International Journal of Applied Engineering Research, ISSN 0973-4562 Volume 13, Number 10 (2018) pp. 7668–7672

Analysis of Multiplication Noise in N^+NP Avalanche Photodiode

Dr. Tarik Baldawi and Dr. Ashraf Abuelhaija
Department of Electrical Engineering,
Applied Science Private University, Amman, Jordan.
Orcid ID : 0000-0001-7315-9088, Orcid ID : 0000-0002-6645-3833

Abstract: Avalanche photodiodes are mainly used in optical communications systems as light detectors. These devices are characterized by their high speed and internal gain, so there is no need in most cases to use an amplifier, which will reduce the bandwidth of the system. However these devices suffer from a main disadvantage, which is the high level of noise due to multiplication phenomena, and thus the minimum detectable power will be affected [1], [2], [3], [4]. In addition to multiplication noise, there is the thermal noise and shot noise. The purpose of this paper is to study and analyze the multiplication noise in these devices using the N^+NP structure and illustrating the factors that affect the noise level such as the junction depth, device material, electric field profile, type of carrier which initiates the multiplication process.

Keywords: Avalanche Photodiodes, Noise in APDs, Noise Factor.

AVALANCHE MULTIPLICATION THEORY

Figure (1) shows a cross-section of such a device with ion implanted layer. In the high electric field region of a highly reversed-biased junction, carriers drift at saturation velocity and gain sufficiently high energy from the electric field to release new electron-hole pairs through impact ionization [5]. A chain of these impact ionizations leads to carrier multiplication. The average number of electron-hole pairs generated by a carrier per unit distance traveled is denoted as an impact-ionization coefficient. The values of the impact ionization coefficients for electrons α and holes β for Germanium as a function of the electric field are shown in figure (2), where the ionization rates used in the calculations are obtained after Mikawa et al, 1980 [6], and are given by

$$\alpha = 2.72 \times 10^6 \times \exp(-1.1 \times 10^6/E) \tag{1}$$

and

$$\beta = 1.72 \times 10^6 \times \exp(-9.37 \times 10^5/E) \tag{2}$$

It can be seen that the ionization coefficients are nearly equals. In this device model, the electrons will be swept by the electric field to the left and holes to the right. In traversing an element of distance (dx),the electron will suffer on average (α·dx) ionizing collisions. Similarly the hole will generate an average of $(\beta \cdot dx)$ hole-electron pairs as it goes a distance of (dx). If M(x) is the average total number of pairs which are generated in the obtained layer as a result of one initial pair being generated at (x), we can write:

$$M(x) = 1 + \int_{x_j-a_1}^{x} (\alpha) \cdot M(x) \cdot dx + \int_{x}^{x_j-a_2} (\beta) \cdot M(x) \cdot dx \tag{3}$$

where a_1 and a_2 are the two components of the depletion layer thickness, i.e. a_1 is width of the depletion layer to the left of point x_j, and a_2 is to the right of x_j and x_j is the junction depth. Differentiating equation (3), getting:

$$dM(x)/dx = (\alpha - \beta) \cdot M(x) \tag{4}$$

Rearranging:

