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STUDY OF THE INFLUENCE OF THE CUTOFF FREQUENCY FOR THE OPTIMIZATION OF THE PHOTO CURRENT IN THE PHOTIO MULTIPLICATION REGIME IN SOLAR PHOTODIODES BASED ON $CuInSe_2$ (CIS) OF P^+N TYPE

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ABSTRACT
The objective of this article is to determine in the field of telecommunications, the frequency from which we note the malfunction of the electrical signal in the photo multiplication regime in solar photodiodes based on $CuInSe_2$ (CIS) of the p+n type. This frequency, called the cutoff frequency, is by definition the useful operating limit frequency of an electronic circuit. Based on this definition, the cutoff frequency is noted when the carriers are insufficient in number, thus leading to a weak (bad) electrical signal. Optical fiber telecommunications are spreading towards long wavelengths. It will be shown that the cutoff frequency strongly depends on the thickness of the space charge zone (or carrier multiplication zone), the speed of the carriers and the multiplication factor. In addition, the long wavelengths correspond to the large multiplication factors. However, the cut off frequency being a parameter weakening the electrical signal, so its reduction leads to an increase in the multiplication factor of the charge carriers. The maximum being 6.7GHz, so it will be shown that devices operating at lower frequencies will see their sensitivity improved. The results obtained by one dimensional simulation of literal expressions show that the multiplication of carriers is much greater for low cut off frequencies.

KEYWORDS: Cutoff frequency, multiplication factor, capacitance, wavelength.

1. INTRODUCTION
One of the means of improving the sensitivity of photodiodes in the photo multiplication regime is through the use of low cut-off frequencies to obtain an internal quantum efficiency greater than 1 [1]. This means that an absorbed photon will give place not to one electron-hole pair but to several (multiplication of carriers).

This technique promotes the multiplication of a large number of carriers which give rise to a large electrical signal corresponding to low frequencies. In addition, the electric field in the space charge zone (carrier multiplication zone) remains high (10^5V/cm) while ensuring carrier multiplication through impact ionization due to high kinetic energy. The ionization coefficients, the multiplication factor and the cutoff frequency are determined in the carrier multiplication region [2]. The ionization coefficients k_n, for electrons and k_p, for holes show a strong approximately exponential dependence on the reverse electric field [2]. The effect of the extension of the space charge zone on the primary photocurrent (photocurrent generated in the absence of reverse bias voltage: Jph(0)) and on the multiplication factor has been demonstrated by V.W Gartner [3]. The extension of the space charge zone allows the multiplication of photo carriers. Indeed, through the results, the decrease in the speed of the carriers decreases the cutoff frequency. In this article, we will therefore analyze the results of the cutoff frequency in relation to the multiplication factor of the charge carriers.

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 [4].

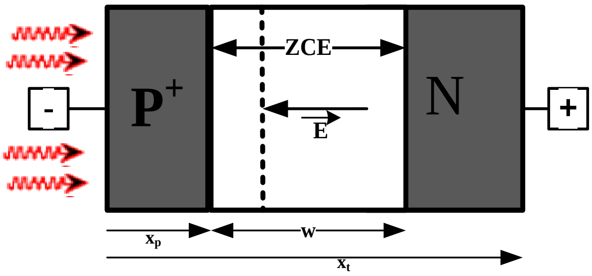

Figure 1. Diagram of a P⁺N junction under reverse polarization and under illumination

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: M_{ph}

In order to simulate P^+N type $CuInSe_2$ (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 $J_{ph}(0)$ to $V = 0V$ or at a low voltage in front of the avalanche voltage [5].

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

V is the applied reverse bias voltage

M_{ph} describes the multiplication of minority carriers contributing to the increase of the current generated by the photodiode under reverse polarization.

