtain:

$$\begin{cases} \ln[K_p(E)] = \ln(A_p) - \dfrac{B_p}{E} \\ \ln[K_n(E)] = \ln(A_n) - \dfrac{B_n}{E} \end{cases}$$

It can be seen that the functions $\ln[K_p(E)] = f(\dfrac{1}{E})$ and $\ln[K_n(E)] = f(\dfrac{1}{E})$ are affine functions. The coefficients A_p, A_n, B_p and B_n can be obtained from a series of values of the applied electric field and values of $\ln[K_n(E)]$ and $\ln[K_p(E)]$.

From the expressions of the ionization coefficients as a function of the multiplication factors of the holes and of the electrons, we were able to access a series of values given in table 1.

Table 1. *Table of values of $\ln[k_p(E)]$ and $\ln[k_n(E)]$ for different values of the electric field E.*

E (V/cm)	$0,5.10^5$	$0,9.10^5$	$1,3.10^5$	$1,7.10^5$	$2,1.10^5$
$\ln[k_p(E)]$(cm^{-1})	12,52	12,533	12,709	12,804	12,869
$\ln[k_n(E)]$(cm^{-1})	9,014	9,027	9,204	9,299	9,363

From this table, we determined the slopes of the characteristic $\ln[K_{n,p}(E)] = f(\dfrac{1}{E})$ corresponding to the values of the parameters B_p and B_n then deduce the values of the parameters A_p and A_n.

Are: $A_p = 3,606.10^4\,cm^{-1}$, $A_n = 3,271.10^3\,cm^{-1}$, $B_p = 2,25.10^5\,V.cm^{-1}$, $B_n = 2,34.10^5\,V.cm^{-1}$

2.3. Determination of the Noise Excess Factor

In multiplication regime, when a carrier enters the multiplication zone, it is multiplied by a factor M_{ph} [10]. However, the fluctuations in the multiplication coefficient M_{ph} lead to noise excess characterized by the noise excess factor. To simulate the effects of this noise on the performance of the photodiode we will therefore determine the relationship between the two factors characterizing the two phenomena.

For this, we use Mc Intyre's theory [11] which defines the factor of noise excess as a function of the multiplication factor by:

$$F(M_{ph}) = M_{ph}\left[1 + \frac{1-k}{k}\left(\frac{M_{ph}-1}{M_{ph}}\right)^2\right]$$

The constant k is the ratio between the ionization coefficient of the electrons and that of the holes. $F(M_{ph})$) is the noise excess factor which describes the noise linked both to the ionization of the carriers and to the multiplication of these carriers.

To better apprehend the impacts of ionization and those of photon multiplication on the performance of our photodiode model, we have made simulations.

3. Results and Discussions

The use of simulation tools makes it possible to predict the behavior of solar photodiodes. The simulations will allow us to appreciate the behavior of our solar photodiode model based on CuInSe$_2$ (CIS) of P$^+$N type. In this article, we are

interested on the impact of ionization and the noise excess factor in CuInSe$_2$ (CIS) solar photodiodes of P$^+$N type. Our photodiode model is under a variable voltage reverse polarization therefore with a variable electric field. To appreciate the noise, we have studied the characteristic parameters of the phenomena responsible for this noise which has a degrading effect on the performance of photodiodes. These parameters are the photomultiplication factors and the ionization coefficients which characterize the photomutiplication and ionization observed following a polarization of the photodiodes.

3.1. The Evolution of the Photomultiplication Factor as a Function of the Electric Voltage Applied for Different Values of Wavelengths

Among the characteristic parameters on which the operation of avalanche photodiodes strongly depends is the polarization voltage. The performance of solar photodiodes also depends on the quality of the materials which constitute it in particular the gap energies of the materials and therefore the wavelengths. Figure 2 shows the variation of the photomultiplication factor as a function of the polarization voltage for different wavelength values.

