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THEORETICAL DETERMINATION OF THE MULTIPLICATION FACTOR IN THE CuInSe2 (CIS) P+N PHOTODIODES

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ABSTRACT

In a CuInSe2 (CIS) photodiode of the P^+Ntype, the extension of the space charge zone under inverse polarization leads to an increase of the initial photocurrent. The object of our work is to determine the multiplication factor leading to the determination of the ionization coefficients of electrons and holes in this material. The capacitance-voltage characteristics and the spectral responses allow first to deduce the photoelectric parameters: profile of the electric field, diffusion length of the carriers, etc. Then the determination of the multiplication factor at several wavelengths is realized. The$k_p$and $k_n$values thus determined for an electric field varying from 0.5 to5.8×10^5V/cmexhibit a high ratio valueshowing the interest of this material for photodetection.

KEYWORDS: Multiplication Factor, CuInSe2, Ionization Coefficients, wavelengths, Internal quantum efficiency, Polarization.

I.   INTRODUCTION

The development of coherent (laser) or incoherent (light-emitting diode) light sources in the field of optical fiber telecommunications to convey information has gone hand in hand with that of fast and sensitive photodetectors [1]. The photodiodes with a wide space charge zone allowtoobtain response times of less than nanosecond. They behave like avalanche photodiodes. They offer a better compromise between amplification and rapidity. In these devices, it is necessary to determine the multiplication factor and the ionization coefficients which are at the origin of the extension of the space charge zone. However, the ratio of the ionization coefficients of the holes and the electrons informs us about the quality of the noise. The effect of the extension of the space charge zone on the primary photocurrent (photocurrent generated at the absence of reverse bias voltage:$J_{ph}(0)$) and on the multiplication factor has been underlined by VW Gartner [2]. The extension of the space charge zone allows the photoporteurs to multiply, thus increasing the total primary photocurrent characterized by a multiplication factor M. We decided to adapt the same theoretical study on solar cells to check the effect of the photomultiplication on the solar junctions and to determine their coefficients.

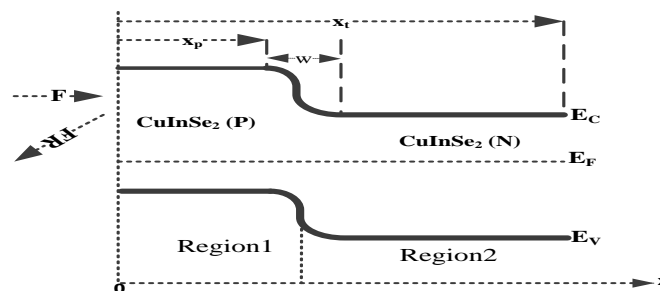## II.   THEORETICAL STUDY

Spectral response

Figure 1: Energy band diagram of CuInSe2p / CuInSe2n homojunction

Let F be the flux of photons, of energy hυ, arriving under normal incidence at the surface of a device (Figure 1). The flux of photons $F = (1 - R)F_0$ penetrating in the crystal for $h\upsilon \geq E_g$ is therefore completely absorbed there. Each photon absorbed is not necessarily active: dispersion by the imperfections of the crystal lattice. Taking into account the absorption coefficient, the rate of generation of electron-hole pairs at a distance x from the surface of the crystal is [1]:

$$G(x) = -\frac{dF(x)}{dx} = \alpha(1 - R)F_0 e^{-\alpha x} \quad (1)$$

where F_0 is the incident photon flux at the surface of the front layer, α is the absorption coefficient and R is the reflection coefficient.

After optical excitation, the concentration of the free carriers in the crystal increases. According to their lifetime, photocarriers move under the influence of the external electric field which is due to the concentration gradient of the excess minority charge carriers. The nature of the photocurrent will depend on the transport process of the photocarriers generated. In the space charge zone, by reason of the intense electric field there, all the generated carriers are separated and participate at the conduction, whereas in the zones P⁺ and N the current is essentially due to the diffusion of the minority carriers. The electric field is equal to zero outside the depletion region and the component of the conduction current is neglected.

The photocurrent density is decomposed as a function of the nature of the carriers injected into the multiplication zone (scz).

Calculation of the J_n Photocurrent Density of Electron Diffusion in Front Layer

This photocurrent density is obtained from the following continuity equation [3]:

$$\frac{d^2\Delta n}{dx^2} + \frac{\alpha_1 F(1-R)\exp(-\alpha_1 x)}{D_n} - \frac{\Delta n}{L_n^2} = 0 \quad (2)$$

where Δn is the electron density in P⁺ layer, D_n is the electron diffusion coefficient in frontal layer, α_1 is the electron absorption coefficient in front layer and L_n electron diffusion length in P⁺ layer.

