Gain Characteristics Of Avalanche Photodiodes Based On Carrier Pair Injected Positions

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Abstrak-- Mean gain characteristics based on carrier pair injected position in avalanche photodiodes (APDs) is investigated by mean of the Random Path Length (RPL) Model that incorporates the carrier history. The model creates a randomly carrier path length to impact ionize following the dead space distance. Dead space distance is a minimum distance required for a carrier to travel to get adequate energy to impact ionizes. Under consideration is an ideal structure that is assumed has a dimensionless multiplication length and a uniform electric field. The simulation will be carried out for double carrier multiplication APDs with various dead spaces distances. An electron-hole pair in various positions is injected into avalanche photodiodes. The mean gain is recorded based on these injected positions of the carriers.

Keywords: Avalanche Photodiodes (APDs), Random Path Length Model, Mean Gain, Dead Space

A. Introduction

There has been a considerable interest in Avalanche Photodiodes (APDs) in the recent advancement of high-speed fiber optic communication systems. APDs are favored to use compared to other photodiodes in such communication systems, due to high gain caused by the ability to increase the number of electron-hole pairs per injected carrier. Electrons and holes produced inside in the region play a role in creating flow of current in the external circuit [1]. Therefore, their output current will be higher compared to those other types of photodiodes. This current extensively improves receiver sensitivity and reduces the need for optical pre-amplification.

A phenomenon behind the production of gain in APDs is carrier impact ionization. Impact ionization is a random process as a result of the randomness of position where the impact ionization occurred. This randomness causes fluctuations in the multiplication gain, M, with the gain average, <M>. This fluctuation produces noise that may be misunderstood as missing of information in communication systems [1].

The model, called random path length (RPL), is developed to model the avalanche process in APDs. The model creates a randomly carrier path length to impact ionize following the dead space distance. Dead space distance is a minimum distance required for a carrier to travel to get adequate energy to impact ionizes. The simulation determines the number of carriers produced in the gain region. Multiplication gain is determined by dividing number of carriers produced per injected carrier. APDs are investigated by observing the performance of mean multiplication based on the carrier-injected positions.

B. Background Study

Optical devices convert information or energy from optical form into electrical signal and recover transmitted data via the

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optical communication system. One device used as an optical receiver is photodiode. There are three processes in the detection of optical energy with a semiconductor photodetector. Firstly is carrier generation by the incident radiation. Secondly is carrier transport and/or multiplication to produce an electric current. And the last is interaction of the photocurrent with an external circuit to yield an output signal. Photodetectors are frequently used in infrared sensors and as detectors for optical fiber communication systems. The performance of a photodetector is a measured in terms of its quantum efficiency, response time, and sensitivity of detection [1].

Avalanche photodiodes (APDs) are photodiodes that operate at reverse biases close to avalanche breakdown voltage to enable avalanche multiplication of generated carriers. Hence, its output current is extremely higher compared to the primary current generated by the incident radiation, and thus this increases its sensitivity and reduces the need for optical amplification. One parameter to see the performance of APDs is avalanche multiplication or gain multiplication, M. Since the number of carriers generated in the multiplication region in the avalanche process is random then the multiplication will be random as well. Hence, the parameter to see the APDs performance is the mean multiplication or mean gain, <M> [2].

Gain multiplication is determined by ratio of the total number carriers, of the type injected, produced in the avalanche process to primary injected electron or hole. Over the years, the avalanche multiplication is predicted by the local model, which is the probability for a carrier to initiate impact ionization was assumed to depend on the local electric field. It means that probability for a carrier to initiate impact ionization does not depend on the carrier history [2]. However, the calculation of multiplication gain must account a carrier history to obtain more accurate results.

The effect of past carrier history to generate new pair carrier by means of impact ionization should also be taken account into the modeling and simulation of avalanche process, as has been shown by Saleh, et.al [4][5][6]. Including carrier history in the calculation is essential [3][7] because after each impact ionization, an ionizing electron or hole is required to travel some distance, namely dead space distance, to obtain sufficient energy that allow it to influence another impact ionization to produce more secondary carriers.