The analysis in Figure 2 shows that the multiplication factor increases with the applied polarization voltage. It also shows a strong dependence on the multiplication of charge carriers as a function of wavelengths..
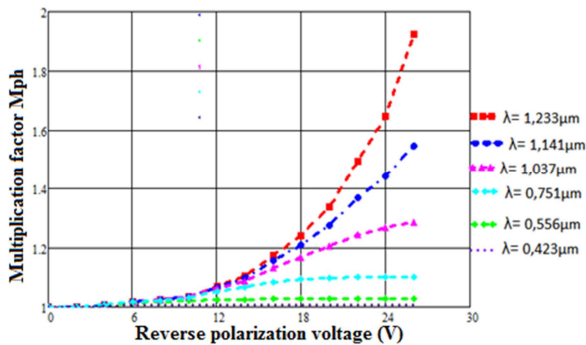

Figure 2. *Variation of the multiplication factor Mph as a function of the reverse polarization voltage for different values of the wavelength. (S$_n$=2.10^{7}cm.s^{-1}; S$_p$=20cm.s^{-1}; L$_n$=0,4µm; L$_p$=5µm; w=0,36µm; x$_p$=0,4µm; x$_t$=6µm; ε=1,327.10^{-10}F.cm^{-1}; V$_d$=0,65V N$_d$=6,2.10^{16}cm^{-3}.*

Figure 2 shows us that the photomultiplication depends on both the polarization voltage and the nature of the material. With our model photodiode based on CuInSe$_2$ (CIS) of PN type, we note that for a polarization voltage greater than 12V, the higher the wavelength the higher the photomultiplication

We notice that this dependence is more marked for polarization voltages greater than 18V. Besides, for wavelengths less than 0.751, the multiplication factor is constant, which shows that no multiplication of charge carriers is observed beyond 18V. On the other hand, for wavelengths greater than 1.037, there is a strong multiplication of the charge carriers with a multiplication factor of the order of 1.92 corresponding to a radiation of wavelength λ=1.233µm for an

applied voltage of around.

However, for λ=0.423µm, the characteristic factor of the multiplication of the charge carriers remains almost equal to 1 and consequently the carriers do not multiply. Indeed, the greater the wavelength, the more the effect of the extension of the space charge zone is sensitive and the photocurrent varies gradually as a function of the applied reverse voltage V.

This variation of the photocurrent increases up to 80% in the near infrared for a wavelength of 1.233 µm. On the other hand, for the wavelength of 0.423 µm, the absence of the multiplication is interpreted by short wavelengths which make that the absorption took place in the vicinity of the surface of emetter very far from the space charge zone. The carriers produced will not reach the space charge zone to contribute to photomultiplication due to their short diffusion length.

Consequently, all the carriers are created toward the surface showing that the photocurrent is independent of the reverse voltage applied V. The considerable increase in the multiplication at 18V is explained by the fact that, when the voltage of reverse polarization becomes very high, the electric field becomes important in turn, the charge carriers will have much more kinetic energy and will be capable in this case to generate new pairs of carriers. These new pairs of carriers generate by shock a new electron-hole pair leading to the avalanche phenomenon. This voltage of 18V corresponding to the avalanche voltage can be caused by two quantum mechanisms; the first is the tunnel effect and the second is the avalanche effect. Neither of these two mechanisms is destructive to the PN junction [12]. However, the increase in temperature in the PN junction, caused by the passage of a strong current resulting from the photomultiplication of the carriers, can destroy the junction.

However, depending on the wavelength, the multiplication is due either to the electrons (λ=0.423µm and λ=0.556µm and λ=0.751µm), either to the holes (λ=1.233µm), or to the electron-holes (λ=1.037µm and λ=1.141µm) respectively in the transmitter, the base and the space charge zone.

When the device is exposed to a relatively long wavelength (λ=1.233µm), most of the photons are absorbed in the depletion zone and in the base. Multiplication is the work of holes. Consequently, we obtain Mph=Mp [13]. When the device is exposed to a relatively long wavelength (λ=1.233µm), most of the photons are absorbed in the depletion zone and in the base.

For an illumination at short wavelengths (λ=0.423µm and λ=0.556µm and λ=0.751µm), the penetration lenght of the photons is very small. It is considered in this case that only the electrons contributes to the multiplication therefore Mph=Mn [10] which justifies the low values of the multiplication factor because few electrons reach the multiplication zone.

For the intermediate wavelengths (λ=1.037µm and λ=1.141µm), we have the contribution of each carriers. These carriers are therefore generated in the space charge zone, in the emitter doped P+ and in the base doped N. Thus the junction is therefore subjected to a simultaneous injection of holes and electrons on both sides.

Summary, the photocurrent does not vary significantly for

reverse polarization voltages below 18V, which means that the multiplication is neglected for these voltages corresponding to the simple extension of the space charge zone. Beyond 18V, the multiplication becomes significant and the signal increases significantly. This is due to impact ionization, making it possible to witness a multiplication of minority holes injected by the base into the junction and accelerated by the electric field.