$$dM(x)/dx - (\alpha - \beta) \cdot M(x) = 0 \tag{5}$$

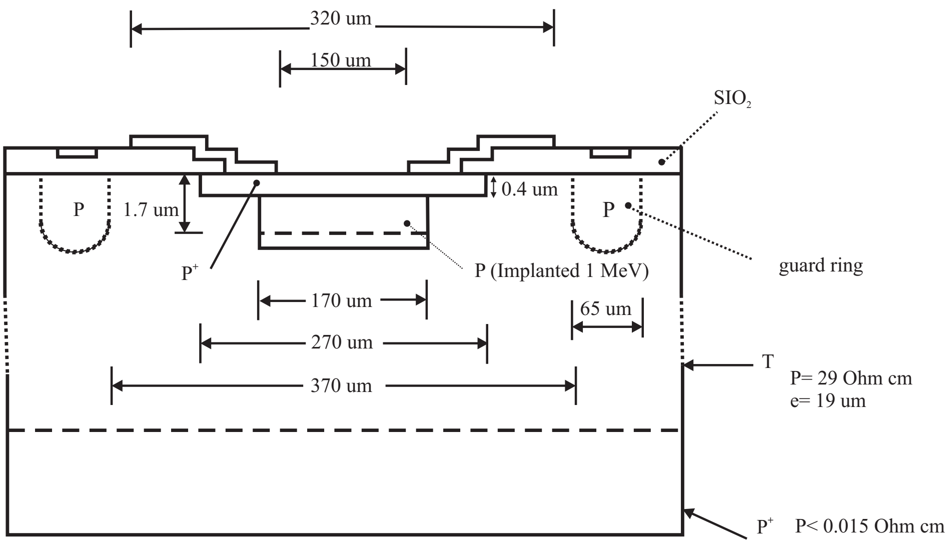

FIGURE 1. A cross-section of the Avalanche photodiode

The general solution of this equation is:

$$M(x) = A_1 \cdot \exp\left(\int_{x_j - a_1}^{x} (\alpha - \beta)\right) \cdot dx \qquad (6)$$

where A_1 is a constant, and the boundary condition is

$$M(x) = M(x_j - a_1) \mid_{x = x_j - a_1} \qquad (7)$$

Substituting equation (7) into equation (6) gives:

$$M(x) = M(x_j - a_1) \cdot \int_{x_j - a_1}^{x} (\alpha - \beta) \cdot dx \qquad (8)$$

Similarly $M(x)$ can be written as:

$$M(x) = M(x_j + a_2) \cdot \exp\left(- \int_{x}^{x_j + a_2} (\alpha - \beta) \cdot dx \right) \qquad (9)$$

Substituting of equation (9) into (3) for $x = x_j + a_2$, manipulating and rearranging terms gives:

$$M(x) = \frac{\exp\left(- \int_{x}^{x_j + a_2} (\alpha - \beta) \cdot dx \right)}{1 - \int_{0}^{x_j + a_2} \alpha \cdot \exp\left(- \int_{x}^{x_j + a_2} (\alpha - \beta) \right) dx} \qquad (10)$$

Equation (9) points out the fact that only electron- hole pairs generated at (x) in the chain of pairs resulting from an initial ionization at (x) will itself be multiplied on the average by $M(x)$, and this is the key to understand the mechanism of noise generation in the depletion layer.

DEVICE NOISE CHARACTERISTICS

The term noise refers to spontaneous fluctuations in the current passing through, or the instability of voltage across the semiconductor devices. So, if the device is used to amplify small signals, spontaneous fluctuation in the current will set a lower limit to the signals to be amplified. It is important to know the factors affecting these limits, so as to optimize the operating conditions, and to find new methods and new technologies to reduce noise [7]. In the N^+NP germanium avalanche photodiode, the noise is classified as: Multiplication noise, Shot noise and Thermal noise. In this work, Multiplication noise is being treated.

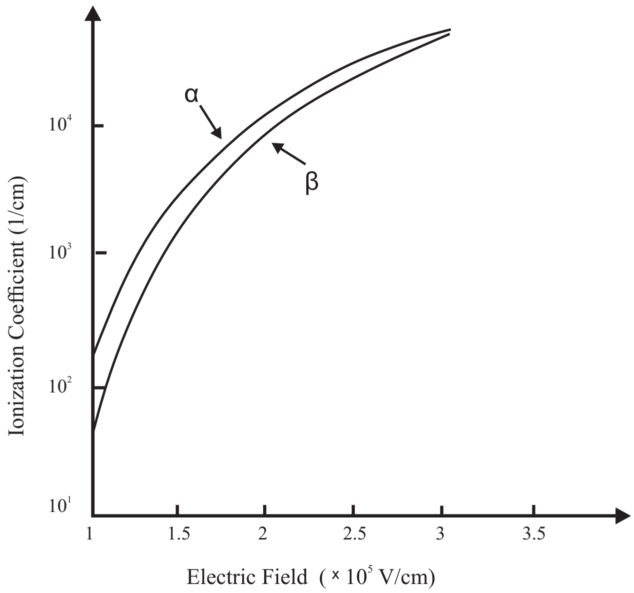

FIGURE 2. Ionization Coefficient

Multiplication Noise: The schematic representation of the carrier multiplication process is shown in figure (3), where the multiplication factor is 8 for example. Figure (3)

