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# CURRENT IMPULSE RESPONSE OF THIN InP $p^+$-i-$n^+$ DIODES

A. H. You[1] and D. S. Ong[2]

[1]Faculty of Engineering and Technology, Multimedia University, Jln Ayer Keroh Lama, 75450 Melaka, Malaysia.
[2]Faculty of Engineering, Multimedia University, Jln Multimedia, 63100 Cyberjaya, Selangor, Malaysia.

***Abstract--*** The simulation of current impulse response using random response time model in avalanche photodiode is presented. A random response time model considers the randomness of times at which the primary and secondary carriers are generated in multiplication region. The dead-space effect is included in our model to demonstrate the impact on current impulse response of thin avalanche photodiodes. Current impulse response of homojunction InP $p^+$-i-$n^+$ diodes with the multiplication widths of 0.1μm and 0.2μm are calculated. Our results show that dead-space gives a slower decay rate of current impulse response in thin avalanche photodiode, which may degrade the bit-error-rate of the optical communication systems.

***Index Terms--*** Avalanche photodiodes, dead-space effect, bit-error-rate, current impulse response, and multiplication gain.

## I. INTRODUCTION

Avalanche photodiodes (APDs) have been used as a detector for long haul optical fiber communication systems. Most particularly APDs exploit avalanche multiplication process to amplify weak optical signals. Although multiplication gain and excess noise factor play an important role in the performance of APDs, the current impulse response determines the bit-error-rate and the bandwidth of optical communication systems.

Recently, longer response time has been obtained in thin multiplication region with increasing dead-space to degrade the performance of APDs [1]. Hayat *et al* [2] treated the dead-space model using the theory of age-dependent branching processes and computed the mean and standard deviation of the impulse response function of the double- carrier multiplication APD as functions of time. A simple time-domain approach to calculate the impulse response and bandwidth was proposed by Bandyopadhyay *et al* [3]. By using impulse response function and multiplication gain, Hayat *et al*. [4] have also investigated the effects of dead-space on the bit-error-rate of an on-off keying optical communication system. In more recent, Hambleton *et al* [5] calculated the current response of thin APDs using a simple Monte Carlo model. The effect of enhancement in average carrier velocity to impact ionise at high electric field was studied in their model. However, these models are ideal and have yet to be concluded.

An alternative approach for time evaluation is therefore desirable to calculate the current impulse response with dead-space effect. In this paper, we apply a random response time model [6] to calculate the current impulse response in double-carrier multiplication APDs. This model is based on the calculation of random ionisation path length [6] of carrier to impact ionise in the multiplication region. The effect of dead-space is incorporated in our model, which also plays an important role in reducing noise in thin APDs. We observed the dynamics of carriers with both electron- and hole-initiated multiplication processes. The current impulse response of InP $p^+$-i-$n^+$ diode with electron- and hole-initiated multiplication is calculated, including the dead-space effect.

## II. CURRENT IMPULSE RESPONSE MODEL

An electron injected at $x = 0$ travels in the $x$-direction with a constant saturation velocity, $v_e$ under the effect of an electric field in a double-carrier multiplication APD. The impact ionisation occurs after the carrier travels a random distance, $l_e$. Upon ionisation, an electron-hole pair is generated in multiplication region. The two electrons behave in a statistically identical and independent manner. On the other hand, hole travels in the $-x$-direction with a constant saturation velocity, $v_h$ and ionises after travelling a random distance $l_h$, resulting in two holes and an electron. The electrons and holes repeat the process as they travel through the multiplication region. The multiplication process will continue until all possible carriers have left the multiplication region.

In our model, the electron hard-threshold dead-space, $d_e^*$ and the random electron ionisation path length, $l_e$ can be generated from random path length model [6]. Similarly, it is also applied to holes. In the theory of the statistics of random response time, random time response is the time measured from the instant a parent electron enters the multiplication region ($x = 0$) to the time when all carriers exit the multiplication region. We traced the probability of time for electron and hole to cross the multiplication region with the electron-initiated multiplication process. The random time for carriers to move across the multiplication region is given by

$$T_{e\_initial} = \begin{cases} \dfrac{w}{v_e} + \sum\limits_i l_i \left( \dfrac{1}{v_e} + \dfrac{1}{v_h} \right), & \text{generated by electron} \\ \sum\limits_j l_j \left( \dfrac{1}{v_e} + \dfrac{1}{v_h} \right), & \text{generated by hole,} \end{cases}$$

where $w/v_e$ is the electron transit-time, and $l_i$ and $l_j$ are the random feedback path lengths generated by hole and electron respectively, in the multiplication region.