The probability that carriers multiply is maximum in the zone with a very strong electric field (space charge zone) and decreases on both sides. In vicinity of emetter, it is naturally the holes which cause the avalanche phenomenon and to the base, these are the electrons which allow to trigger the avalanche phenomenon. To be able to differentiate the useful signal from the background noise, it is therefore important to properly calculate the maximum electric field to deduce its influence on the ionization and multiplication phenomena of the charge carriers.

3.2. The Influence of the Electric Field E on the Ratio of the Ionization Coefficients $k = \dfrac{k_p}{k_n}$

In the reverse polarized P^+N structure, the space charge zone extends essentially in N doped. In this zone, there is a field which allows all the carriers created to reach on edge of the space charge zone and to be collected. Thus the holes which are the minority carriers in this layer, will be more likely to be collected in large numbers.

Figure 3 shows Variation of ionization coefficients ratio $k = \dfrac{k_p}{k_n}$ as a function of the reverse of the electric field E. We note that whatever the value of the electric field E, the ratio $k = \dfrac{k_p}{k_n}$ is greater than the unit, therefore the holes ionization coefficient k_p remains higher than electrons ionization coefficient k_n. However, there is a decrease in the ratio when the electric field E increases.
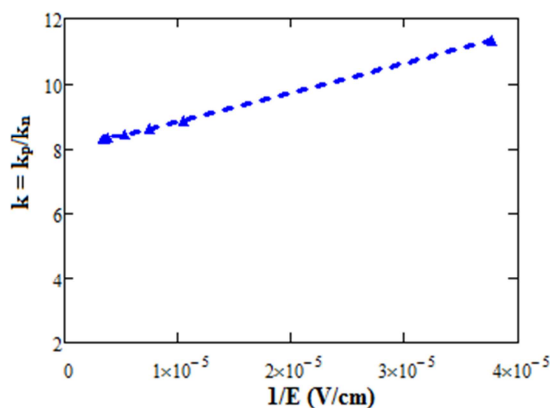

Figure 3. *Variation of ionization coefficients ratio $k = \dfrac{k_p}{k_n}$ as a function of the reverse of the electric field E.*

These electron-hole pairs are accelerated by the electric field and generate new electron-hole pairs by shocks thus leading to a enough multiplication of electrons. These ionization phenomena are not without effect on the background noise which has an impact on the performance of solar photodiodes. To better appreciate their impact, we simulated the influence of the multiplication factors on the noise excess factor for different values of the ratio k of the ionization coefficients.

3.3. The Influence of the Multiplication Factor on the Noise Excess Factor for Different Values of the Ratio k of the Ionization Coefficients

The multiplication of carriers increases the electrical signal detected, it also increases the noise characterized by the noise excess factor.
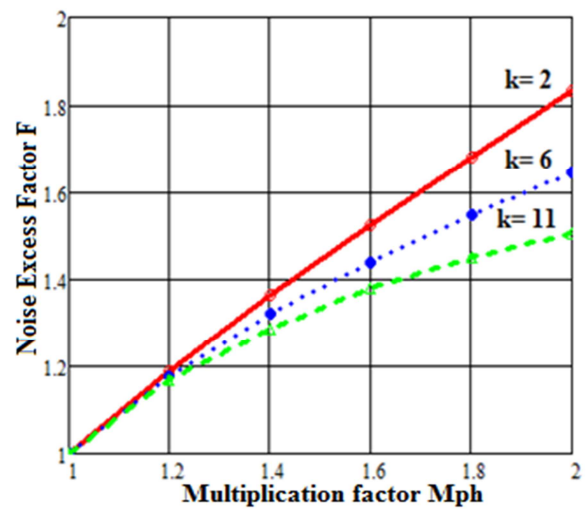

Figure 4. *Variation of the noise excess factor as a function of the multiplication factor for different values of the ratio k of the ionization coefficients.*

Figure 4 shows the variation of the noise excess factor as a function of the multiplication factor for different values of the ratio k of the ionization coefficients.

The analysis of figure 4 shows that the noise increases with the multiplication of the charge carriers, on the other hand it decreases with the increase of the ionization coefficients ratio k. This is explained by the fact that electrons have a greater mobility than that holes. The mobility of electrons allows them to acquire a significant kinetic energy. This significant value of the kinetic energy of the electrons produces strong shocks of the electrons with the atoms of the material which contributes to an increase in the vibrations of the network and therefore to the increase in the background noise. For a value of k equal to 2, the calculated noise excess factor is 1.82; it decreases to 1.63 and 1.5 for values of k respectively equal to 6 and 11. In fact, the multiplication of the carriers due to a strong electric field is accompanied by fluctuations and thermal agitations which favor the interactions diffusing, source of noise. However, when the electric field decreases, the ionization coefficients ratio k increases (Figure 3); which therefore reduces the noise excess factor.

