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Avalanche Speed in Thin APDs

Duu Sheng Ong

Faculty of Engineering, Multimedia University, Jalan Multimedia,
Cyberjaya, 63100, Selangor D.E. Malaysia.
Phone: +606-03-83125377 Fax: +606-03-83183029 Email: dsong@mmu.edu.my

1. Introduction

A study by Hayat et al.[1] suggested that the large dead space in thin avalanche photodiodes will lead to a longer response time and degrades the APD performance at high bit rates. Recently, Ng et al.[2] found that the main mechanism responsible for the increase in response time with dead space is the increase in average length of the multiplication chains as impact ionization events initiated by feedback carriers become more important. Their simulations show that the dead space significantly degrades the improvement achieved by shorter carriers transit time in thin APDs. In their model, electrons and holes are assumed to travel at a constant velocity within the multiplication region and the random ionization path length (RPL) approach described by Ong et al.[3] is used to generate the gain and bandwidth of APDs. Using a multi-valleys Monte Carlo model, Plimmer et al.[4] have shown that electrons in high field region may travel several times faster than the saturation velocity and impact ionize at short distances. This implies that the simple RPL model assuming that carriers travel always at their saturation velocity will underestimate the speed in thin APDs.

2. The Models

In this work, the full band Monte Carlo (FBMC) model of ref.[5] is used to calculate the random response time in thin GaAs p^+-i-n^+ diodes. The random response time, T_R, is defined as the time measured from the instant an electron enters the multiplication region to the time when all carriers exit the multiplication region. In the calculation of avalanche multiplication and time response, the p^+-i-n^+ structures were idealized by assuming a uniform electric field confined to the i-region. A carrier is injected 'cool' into the i-region and after an ionizing collision the excess energy is distributed randomly among the two newly generated carriers and the impacting carrier. The momenta of these carriers are chosen randomly according to the density of states in the first conduction or valence band. The motions of both the primary carrier and of the carriers generated subsequently are considered simultaneously within the Monte Carlo framework and the numerical experiment proceeds until all carriers have left the multiplication region. The multiplication, *M*, for such a trial is given by the total number of carriers, of the type injected, which exit on the far side. By repeating the procedure for many trials, mean multiplication, <M> and mean response time, $<T_R>$, can be calculated. Parameters generated from the FBMC model such as the average electrons and holes ionization path length, $<\ell>$, the average electrons and holes impact ionization time, $<t>$, and mean multiplication values, <M>, in thin devices are used to build a RPL model. In the simple hard threshold dead space model [3], the carrier transport is modeled by generating trajectories ending in ionization consistent with the ionization path length probability distribution function,

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

$P(x)$ is the probability for a carrier to impact ionize for the first time after travelling a distance x in an uniform electric field, E. α^* is the ionization probability per unit distance after the dead space and the hard threshold dead space, d is given by $d = E_{th}/eE$, where e is the electronic charge, E_{th} is the ionization threshold energy, and E is the applied field. The mean ionization coefficient is $\alpha = 1/(d + 1/\alpha^*)$. This is equal to the inverse of mean ionization path length calculated from FBMC model for both electrons and holes. The electrons and holes constant velocities are estimated from their mean ionization path length and mean impact ionization time calculated from the FBMC. This means that $1/\alpha v_e$ is the mean impact ionization time for electrons in the RPL model. The RPL simulation procedure of avalanche process can be found in ref.[3].

3. Simulation Results

To examine the validity of RPL model in modeling the time response of thin APDs, the model is first used to reproduce the electron and hole mean multiplication that generated by the FBMC model. The electron initiated multiplication results ($<M_e>$) from FBMC and RPL are shown in Fig.1 as a function of electric field for multiplication widths of 0.1μm and 0.2μm. The good agreement between the two models is obtained by using the ionization threshold energy (E_{th}) for electron and holes as fitting parameters. The best fit hard ionization threshold energy for electrons is 3.5 eV and 3.7 eV for holes. These values are close to the mean impact ionization energy recorded in the FBMC model, which is ~4 eV. The FBMC and RPL simulated mean random response time, $\langle T_R \rangle$ are compared in Fig.2 for electron initiated multiplication. $\langle T_R \rangle$ generated by FBMC increases at a lower rate with $\langle M_e \rangle$ as compare to that of RPL for both 0.1μm and 0.2μm devices. The RPL results are only similar to that of FBMC at low $\langle M_e \rangle$ (< 3) but it predicts larger $\langle T_R \rangle$ as the $\langle M_e \rangle$ increases. This shows that on average the carriers in FBMC model travel at a higher speed as compare to RPL model. The PDF of random response time, $R_T(t)$, generated from RPL and FBMC are shown in Fig.3 for 0.1μm device at $\langle M_e \rangle \sim 9.5$. The hard threshold dead space and constant drift velocity assumed in RPL model produces oscillations in $R_T(t)$, which are not seen in the FBMC result. The inset of Fig.3 shows the cumulative probability density distribution function, $P_T(t)$, calculated from $R_T(t)$. For $P_T(t)$ > 0.8, we can estimate that the FBMC predicts almost twice the speed of that calculated by the simple RPL model for 0.1 μm device.