The solution of this equation is in the form:

$$\Delta n = A\exp\left(\frac{x}{L_n}\right) + B\exp\left(-\frac{x}{L_n}\right) - \frac{\alpha_1 . L_n^2 . F_0 (1-R) . e^{-\alpha_1 x}}{D_n(\alpha_1^2 . L_n^2 - 1)} \quad (3)$$

The constants A and B are obtained from the following boundary conditions [3]:

$$D_n \frac{d\Delta n}{dx} = S_n \Delta n \quad \text{for} \quad x = 0 \quad (4)$$

$$\Delta n = 0 \quad \text{for} \quad x = x_p \quad (5)$$

The diffusion photocurrent density in this region is defined by [3]:

$$J_n = qD_n \frac{d\Delta n}{dx}\Big|_{x = x_p} \quad (6)$$

q: elementary electrical charge and x_p: thickness of the front layer.

$$J_n = \frac{qF_0(1 - R)(\alpha_1 . L_n)}{(\alpha_1^2 . L_n^2 - 1)} \times$$

$$\left\{ \frac{\left(\alpha_1 . L_n + \frac{S_n . L_n}{D_n}\right) - e^{-\alpha_1 x_p}\left(\frac{S_n . L_n}{D_n}\cosh\left(\frac{x_p}{L_n}\right) + \sinh\left(\frac{x_p}{L_n}\right)\right)}{\cosh\left(\frac{x_p}{L_n}\right) + \frac{S_n . L_n}{D_n}\sinh\left(\frac{x_p}{L_n}\right)} - \alpha_1 . L_n e^{-\alpha_1 x_p} \right\} \quad (7)$$

S_n is the recombination velocity of the minority carriers (electrons) at the surface of the frontal layer.

Calculation of the Diffusion Photocurrent Density of the Carriers created in the zone of multiplication (scz)

This component of the photocurrent density is due to the carriers created only in the multiplication zone, whether:

$$J_{ZCE} = q \int_{x_p}^{x_n} G_n(x)dx \quad (8)$$

This gives by integrating:

$$J_{ZCE} = qF_0(1 - R) \times \exp(-x_p\alpha_1)[1 - \exp(-\alpha_1 w)] \quad (9)$$
$$\text{with} \quad w = w_1 + w_2 = x_n - x_p \quad (10)$$

where w is the total thickness of the space charge zone, w_1 is the thickness of the space charge region in the front layer and w_2 is the thickness of the space charge region in the base.

Calculation of the J_p Hole Diffusion photocurrent Density in base

The photocurrent density is obtained from the following continuity equation [3]:

$$\frac{d^2\Delta p}{dx^2} + \frac{\alpha_2 F(1-R)\exp(-\alpha_2 x)}{D_p} - \frac{\Delta p}{L_p^2} = 0 \quad (11)$$

Where Δp is the hole density in the base, L_p is the diffusion length of the holes in the base, D_p is the diffusion coefficient of the holes in the base and α_2 is the absorption coefficient in the base.

The solution of equation (11) is of the form

$$\Delta p = A' \exp\left(\frac{x}{L_p}\right) + B' \exp\left(-\frac{x}{L_p}\right) - \frac{\alpha_2 F(1-R)L_p^2}{Dp(\alpha_2^2-1)} \exp(-\alpha_2 x) \quad (12)$$

The constants A' and B' are obtained from the following boundary conditions:

$$D_p \frac{d\Delta p}{dx} = -S_p \Delta p \quad \text{for} \quad x = x_t \quad (13)$$
$$\Delta p = 0 \quad \text{for} \quad x = x_{p+}W \quad (14)$$

x_t is the depth of the base and S_p is the recombination velocity of the holes at the back face.
The photocurrent density in this region is defined by [3]:

$$J_p = -qD_p \frac{d\Delta p}{dx}\bigg|_{x=x_p+w} \quad (15)$$

He comes :

$$J_p = \frac{-\alpha_2 Lpe^{-\alpha_2(x_p+W)}qF_0(1-R)}{(\alpha_2)^2(Lp)^2 - 1} \times$$
$$\left[\frac{(\alpha_2 Lp - \frac{SpLp}{Dp})e^{-\alpha_2(x_t-(x_p+W)} + \sinh(\frac{x_t-(x_p+W)}{Lp}) + \frac{SpLp}{Dp}\cosh(\frac{x_t-(x_p+W)}{Lp})}{\cosh(\frac{x_t-(x_p+W)}{Lp}) + \frac{SpLp}{Dp}\sinh(\frac{x_t-(x_p+W)}{Lp})} - \alpha_2 Lp\right] \quad (16)$$

The total photocurrent passing through the diode is the sum of the three relations (7), (8) and (16), that is to say $(J_{ph} = J_n + J_{ZCE} + J_p$). However, knowing J_{ph} we can deduce the internal quantum efficiency (η) by the relation [3]:

$$\eta = \frac{J_{ph}}{qF_0(1-R)} \quad (17)$$

J_{ph} is the density of the total photocurrent of the photodiode.