In complementary, the random time for carriers to move across the multiplication region with hole-initiated multiplication is obtained by substitute the electron with hole. The probability of time for hole-initiated multiplication can be obtained by the mean of the same method.

The current can be calculated from Ramo's theorem [7], so that a carrier always contributes a current throughout the time it spends in the multiplication region. By applying the Ramo's theorem in our model, current impulse response is calculated using $I = \frac{q}{w}(n_e v_e + n_h v_h)$, where $q$ is the electronic charge, $n_e$ and $n_h$ are the number of instantaneous electrons and holes in the multiplication region. The mean values of multiplication gain, excess noise factor and current impulse response are calculated by averaging many trials.

In our device structure, a uniform electric field across the multiplication region is calculated from the doping profile, $p^+ = n^+ = 2 \times 10^{18}\,\text{cm}^{-3}$ by applying a voltage, $V_a$ in InP $p^+$-i-$n^+$ diode. The relation between the electric field and impact ionisation coefficients of electron and hole at high field region in InP are quoted from Cook *et al* [8]. Dead-space is calculated from the threshold energy at different electric fields, where the electron threshold energy, $E_{the} = 1.88\,\text{eV}$ and the hole threshold energy, $E_{thh} = 1.91\,\text{eV}$ are taken from full-band Monte Carlo model

[9]. The saturation velocities of hole and electron are $v_h = 4.13 \times 10^4$ m/s and $v_e = 7.27 \times 10^4$ m/s at high field region in InP. The electron and hole ionisation coefficients for InP are fitted from the established Cook *et al* measurements [8]. By using the electric field calculated from the doping concentrations, our model simulated the current impulse response of homojunction InP $p^+$-i-$n^+$ diode with and without dead-space effect at multiplication lengths of $0.1\mu m$ and $0.2\mu m$.

## III. RESULTS AND DISCUSSION

Our model is used to simulate the InP $p^+$-i-$n^+$ diode with the multiplication lengths of $0.1\mu m$ and $0.2\mu m$. Figure 1 shows the mean multiplication gains of electron and hole-initiated multiplication with and without dead-space effects for $w = 0.1\mu m$ and $0.2\mu m$. The significance of dead-space effect can be clearly observed in the thin device from our simulation results. In general, the device with the dead-space effect needs higher applied voltage to initiate the multiplication process. The corresponding excess noise factors of thin devices are shown in Fig. 2. Our simulated results show that the device with dead-space effect gives lower excess noise factor as compared to the device without dead-space effect. In our work, we found that less feedback ionisation events occur in the dead-space model causes the reduction of excess noise factor in the device. In the dead-space model, carriers will travel a significant distance before it starts to ionise in the multiplication region. Most of the feedback-carriers will immediately leave the multiplication region without further multiplication in the thin device as the dead-space take up some extra space in the thin multiplication region. This process makes the impact ionisation becomes more deterministic in thin devices.

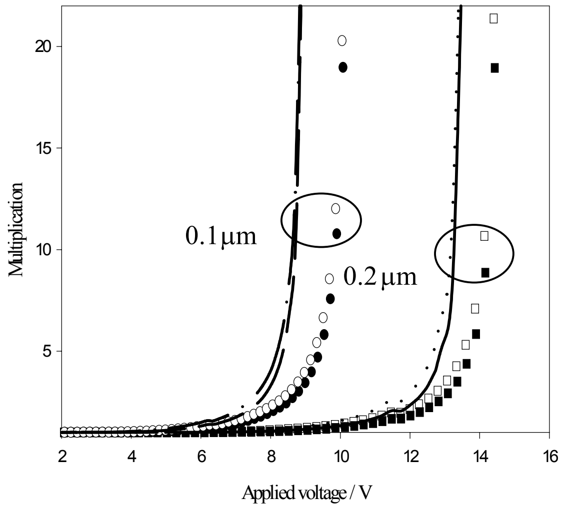


Fig. 1. Mean multiplication versus applied voltage of InP $p^+$-i-$n^+$ diodes with $w = 0.1\mu m$ and $0.2\mu m$. The open (hole) and closed (electron) symbols represent the model with dead-space effect. The dash-dotted- and dot-lines (hole), and the dash- and solid-lines (electron) represent the model without dead-space effect.