C. Research Methods

The Model and Algorithm

The random path length (RPL) model of avalanche process is developed to model the performance of avalanche photodiode. The model generates a randomly ionization path length by including the dead space prior to impact ionize. These random distance variables are assumed to be statistically independent and have probability density function. The probability density function for an electron to initiate impact ionization after traveling a distance *x* in a uniform electric field, *E*, is given by [2]

$$P_e(x) = \begin{cases} 0 & , x \le d_e^* \\ \alpha^* \exp[-\alpha^*(x - d_e^*)] & , x > d_e^* \end{cases} \quad (1)$$

Where d_e* is the electron hard threshold dead space, and α* is the ionization coefficient for electron after dead space occurred. The value of d_e* is determined by electron charge, *e*, ionization threshold energy, ε_{th}*, and electric field, *E* [2].

$$d_e^* = \frac{\varepsilon_{th}^*}{eE} \quad (2)$$

Hence, the probability for an electron to ionize in a given position does not depend only on applied electric field, as in the local model, but also on its history.

From equation (1) the average distance between the position where the electron impact ionize is given by the following equation,

$$< l >= \int_0^\infty x P_e(x) dx = \frac{1}{\alpha *} + d_e * \qquad (3)$$

Since the electron ionization coefficient, α, is the inverse of average length of the electron impact ionize, therefore

$$\alpha = \frac{1}{d_e * + 1/\alpha *} \qquad (4)$$

The probability that a carrier travels distance x without generating secondary electron-hole pair, $S_e(x)$, can be obtained from equation (1).

$$S_e(x) = \begin{cases} 1 & , x \le d_e * \\ \exp[-\alpha * (x - d_e *)] & , x > d_e * \end{cases} \qquad (5)$$

In order to get a random path length for electron to impact ionize, l_e, in this RPL model, a random number, r, between 0 and 1 is injected into $S_e(x)$ in equation (5).

$$r = \exp[-\alpha * (l_e - d_e *)] \qquad (6)$$

$$l_e = d_e * - \frac{\ln(r)}{\alpha *} \qquad (7)$$

Thus by substituting, $P_h(x)$, $S_h(x)$, β, β*, d_h* and l_h for $P_e(x)$, $S_e(x)$, α, α*, d_e* and l_e, the RPL model for hole can be obtained.

To begin an avalanche multiplication process, a carrier pair is injected inside the gain region then traveling a random distance to impact ionize, according to equation (7). Hence, at this position in addition to the original electron, there will be a new electron and a new hole generated. All three carriers then will travel new random length, selected independently according to equation (7), to initiate impact ionization and produce many secondary carriers. Electrons and holes repeat this process independently until all carriers have left the multiplication region. The total number of carrier pairs produced including the primary electron that initiate the whole avalanche process is counted.

Multiplication, M, is calculated by taking ratio of the total number of carriers produced in the avalanche process to primary injected electron or hole or in other words it is a quantity of carrier pairs generated by injecting an electron-hole pair at location x. By using this model, we can estimate multiplication in double carrier avalanche photodiodes by including the dead space.

Simulation

Under consideration is an ideal structure that is assumed has a dimensionless multiplication length of w and a uniform electric field. The simulation will be carried out for double carrier multiplication APDs with various dead spaces distances, d*. To begin an avalanche multiplication process, an electron-hole pair is injected at position within the region. Subsequently it travels a random distance (including the dead space distance) to commence the impact ionization. At this position, in addition to the original electron, there will be a new electron and a new hole generated. All these three carriers will travel in new random distances, with the hole in opposite direction, to initiate another impact ionization and produce more offspring carriers. All carriers will repeat the same process independently until they have left the gain region. The total number of carrier generated including the primary injected carrier that initiate the whole avalanche process is counted.

The experiment above is repeated by injecting more carriers in various positions within the gain region to kick off the avalanche process. Each experiment is reiterated until 10000 trials. This number is as much as necessary to achieve the precise data. The mean gain, <M>, is obtained by taking average from all multiplication process from all trials.

D. Results and Discussions

Mean multiplication of APDs, as a function of position where a carrier pair is injected, is determined using random path length (RPL) model. A carrier pair is injected within the gain region from the position at $x = 0$ until $x = w$. The simulation is carried out for APDs with various hole-to-electron ionization ratio, $k = \beta/\alpha$ = 0.0, 0.1, 0.1 and 1.0. Each case is computed for different dead space ratio, d^*/w = 0.0, 0.05 and 0.1. The value of dimensionless mean electron ionization coefficient, αw, is selected in order that the mean gain, resulted by the injected carrier at position $x = 0$, <M> = M(0), has value around 40 in the case of no dead space, $d^*/w = 0$