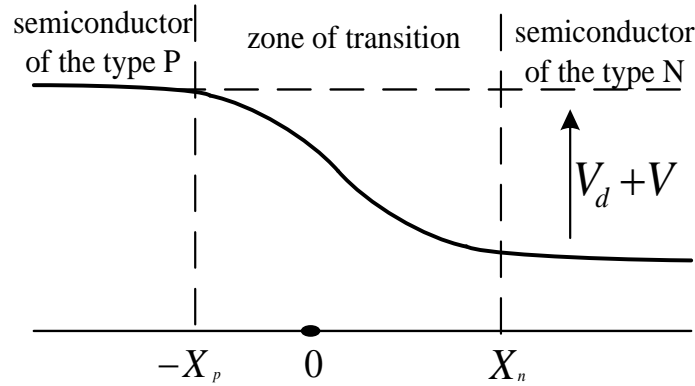## III. DETERMINATION OF THE TRANSITION CAPACITANCE FOR REVERSE POLARIZATION

Figure 2: Diagram of the evolution of the potential in the structure P⁺ N polarized in inverse [4]

The extension of the space charge zone is evaluated using the doping levels on both sides of the junction [5]. The increase of the bias voltage V causes anincrease of the depletion region width. It is shown that an inverse polarized PN junction behaves like a plane capacitor with capacitance [4]:

$$C = \frac{\varepsilon S}{W} \quad (18)$$

The capacitance C is as a function of the inverse voltage V, W is the thickness of the space charge region, ε is the material permittivity and S is the junction surface.

$$dV = -\vec{E}\vec{dl} = -Edx \quad (19)$$

$$\text{with} E = \frac{qN_a x_p^2}{2\varepsilon} + \frac{qN_d x_n^2}{2\varepsilon} \quad (20)$$

By integrating equation (19) into the space charge zone and applying relation $(E(0) = \frac{N_A q}{\varepsilon} x_n = \frac{N_D q}{\varepsilon} x_p)$ we obtain:

$$V_d + V = \frac{N_a q x_p^2}{2\varepsilon}\left(1 + \frac{N_a}{N_d}\right) \quad (21)$$

where E is the electric field, V_d is the diffusion voltage, V is the bias voltage applied, q is the charge of the carrier, N_d is the doping rate of the N-type semiconductor and N_a is the doping rate of the one of type P, x_p is the thickness of the space charge zone in the P-type semiconductor and x_n is the thickness of the space charge zone in the N-type

The charge Q of the transition zone for the P-type semiconductor is written:

$$Q = N_a q x_p S \quad (22)$$

After obtaining x_p from equation (22), the relation (21) becomes:

$$V_d + V = \frac{N_a q}{2\varepsilon}\left(1 + \frac{N_a}{N_d}\right)\frac{Q^2}{q^2 S^2 N_a^2} \quad (23)$$

$$\text{whether} Q = \sqrt{\frac{2\varepsilon q S^2 (V_d + V)}{\frac{1}{N_a} + \frac{1}{N_d}}} \quad (24)$$

An elementary variation dV of V leads to an elementary variation dQ of Q:

$$dQ = \sqrt{\frac{2\varepsilon q S^2}{\frac{1}{N_a} + \frac{1}{N_d}}} \times \frac{1}{2\sqrt{V_d + V}} dV \quad (25)$$

Now dQ = CdV, therefore we obtain:

$$C = S\sqrt{\frac{\varepsilon q}{2\left(\frac{1}{N_a} + \frac{1}{N_d}\right)}} \times \frac{1}{\sqrt{V_d + V}} \quad (26)$$

The concentration of impurities in the P^+ zone is high enough to assume that the space charge zone extends only in the zone N, consequently $N_a \gg N_d$ and consequently $(N_a + N_d \sim N_a)$. For this purpose, the expression of the capacity is written:

$$C = S\sqrt{\frac{\varepsilon q N_d}{2(V_d+V)}} \quad (27)$$

Equalizing (19) and (27), we obtain:

$$w = \sqrt{\frac{2\varepsilon(V_d+V)}{qN_d}} \quad (28)$$

The relation (26) shows that the transition capacitance varies with the inverse voltage as $(1/\sqrt{V_d + V})$. The same relationship can also be written:

$$\frac{1}{C^2} = \frac{2(V_d+V)}{S^2 q \varepsilon N_d} \quad (29)$$

Hence the following linear equation:
$$\frac{1}{C^2} = \frac{2V}{\varepsilon q S^2 N_d} + \frac{2V_d}{\varepsilon q S^2 N_d} \quad (30)$$

The function $\frac{1}{C^2} = f(V)$ varies linearly with the inverse bias.