4. Conclusion

The multiplication factor and the excess noise factor were calculated in the multiplication layer (or space charge zone). We were able to show that ionization in the N-doped region increases the noise excess of photodiodes based on CuInSe$_2$. This effect becomes more pronounced for the strong electric fields. In addition, impact ionization imposes the upper limit of the electric field. The inequality of the ionization coefficients (kp> kn), shows that the multiplication is more linked to the holes than to the electrons. Thus this difference with the ionization coefficients allowed us to appreciate the performance of the device through the low value of the noise excess factor (1.5) for a ratio of the ionization coefficients equal to 11. Our results show that through the multiplication factor, we can improve the quantum efficiency and consequently the performance of solar photodiodes based on CuInSe$_2$ (CIS).

For this, it is necessary to increase the space charge zone by increasing the reverse polarization voltage so that the maximum of carriers are generated there. The values of the ratio of our ionization coefficients calculated from the expressions of the multiplication factors (Mn and Mp) and the noise excess factor, are in good agreement with the experimental results presented by other authors [1]. This allowed us to validate our calculation method.

However, to make low noise avalanche photodiodes, you must therefore choose:

a material which has the greatest possible difference between the ionization coefficients kp and kn,

a structure which carries out the pure injection of the carriers into the multiplication layer.

References

[1] J. S. 0, Member, IEEE, C. H. Tan, Member, IEEE, J. P. R. David, Senior Member, IEEE, and G. J. Rees «Effect of Impact Ionization in the InGaAs Absorber on Excess Noise of Avalanche Photodiodes». IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 41, NO. 8, AUGUST 2005.

[2] J. C. Campbell et al.,"Recent advances in avalanche photodiodes," IEEE J. Sel. Topics Quantum Electron, vol. 10, no. 4, pp. 777–787, Jul./Aug. 2004.

[3] GARTNER, W. W., Depletion-Layer Photoeffects in Semiconductors, Article in Physical Review. 116 (1): 84-87. October1959.

[4] Alabedra, C. Maille, D. Ratsira, G. Lecoy. Utilisation des mesures de bruit pour la détermination du photocourant primaire dans les photodiodes à avalanche N+P∏P+ au Silicium. Revue de Physique Appliquée, 1980, 15 (7), pp. 1201–1208.

[5] A. Aziz Corréa, B. Mbow, M. Dia, Y. Tabar, E. Mamadou Keita, C. Sène «Theoretical determination of the multiplication factor in the CuInSe$_2$ (CIS) P$^+$N Photodiodes». Université Cheikh Anta Diop de Dakar. J. IJESRT. Vol. 6, ISSN: 2277-9655. Octobre, 2017.

[6] Mamadou DIA. «Etudes Théoriques de la Réponse Spectrale dans le Proche Infrarouge des Photodétecteurs à base des Antimoniures et leurs Alliages». Thèse de Doctorat Unique, Université Cheikh Anta Diop de Dakar, (07 Décembre 2017).

[7] H. Luquet, M. Pétrotin, L. Gouskov, C. Llinares, H. Archidi, M. Lahbabi, M. Karim, and B. Mbow «Coefficients d'ionisation dans Ga$_{0.96}$Al$_{0.04}$Sb». J. Appl. Phys., Vol. 68, No. 8. 15 October, 1990.

[8] G. E. Stillman, L. W. cook, N. Tabatabaie, G. E, Bulman, and V. M. Roblins. IEEE Trans. Devices ED-30, 364 (1983). «Photocurrent amplification and noise-signal ratio in avalanche photodiodes».

[9] Karine ISOIRD, Thèse de Doctorat "Etude de la tenue en tension des dispositifs de puissance en carbure de silicium par caractérisations OBIC et électriques" Lyon (2001).

[10] P. Denis «Modélisation, fabrication et évaluation des photodiodes à avalanche polarisées en mode Geiger pour la détection du photon unique dans les applications Astrophysiques», Université Toulouse III-Paul Sabatier, (2008).

[11] François CERF, Hermes «Les composants optoélectroniques», Science Publications, 1999.

[12] S. M. Sze, John Wiley and Sons «Physics of Semiconductor Devices» 3rd édition, Welley-intersciencePublication. 1981.

[13] MC INTYRE, R. J., IEEE Trans. Electron. Devices TED 13 (1966) 164-168. «Multiplication noise in uniform avalanche diodes».