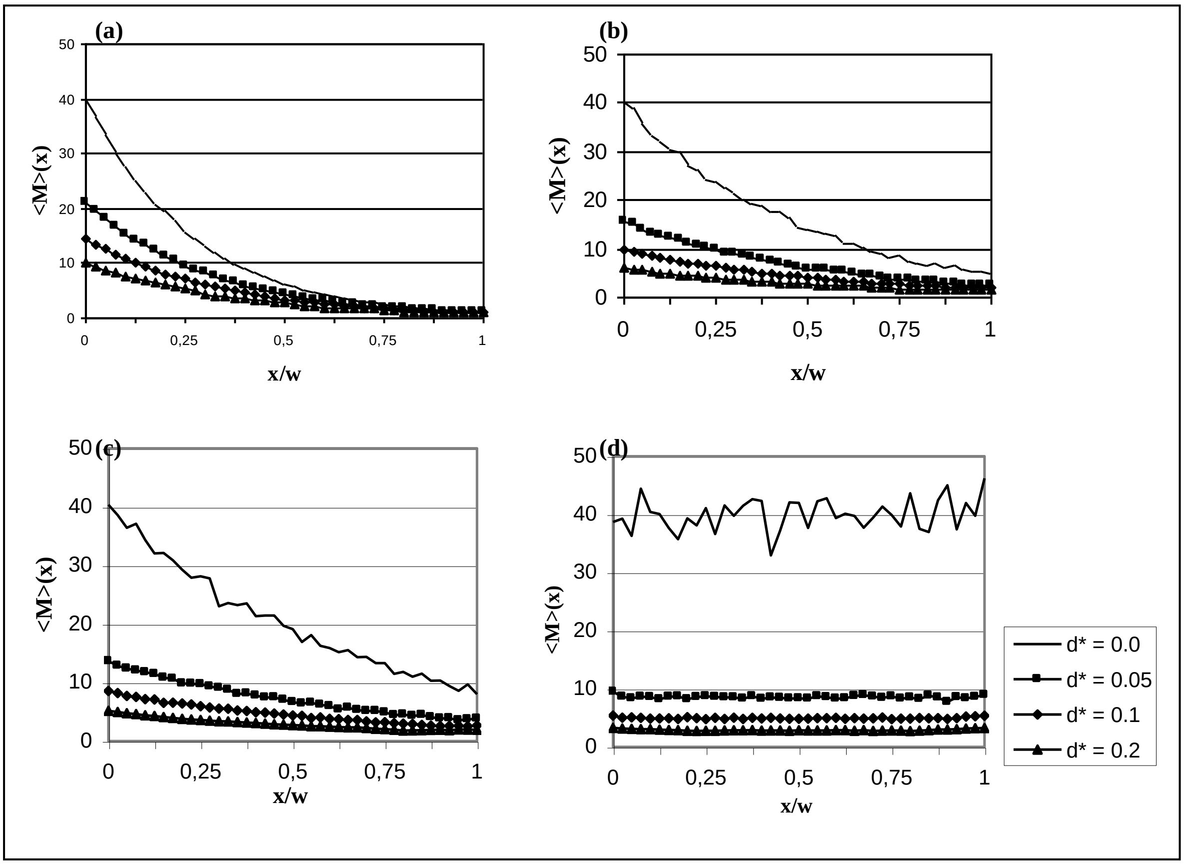

Figure 1. Mean number of carriers produced as a result of injection an electron-hole pair at location x in the gain region of width w, with value of value of dimensionless mean electron ionization coefficient, αw, is selected to obtain the mean gain, <M>(0), about 40 in the absence of dead space. The computation are carried in the four cases of ionization coefficient ratio: (a) k = 0.0 (αw = 3.689), (b) k = 0.1 (αw = 2.333), (c) k = 0.2 (αw = 1.893) and (c) k = 1.0 (αw = 0.975), each is calculated in the dead space ratio, d^*/w = 0.0, 0.05, 0.1, and 0.2.

The simulation results are presented in the figure 1. Generally, the graphs show that the dead space give effects in the reduction of mean gain, M(x), within the region from interval x = 0 until x = w. The effect is likely much higher when the electron is more to impact ionize compared to hole, or in other words the hole-to-electron ionization ratio, $k = \beta/\alpha$, is higher.

E. Conclusions

This report presents a theoretical study of avalanche multiplication process in APDs by evaluating the performance of mean multiplication based on the carrier-injected positions. Random path length (RPL) model is performed to simulate the avalanche process and determine the quantity of mean multiplication of APDs. The RPL model represents the carrier transport by developing random path lengths after impact ionization by incorporating dead space. The simulation results show that the dead space reduces the mean gain everywhere within the interval of the gain region. The finding results in this research show that the incorporating of dead space in the examination of the performance of avalanche photodiodes (APDs) is essential.

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