To increase the total photocurrent J_{ph}, we can either increase the light power or to increase the multiplication factor.

Determination of the Multiplication Factor
The multiplication factor M_{ph} is usually defined as the ratio of the photocurrent $J_{ph}(V)$ to the V voltage on the photocurrent $J_{ph}(0)$ to the voltage 0V or to a low voltage in front of the breakdown voltage [1].

Where $J_{ph}(V)$ is the photogenerated total photocurrent at a given inverse bias voltage V and $J_{ph}(0)$ is the photogenerated total photocurrent in the absence of an inverse bias voltage applied and,

$$M_{ph} = \frac{J_{ph}(V)}{J_{ph}(0)} = \frac{M_n J_n + M_{ZCE} J_{ZCE} + M_p J_p}{J_n + J_{ZCE} + J_p} \quad (31)$$

Where M_{ph} is the total multiplication factor, M_p is the multiplication factor of the holes, M_n is the electron multiplication factor, M_{ZCE} is the electron-hole multiplication factor and J_p, J_n and J_{ZCE} are respectively the base, frontal and space charge zone photocurrent density.
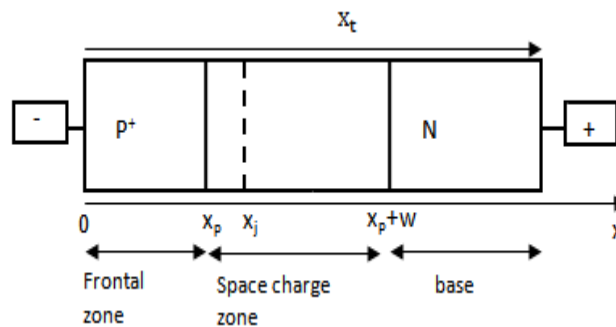

Figure 3: Schemes of an inverse polarised P⁺ / N junction.

Either the P + / N junction shown in figure 3, the multiplication coefficients M_n (for electrons), M_{ZCE} (in the space charge zone) and M_p (for the holes) are defined in equations (32), (33) and (34) respectively.

$$M_n = \frac{J_n(V)}{J_n(0)} \quad (32)$$

$J_n(V)$ is the photocurrent density of electrons at voltage V and $J_n(0)$, that at zero bias voltage.

$$M_{ZCE} = \frac{J_{ZCE}(V)}{J_{ZCE}(0)} \quad (33)$$

$$M_p = \frac{J_p(V)}{J_p(0)} \quad (34)$$

$J_p(V)$ is the photocurrent density of the holes at the voltage V and $J_p(0)$, that at the zero bias voltage. Thus the terms J_n, J_{ZCE} and J_p are respectively defined in equations (7), (9) and (16).

The multiplication factors M_n, M_{ZCE} and M_p were respectively deduced from equations (32), (33) and (34).

$$M_n = \frac{\frac{(\alpha_1 . L_n + \frac{S_n . L_n}{D_n}) - e^{-\alpha_1(x_p - (W - W_0))}\left(\frac{S_n . L_n}{D_n}\cosh\left(\frac{x_p - (W - W_0)}{L_n}\right) + \sinh\left(\frac{x_p - (W - W_0)}{L_n}\right)\right)}{\cosh\left(\frac{x_p - (W - W_0)}{L_n}\right) + \frac{S_n . L_n}{D_n}\sinh\left(\frac{x_p - (W - W_0)}{L_n}\right)} - \alpha_1 . L_n e^{-\alpha_1(x_p - (W - W_0))}}{\frac{(\alpha_1 . L_n + \frac{S_n . L_n}{D_n}) - e^{-\alpha_1 x_p}\left(\frac{S_n . L_n}{D_n}\cosh\left(\frac{x_p}{L_n}\right) + \sinh\left(\frac{x_p}{L_n}\right)\right)}{\cosh\left(\frac{x_p}{L_n}\right) + \frac{S_n . L_n}{D_n}\sinh\left(\frac{x_p}{L_n}\right)} - \alpha_1 . L_n e^{-\alpha_1 x_p}} \quad (35)$$