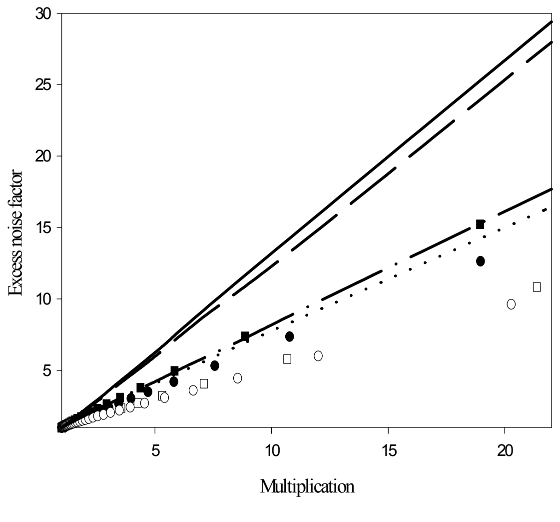


Fig. 2. Excess noise factor versus multiplication of InP $p^+$-i-$n^+$ diodes with $w = 0.1\mu m$ and $0.2\mu m$. The notations are similar with the Fig. 1.

Our model is applied to simulate the current impulse response of homojunction InP $p^+$-i-$n^+$ diodes. The current impulse response in multiplication regions, $w = 0.1\mu m$ and $0.2\mu m$ with and without dead-space for electron- and hole-initiated multiplication at mean multiplication gain, $< M >= 10$ are shown in Figs. 3 and 4. Our results show that the device with dead-space gives a slower current impulse response than that without the dead-space in all device lengths. Although the dead-space effect becomes dominant as the device length decreases, our results show that for both electron- and hole- initiated multiplication, our model predicts a faster current impulse response in thin device. It is mainly owing to the shorter transit time of the carrier in thinner device and hence the built-up time. Thus, thin device still gives the faster current impulse response than that in the thick device. It is also observed that the hole-initiated multiplication with the lower saturation velocity have a slower decay rate of current impulse response as compare to the electron-initiated multiplication. Obviously, dead-space causes the slower decay rate of current impulse response in APDs and hence degrades the bit-error-rate of optical communication systems due to intersymbol interference.

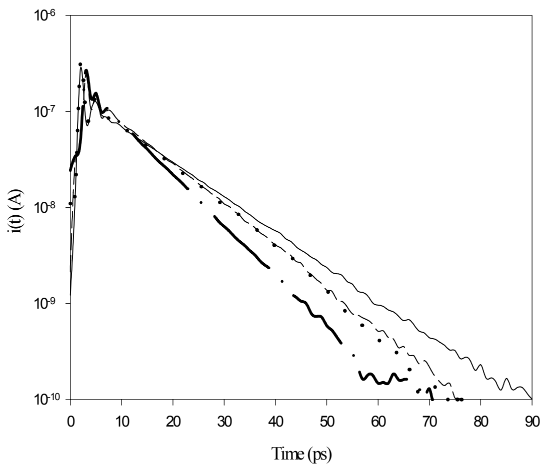


Fig. 3. Current response of $0.1\mu m$ InP $p^+$-i-$n^+$ diode calculated by a simple MC model at mean gain, $< M >= 10$ with (normal-lines) and without (heavy-lines) dead-space effect for electron- (solid- and dot-lines) and hole- (dash- and dash-dotted-lines) injection.

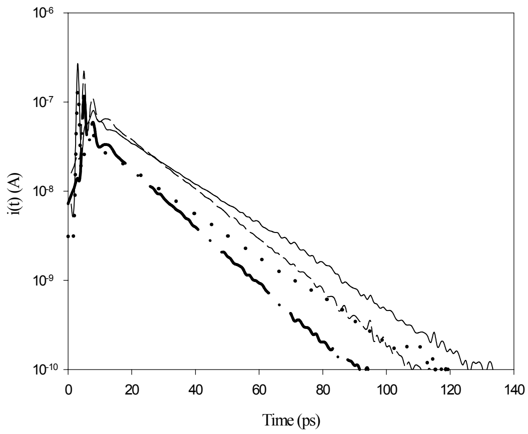


Fig. 4. Current response of $0.2\mu m$ InP $p^+$-i-$n^+$ diode calculated by a simple MC model at mean gain, $< M >= 10$ with (normal-lines) and without (heavy-lines) dead-space effect for electron- (solid- and dot-lines) and hole- (dash- and dash-dotted-lines) injection.

## IV. CONCLUSION

We developed a random response time model using ionisation path length to simulate the current impulse response of APDs. Our model is able to demonstrate the effect of dead-space on current impulse response in InP $p^+$-i-$n^+$ diode. It is shown that device with dead-space effect has a slower decay rate of current impulse response to be used as a photodetector.

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