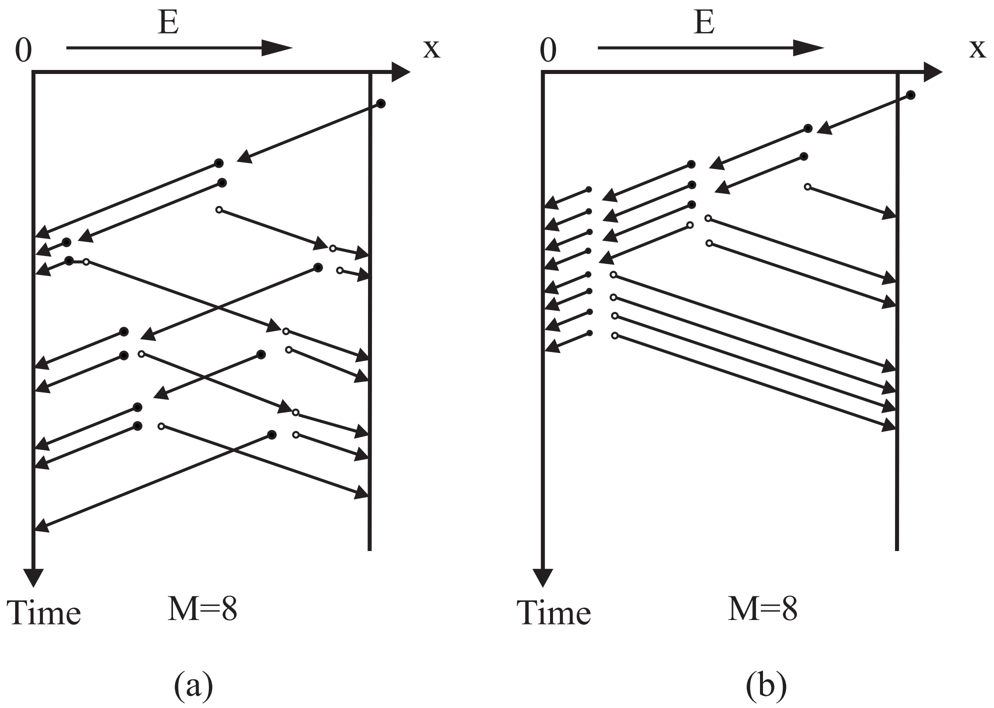

FIGURE 3. Carrier mutiplication process

shows the case in which the semiconductor has equal ionization coefficient for electrons and holes (i.e. $\alpha = \beta$).

As we see the multiplication process buildup is aided by the hole feedback mechanism. The feedback greatly depends on the impact ionization coefficient ratio between electrons and holes and is more pronounced as the symmetry in the carrier ionization coefficient becomes larger. Moreover, not every carrier-injected into the avalanche region undergoes the same feedback. In fact, there is a quite wide probability distribution for the feedback mechanism, so the possible multiplication factor for injected carriers is also widely distributed. Let us say that on average, each photo-generated carrier leads to the generation of (M) carriers at the end of the multiplication process.

Any carrier initiating an avalanche may produce more than (M) carriers and this statistical nature of the process introduces further noise. Therefore the mean square of the multiplication factor $< M^2 >$ becomes larger than the square of the average multiplication factor $< M >^2$, where the symbol (<>) denotes an average. Multiplication noise is commonly characterized by an excess noise factor F_{av}, defined as

$$F =< M^2 > / < M >^2 \tag{11}$$

The excess noise factor can be written as:

$$F_{av} = \bar{I}/2q(j_t) < M >^2 \tag{12}$$

where $(\bar{I})$ is the noise spectral density of multiplication noise, and J_t is the total photocurrent at a given wavelength.