$$M_{ZCE} = \frac{1 - \exp(-\alpha_1 W)}{1 - \exp(-\alpha_1 W_0)} \quad (36)$$

$$M_p = \frac{e^{-\alpha_2 W}}{e^{-\alpha_2 W_0}} \times \left\{ \frac{\left[\frac{(\alpha_2 L_p - \frac{S_p L_p}{D_p})e^{-\alpha_2(x_t - (x_p + W)} + \sinh(\frac{x_t - (x_p + W)}{L_p}) + \frac{S_p L_p}{D_p}\cosh(\frac{x_t - (x_p + W)}{L_p})}{\cosh(\frac{x_t - (x_p + W)}{L_p}) + \frac{S_p L_p}{D_p}\sinh(\frac{x_t - (x_p + W)}{L_p})} - \alpha_2 L_p\right]}{\left[\frac{(\alpha_2 L_p - \frac{S_p L_p}{D_p})e^{-\alpha_2(x_t - (x_p + W_0)} + \sinh(\frac{x_t - (x_p + W_0)}{L_p}) + \frac{S_p L_p}{D_p}\cosh(\frac{x_t - (x_p + W_0)}{L_p})}{\cosh(\frac{x_t - (x_p + W_0)}{L_p}) + \frac{S_p L_p}{D_p}\sinh(\frac{x_t - (x_p + W_0)}{L_p})} - \alpha_2 L_p\right]} \right\} \quad (37)$$

with: $W = \left(\frac{2\varepsilon(V_d + V)}{qN_d}\right)^{1/2}$ and $W_0 = \left(\frac{2\varepsilon V_d}{qN_d}\right)^{1/2}$

In the case of pure frontal injection (n) ($\lambda = 0.423\mu m$, $\lambda = 0.556\mu m$ and $\lambda = 0.751\mu m$) we have $M_{ph} = M_n$ (Fig.9); in the case of mixed injection ($\lambda = 1.037\mu m$, $\lambda = 1.141\mu m$) we obtain $M_{ph} = M_{ZCE}$ (Fig.9); in the case of pure injection of the base (p) ($\lambda = 1.233\mu m$) $M_{ph} = M_p$ (Fig.9).

Thus, if the electric field varies in a simple way in the space charge region, the simplified expression of M_{ph} allows to deduce k_p and k_n [6] which are respectively the ionization coefficients of the holes and the electrons. Stillman et al. [7] have described in detail this method andhave giventhe simplified expression of k_p and k_n as a function of M_p and M_n for a constant electric field (p-i-n junction) and for linearly varying electric fieldsofabrupt p-n junction.

For an abrupt p⁺-n junction with a triangular electric field E, k_p and k_n can be written [6]:

$$k_p(E) = \frac{2}{W_0^2}\frac{M_p(V)}{M_n(V)}\frac{d\{1 - [1/M_p(V)]\}}{dV} \quad (38)$$

Equation (38) becomes after simplification:

$$k_p(E) = E \frac{1}{M_n(V)M_p(V)}\frac{dM_p(V)}{dV} \quad (39)$$

and the ionization coefficient of the electrons is given by

$$k_n(E) = E\left(\frac{1}{M_n(V)}\frac{dM_n(V)}{dV} - \frac{1}{M_p(V)}\frac{dM_p(V)}{dV}\right) + k_P \quad (40)$$

with: $E = \left(\frac{2qN_d}{\varepsilon}\right)^{1/2}(V + V_d)^{1/2}$ (41)

Determination of k_p and k_n

The k_p and k_n values cannot be deduced directly from relation (39) and (40) for two reasons: (1) the multiplication at 0.751μm is not exactly M_n and (2) its variation is rather weak and the determinations of the derivatives $\frac{dM(V)}{dV}$ arevery imprecise [6]. However, k_p and k_n can be written as [8]:

$$k_p(E) = A_p \exp\left(-\frac{B_p}{E}\right) \quad (42)$$

$$k_n(E) = A_n \exp(-\frac{B_n}{E}) \qquad (43)$$

where A_p, A_n, B_p and B_n are parameters whose their determination was made in three steps:

First, we have established equations (44) and (45) obtained from equations (42) and (43).

$$\ln(k_p(E)) = \ln A_p - \frac{B_p}{E} \qquad (44)$$
$$\ln(k_n(E)) = \ln A_n - \frac{B_n}{E} \qquad (45)$$

In equations (44) and (45), we have determined the values of $\ln(k_p(E))$ and $\ln(k_n(E))$ illustrated in the table below. These values have been deduced from the values of $k_p(E)$ and $k_n(E)$ in equations (39) and (40).

$\ln(k_p(E))$ (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

Then from the table above we have obtained the characteristics $\ln(k_p(E))$ and $\ln(k_n(E))$ as a function of 1/E represented in figure4 in the interval of the electric field $(0,5 < E < 5,8 \times 10^5 \text{ Vcm}^{-1})$.

Figure 4: $ln(k_p(E))$ and $ln(k_n(E))$ as a function of the inverse of the electric field.