$J_{ph}(V \neq 0)$ 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 [1]. 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 Mn, that of the holes by Mp and that of the carriers generated in the space charge zone by Mzce and their expressions are given by :

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

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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.

$$\text{So}: M_{ph} = \frac{M_n J_n(V=0) + M_p J_p(V=0) + M_{zce} J_{zce}(V=0)}{J_n(V=0) + J_p(V=0) + J_{zce}(V=0)}$$

M_{ph} is the total multiplication factor, M_p is the hole multiplication factor, M_n is the electron multiplication factor, M_{scz} is the carrier multiplication factor in the space charge zone and J_p , J_n , 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 $M_n J_n(V=0)$, $M_{scz} J_{scz}(V=0)$ 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 $M_{ph} = M_{scz}$; 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 the cutoff frequency: f_c

In the multiplication regime, when a carrier enters the multiplication zone, it is multiplied by a factor Mph [8]. However, a regression of the multiplication factor induces a cutoff of the electrical signal characterized by the cutoff frequency. Thus the formula related to this cutoff frequency is given by [9]:

$$f_c(M_{ph}) = \frac{V_p}{2\pi w M_{ph}}$$

V_p is the speed of charge carriers
w is the thickness of the space charge zone or the thickness of the multiplication layer

3. RESULTS AND DISCUSSION

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 P^+N type $CuInSe_2$ (CIS). In this paper, we are interested in the effect of the cutoff frequency on the charge carrier multiplication factor in P^+N-type $CuInSe_2$ based solar photodiodes (CIS). Our photodiode model is under a variable voltage reverse bias and therefore a variable electric field. To assess the cutoff frequency, we have studied the characteristic parameters of the phenomena responsible for this cutoff frequency which reduces the performance of photodiodes. These parameters are the multiplication factor, the thickness of the space charge zone and the speed of the charge carriers.

3.1. The Evolution of the multiplication Factor of the charge carriers as a function of the applied reverse bias voltage 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. Figure2 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.

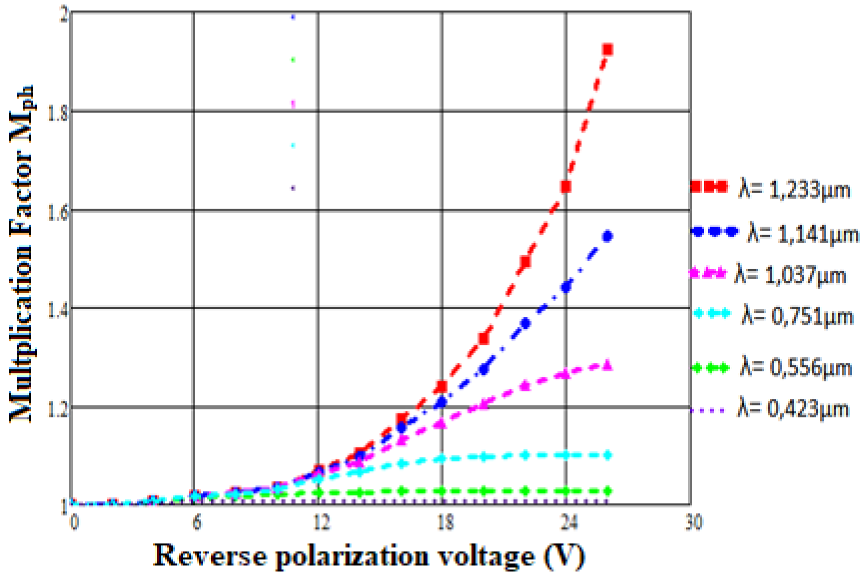

Figure 2: Variation of the multiplication factor Mph as a function of the reverse bias voltage for different values of the wavelength (S_n=2.10^{7}cm.s^{-1} ; S_p=20cm.s^{-1} ; L_n=0,4µm ; L_p=5µm ; w=0,36µm ; x_p=0,4µm ; x_t=6µm ; ε=1,327.10^{-10}F.cm^{-1} ; V_d=0,65V ; N_d=6,2.10^{16}cm^{-3})

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 [10]. 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 [11]. 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 [11] which justifies the low values of the multiplication factor because few

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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 capacitance on the thickness of the multiplication zone of the charge carriers

In reverse bias, the capacitive effects are due to the variation of the space charge dQ in the depletion region. Thus, this capacitance depends on the applied reverse bias voltage around which variations in voltage dV are caused which in turn causes a variation in the thickness of the multiplication layer.