We assume that the avalanche region is so thin that the carrier generation can be neglected and the ratio of the hole to electron ionization coefficient (K) has a constant value and can be given by:

$$K = \beta/\alpha = [M(x_j - a_1) - 1]/[M(x_j + a_2) - 1] \tag{13}$$

So the noise spectral density can be given by (Kaneda et al. 1976):

$$\begin{aligned}\bar{I} = {} & 2qj_{P1} \cdot M^3 \cdot (x_j - a_1) \\ & \cdot [1 + ((1 - K)/K)\{M(x_j - a_1) - 1/M(x_j - 1)\}^2] \\ & + 2qj_{PJ} \cdot M^3 \cdot (x_j + a_2) \\ & \cdot [1 - (1 - K) \cdot \{(M(x_j - a_2) - 1)/(M(x_j + a_2\}^2]\end{aligned} \tag{14}$$

where j_{P1} is the photocurrent density in the n type region and JPJ is the photocurrent density generated in the p type region, and $< M >$ is given by:

$$< M >= [j_{p1} \cdot M(x_j - a_1) + j_{pj} \cdot M(x_j + a_2)]/j_t \tag{15}$$

Using equations (13) and (15), $M(x_j - a_1)$ and $M(x_j + a_2)$ may be written as below:

$$M(x_j - a_1) = K(< M > -1)/[1 - (j_{P1}/j_t)(1 - K)] \tag{16}$$

and

$$M(x_j + a_2) = [< M > (j_{P1}/j_t)(1 - K)]/[1 - (j_{P1}/j_t)(1 - K)] \quad (17)$$

However, when the multiplication is initiated by electrons, the excess noise factor is given by

$$F_{av} = M_n[1 - (1 - K)\{(M_n - 1)/M_n\}^2] \quad (18)$$

and when the multiplication is initiated by holes, then the multiplication factor is given by:

$$F_{av} = M_P[1 + ((1 - K)/K)\{(M_P - 1)/M_P\}^2] \quad (19)$$

where M_n and M_P are the multiplication factors for injected electrons and holes respectively.

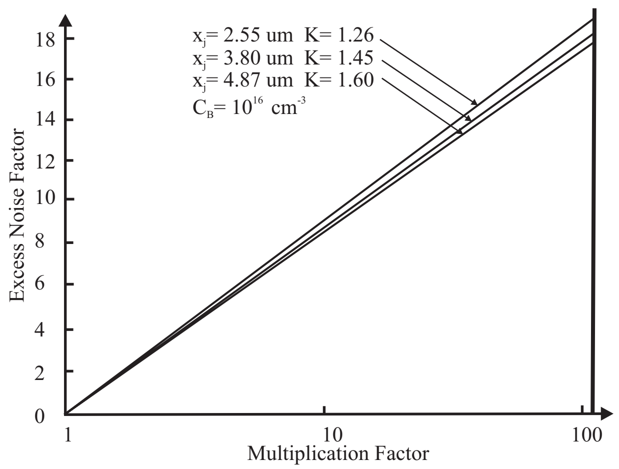

FIGURE 4.

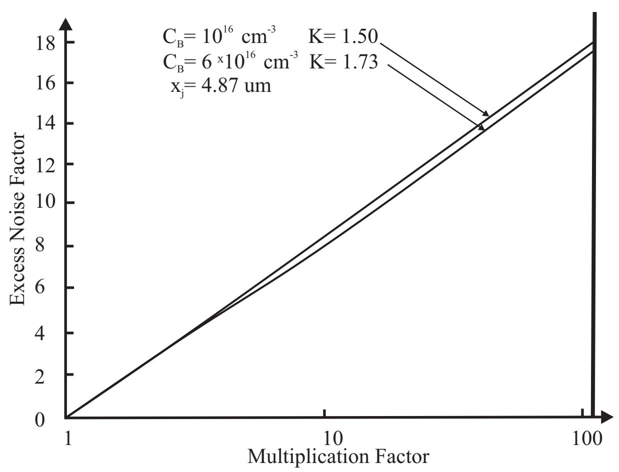

FIGURE 5.

The excess noise factor as a function of the multiplication factor is shown in figure 4. For hole injection and using equation (19), it can be seen that the excess noise factor is increasing function of (M) and the curve can be approximated by the relation:

$$F_{av}(M) = M^x \quad (20)$$

where x is a constant ranging from 0.7 to 1 for germanium. The excess noise factor decreases with increasing impact ionization coefficient ratio. This is demonstrated in figure(4) and (5), where (F_{av}) is decreasing with increasing (K), so a large symmetry in carrier ionization coefficient is required to obtain low multiplication noise by decreasing the carrier feedback effect. However the carrier ionization rates in germanium is nearly equal ($\alpha \approx \beta$) as shown in figure (2), giving a high level of excess noise.