Finally, we have used the equations (44), (45) and figure 4 to give the values of these parameters. $A_p = 3,606 \times 10^4$ (cm^{-1}), $B_p = 1,702 \times 10^5$ (Vcm^{-1}), $A_n = 3,271 \times 10^3$ (cm^{-1}) and $B_n = 1,702 \times 10^5$ (Vcm^{-1}).

IV. RESULTS AND DISCUSSION
The results obtained from the theoretical study are mentioned below through the graphs.

The internal quantum efficiency
This quantum efficiency is illustrated by Figure 6 obtained from of the data of the absorption coefficient as a function of the energy presented in Figure 5 [9]
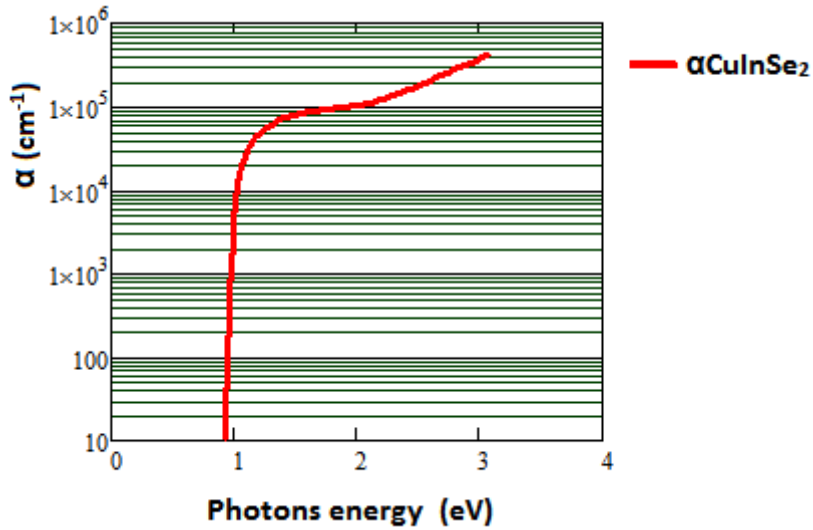
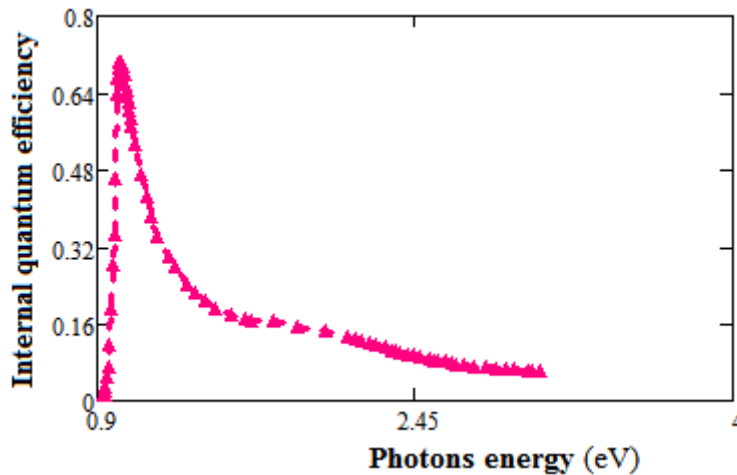*Figure 5: Absorption coefficient of CuInSe₂ vs photons energy*

Figure 6: Total internal quantum efficiency as a function of photon energy of CuInSe2p⁺/CuInSe2n ($S_n = 2.10^6 cm/s, x_p = 0,4\mu m, x_t = 6\mu m, L_n = 0,14\mu m, L_p = 5\mu m, \ w = 0,7\mu m$)

We observea considerable increase in the internal quantum efficiency about 68% at low energies (0.9 to 1.2 eV); followed of a gradual decrease at the high energies. Indeed most photons are absorbed in the base (N-type), carriers are created and will diffuse at the junction to be collected. The low level of internal quantum at the high energies is interpreted as a low absorption in this region and to the phenomena of recombination which are very important in volume and surface.

The capacitance and the inverse of the square of the capacitance as a function of the applied inverse voltage V.