4. Conclusions

The avalanche process in thin GaAs p^+-i-n^+ diodes have been modeled using a Full band Monte Carlo model and a simple hard threshold dead space RPL model. Although the electrons and holes velocities used in the RPL model are estimated from the FBMC model, the response time calculated by this simple model is significantly larger than that from FBMC.

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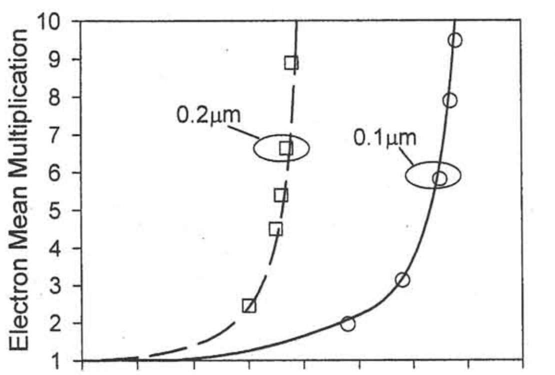

Fig. 1: Electron mean multiplication as a function of electric field. The FBMC simulated multiplication characteristics are represented by symbols. The lines are result of the RPL model.

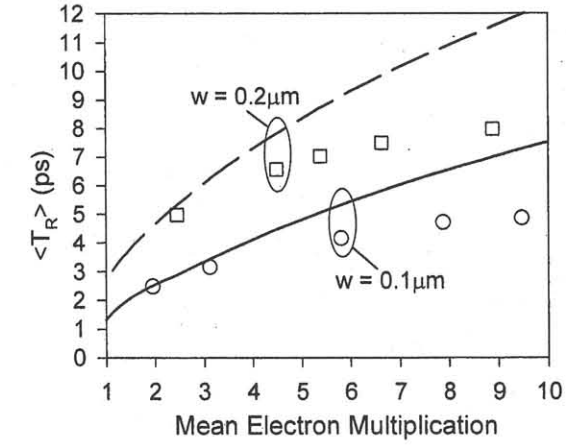

Fig. 2: Mean Random Response Time as a function of Electron Mean Multiplication. The square and circle symbols represent the FBMC results for 0.1μm and 0.2μm, respectively. The corresponding results from RPL are shown by solid and dashed lines, respectively.

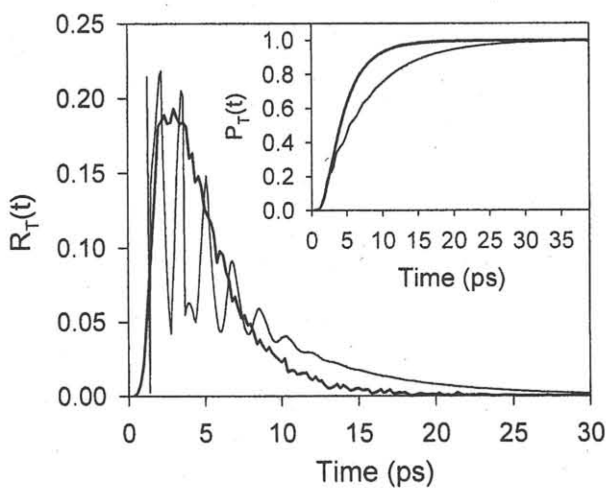

Fig. 3: The probability density function of random response time for 0.1μm device at $\langle M_e \rangle$ = 9.5. The inset is the cumulative probability density function of $R_T(t)$.

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