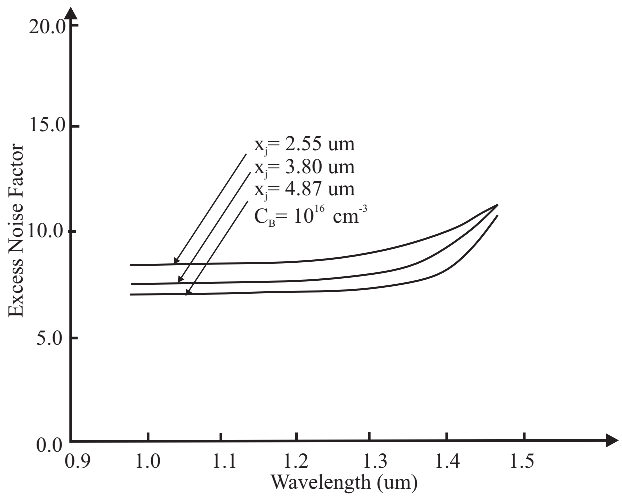

FIGURE 6.

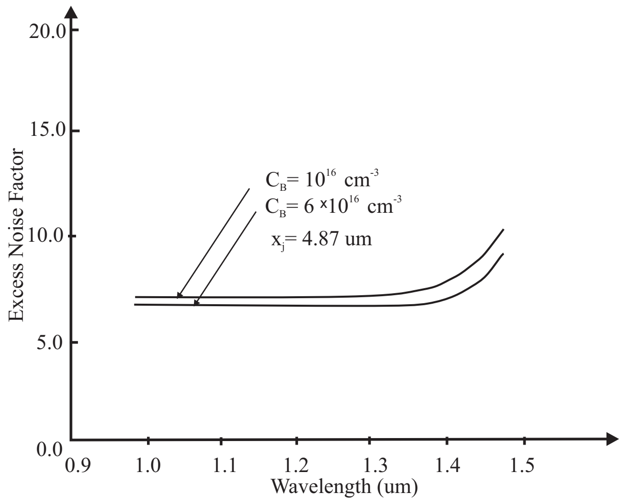

FIGURE 7.

Excess noise factors also depends strongly on carriers injection to obtain low multiplication noise, carriers having higher ionization coefficients should be injected mainly

International Journal of Applied Engineering Research, ISSN 0973-4562 Volume 13, Number 10 (2018) pp. 7668–7672

into the avalanche region to minimize the carrier feedback effect.

The excess noise factor as a function of wavelength for different junction depths is shown in figure(6), using equation (15) & (19), it can be seen that excess noise factor has a constant value in the wavelength region less than 1.3 μm, it is obvious that in this wavelength region incident light is absorbed mainly in the N-layer, resulting in almost pure hole injection into the high field avalanche region. In the wavelength above 1.3 μm, however, because most incident light enters the P-layer through the N-layer, excess noise factors show high values because of increased electron injection currents.

It is also noticed that F_{av} is decreasing with increasing the junction depth. This is due to the fact that in deeper junction, hole injection into the high field region predominates. Also it has been observed that the magnitude of the maximum field decreases with increasing the junction depth, this leads to lower multiplication noise because a greater hole to electron ionization rate ratio is achieved. The excess noise factor is further decreased with decreasing the bulk concentration as shown in figure(7) due to lower electric field.

CONCLUSION

The value of the excess avalanche noise factor depends upon the detector material, the shape of the electric field profile within the device and whether the avalanche is initiated by holes or electrons. The excess noise factor decreases from 8.27 to 6.9 in the wavelength region 1 μm to 1.3 μm as the junction depth increases to 2.55 μm because the value of the maximum field is reduced accordingly and hence the impact ionization coefficient ratio is higher. The excess noise factor is further decreased to 6.55 with decreasing the bulk concentration from $10^{16}/cm^3$ to $6 \times 10^{15}/cm^3$, because the value of the maximum field is decreased.

Acknowledgement

This work has been done at the Applied Science Private University, Amman, JORDAN, Faculty of Engineering, department of Electrical Engineering. The author would like to thank this university for their strong support to this work.

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