We represent on the following graphs the behavior of curves C (V) and $\frac{1}{c^2}$(V).
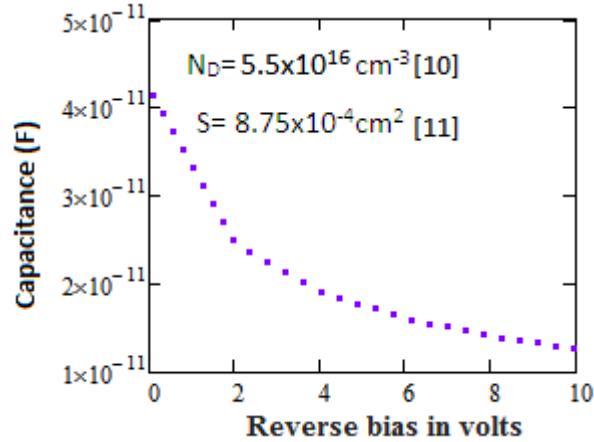
Figure7: Variation of the capacitance as a function of the inverse voltage(V_d =0,70V, $\varepsilon = 1,204 \times 10^{-12} Fcm^{-1}, e = 1,6 \times 10^{-19}C$)
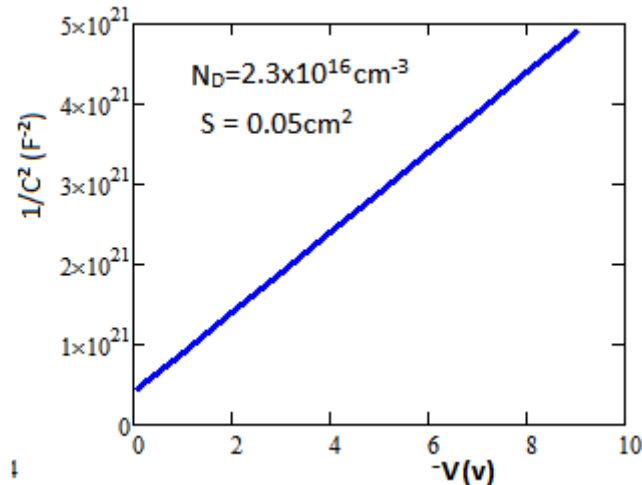

Figure 8: Variation of the inverse square of the capacity of the reverse bias voltage(V_d =0,70V, $\varepsilon = 1,204 \times 10^{-12}Fcm^{-1}, e = 1,6 \times 10^{-19}C$)

The capacitance of the junction depends on the thickness of the depletion zone W which varies with the inverse bias voltage applied (Figure7). However, the increase of capacitance in a circuit slows down its response speed.

Therefore, it is common to specify the junction capacitance at zero external polarization.

The thickness of the space charge zone binds the doping level and the capacitance (relationship 29). Thus, a decrease in the doping rate leads to an increase of the depletion zone but lowers the transition capacitance and consequently $\frac{1}{C^2}$ increases.

The multiplication factor
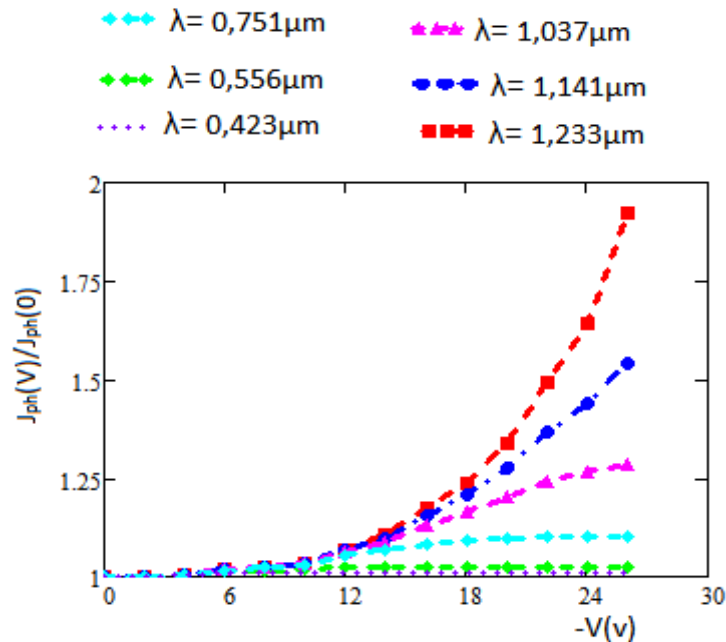The variation of the multiplication factor is represented by Figure 9.

Figure 9: Calculated variation of the ratio Jph (V) / Jph (0) as a function of the polarization voltage applied for different values of the wavelength of CuInSe2p⁺ /CuInSe2n ($S_n = 2.10^6 cm/s, L_n = 0,14 \mu m, xp = 0,4 \mu m, L_{p_2} = 5 \mu m, x_t = 6 \mu m$)