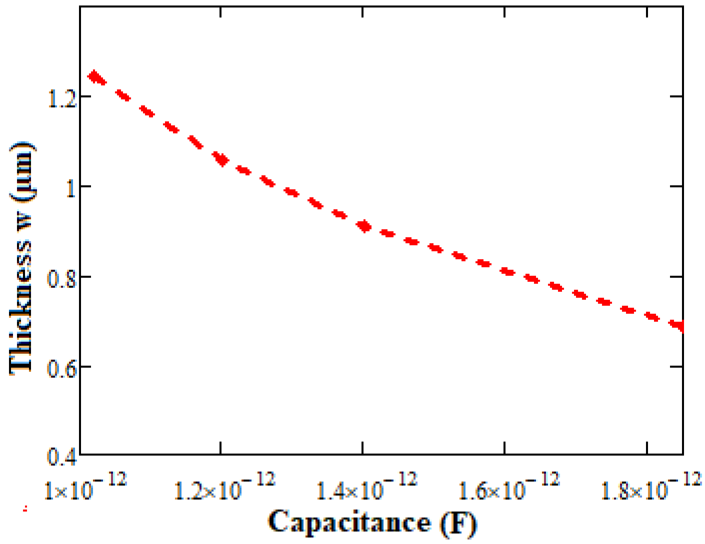

***Figure 3:** Variation in the thickness of the space charge zone (carrier multiplication zone) as a function of the capacity*

The carrier multiplication layer decreases for large capacities. Indeed, the junction capacitance by definition is the quantity of charge accumulated just to the left and to the right of the junction, due to the diffusion of the majority carriers. Furthermore, when the photodiode is reverse biased, the electric field increases and opposes the diffusion of the majority carriers; which therefore reduces the quantity of charges characterized by the capacitance. The thickness of the multiplication layer has a lot of influence on the capacitance, which shows that for fine multiplication layer structures (w <0.4 µm) the electrical signal cut by the capacitance is the dominant effect.

3.3. The influence of the multiplication factor on the cutoff frequency for different values of w and v_p

The multiplication of carriers increases the photocurrent and reduces the cutoff of the collected electrical signal characterized by the cutoff frequency. Figure 4 and Figure 5 show the variation of the cutoff frequency as a function of the multiplication factor for different values of the thickness of the space charge zone and the speed of the charge carriers.

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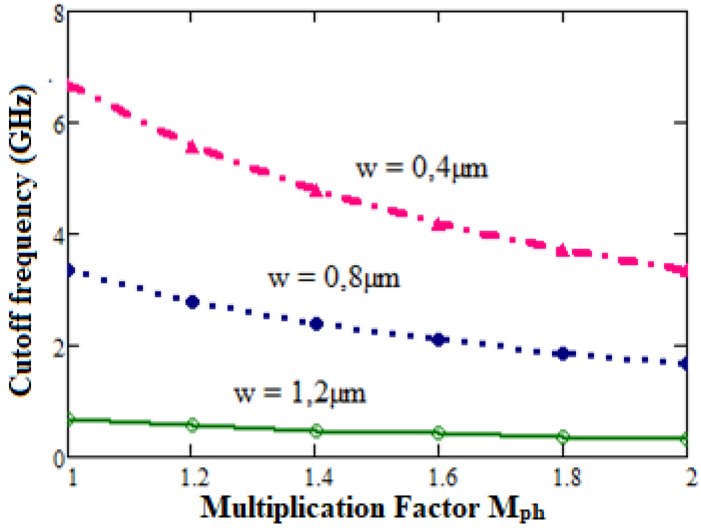

Figure 4: Variation of cutoff frequency f_c as a function of the multiplication factor for different values of w $(v_p = 4,2 \times 10^6\ cm/s)$.