We notice that from V = -12V and for the wavelengths (1.037μm, 1.141μm and 1.233μm), multiplication of the carriers characterized by the ratio Jph (V) / Jph (0) increases with the voltage of reverse polarization. This increase is very important at V = -24 V for a wavelength of 1.233 μm. We note that from -12V to -18V, and for λ = 0.751μm the ratio Jph (V) / Jph (0) increases, and becomes constant from -18V. As for the wavelength of 0.556μm, we note from -12V the absence of the variation of the ratio Jph (V) / Jph (0) as a function of the inverse voltage. However, for λ = 0.423μm, Jph (V) / Jph (0) remains almost equal to 1 and consequently the carriers do not multiply. Indeed, more the wavelength is great, more the effect of the extension of the space charge zone is sensitive and the photocurrent varies progressively as a function of the inverse applied voltage V. This variation of the photocurrent increases to 80% in the near infrared for a wavelength of 1.233 μm. On the other side, for the wavelength (0.423μm), the absence of the multiplication is interpreted by short wavelengths not reaching the space charge zone. Consequently, all carriers are created on the surface showing that the photocurrent is independent of the inverse applied voltage V. The considerable increase of the multiplication at V = -24V is explained by the fact that when the inverse bias voltage becomes very high, the electric field becomes important in turn; the charge carriers will have much more kinetic energy and will in this case be able to generate new pairs of carriers. The latter, inturn create by shocks of new pairs leading to the avalanche. However, according to the wavelength, multiplication is due either to electrons (λ = 0.423μm and λ = 0.556μm and λ = 0.751μm), to holes (λ = 1.233μm) or to electron-holes (λ = 1.037μm and λ = 1.141μm).

When the device is subjected to illumination by a relatively long wavelength (λ = 1.233 μm), most photons are absorbed in the depletion zone and in the base. The multiplication is the work of the holes. It is essentially the holes that generate multiplication. Consequently, one obtains $M_{ph} = M_p$[12].

For an illumination at short wavelengths (λ = 0.423μm and λ = 0.556μm and λ = 0.751μm), the photon penetration distance is very small. In this case, we consider that only the electrons participate of the multiplication and therefore $M_{ph} = M_n$[12].

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

The ionization coefficients k_p and k_n

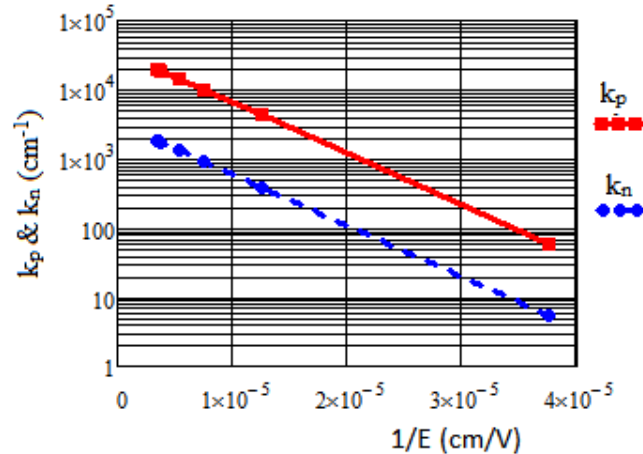These ionization coefficients are illustrated in Figure 10

Figure10: Coefficients of ionization of the holes and of the electrons as a function of the inverse of the electric field of CuInSe2p + / CuInSe2n

We notice a reduction of the ionization coefficients as a function of the inverse of the electric field (1 / E). This variation is inversely as a function of the electric field that is to say to decreasing values of the electric field. Indeed, the strong electric field allows the charge carriers to acquire much more kinetic energy allowing them to create new pairs of electron-hole carriers by shock. The latter in their turn are accelerated by the electric field and generate new pairs by shocks, thus leading to an important multiplication of carriers.

The ionization coefficient of the holes is greater than that of the electrons. This deviation of the ionization coefficients is shown through the ratio (k_p / k_n = 11.024). In the inverse polarized P^+ N structure, the space charge zone extends essentially in the least doped region, which is the N zone. In this zone, we attend to an electric field which allows all the carriers created to reach the edge of the space charge area and be collected. Thus the holes which are the minority carriers in this layer will have more luck to be collected in large numbers. However, the ratio being much greater than unity, consequently we can minimize the excess of noise, according to [6].

V.   CONCLUSION

The inequality of the ionization coefficients ($k_p > k_n$) shows that the multiplication is linked to the holes. However, this difference of the ionization coefficients has allowed us to appreciate the performance of the device through the small excess of noise that can be manifested through the experiments. The ionization coefficients k_p and k_n have been determined using indirect calculation, and using the hypothesis that ionization takes place for a linearly varying electric field. Our results show that through the multiplication factor, the quantum efficiency can be improved compared to the structure of the window effect. In order to do this, it is necessary to increase the space charge zone (doping reduction, inverse bias increase) so that the photoporteurs are all created there. The values of our ionization coefficients calculated from the expressions of multiplication factors (M_n and M_p) are in agreement with those published by some authors, namely H. Luquet et al [6], Karine ISOIRD [8]; which has allowed us to validate our method of calculation. This work will be extended to the comparative study between photomultiplication and the window effect

VI.   REFERENCES

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