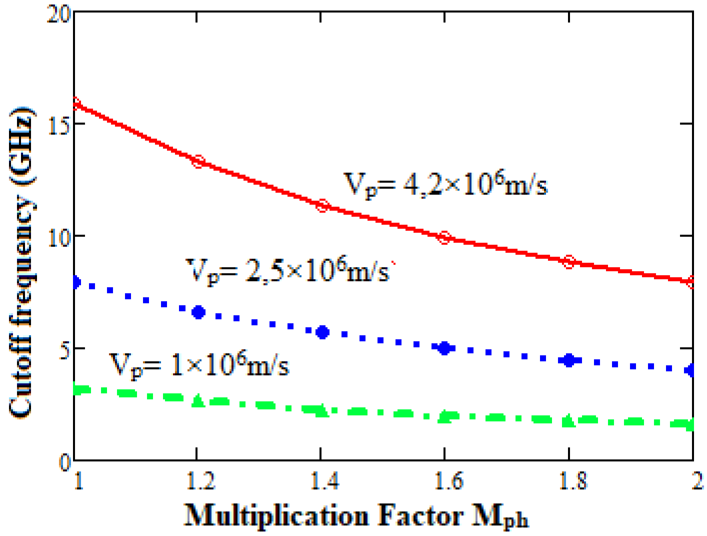

Figure 5: Variation of cutoff frequency f_c of the multiplication factor for different values of v_p (w=1,2µm)

The cutoff frequency is much more felt for low multiplication factors Mph (1.2; 1.4 and 1.6), and less felt for large values of Mph (1.8 and 2). Indeed, these large multiplication factors thus lead to a considerable multiplication of charge carriers which are collected and contribute to the amplification of the electrical signal, thus reducing the phenomena of cuts and therefore a low cutoff frequency. This also explains the use of long wavelengths (1.3µm and above all 1.55µm) in the field of optical fiber telecommunications, to minimize the cutoff frequency in order to have good electrical signal quality, source of the sound effect. For this purpose, we can make a large number of phone calls at the same time with fewer signal cuts. The rapid increase in f_c when the thickness of the space charge zone decreases (Figure 4), shows that there is a limit value w_0 (0.4µm) below which the breaking phenomena disturb the correct functioning of the component through a bad electrical signal. However, in avalanche photodiodes, the sensitivity is higher the greater the multiplication of carriers, that is to say that the wavelength is large. From this point of view, the high frequencies limit the sensitivity of the photodiode. Therefore, the low multiplication factors are the source of the high frequencies and the weak electrical signal. Furthermore, the external electric field repels the charges which will be at a distance (thickness of the multiplication layer) substantially proportional to V, thus creating a capacitance proportional to the frequency

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[12]. This capacitance is inherent in any semiconductor junction, and will constitute the main limit to the high frequency operation of electronic components in a multiplication regime through the thickness of the space charge zone.

The plotted curves show that under these conditions, the cutoff frequency due to the multiplication factor is greater than 6.7GHz or 15.2GHz. There is therefore no particular precaution to be taken if it is desired to design a component operating at a lower frequency. When w is low (less than a micron), the cutoff is mainly due to capacitance. On the other hand, when w is large (greater than 1.2 µm), it is the transit of the carriers (speed of the carriers: holes) which has a preponderant influence on the cutoff frequency (Figure 5). There is therefore a value of w which makes it possible to obtain a maximum cutoff frequency. Thus in the range 0.4µm ≤ w ≤ 1.2µm, the lowest cutoff frequencies are reached, the minimum being 0.8GHz (Figures 4). However, it is absolutely necessary that the whole of the multiplication layer is deserted at the operating voltage, otherwise the slow diffusion of the photocreated holes would ruin all the efforts to optimize the dynamic behavior of the photodiode. The increase of the cutoff frequency for low carrier speeds (Figure 5), is interpreted by a strong electric field which increases the multiplication factor which in turn increases the excess noise factor.

4. CONCLUSION

It is very beneficial to design avalanche photodiodes of great thickness to improve performance. From this point of view, the cutoff frequency is reduced. The absolute limit of the latter is 0.5GHz for Mph equal 2 and 0.8GHz for Mph equal 1. However, to obtain a low cutoff frequency, the multiplication layer must be carefulled so as to have a strong electric field, and take into account the effect of carrier capacitance and speed. For multiplication layer thicknesses greater than or equal to 1.2 µm, it is possible to obtain a cutoff frequency of the order of 0.5 GHz. However, this depends on the influence of the capacitance on the thickness; problem that we did not consider in our own right and that must be addressed during the design.

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