Statistics of Avalanche Current Buildup Time in Single-Photon Avalanche Diodes

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***Abstract*—The effects of avalanche region width, ionization coefficient ratio, and dead space on the breakdown time and timing jitter of a single-photon avalanche diode are investigated. Using a random ionization path length model, the breakdown time and the timing jitter are shown to decrease with breakdown probability, but increase with avalanche region width, decreasing ionization coefficient ratio, and ionization dead space. The model is used to compare the dependence of avalanche timing performance in Si and InP on avalanche region width.**

***Index Terms*—Avalanche breakdown, impact ionization, jitter, single-photon avalanche diodes (SPADs).**

I. Introduction

Avalanche photodiodes operated in the Geiger mode, also known as single-photon avalanche diodes (SPADs), are used in ultrasensitive optical detection and spectroscopy, with applications in optical testing of CMOS [1], time-resolved photon counting [2], quantum key distribution [3], and satellite laser ranging [4], where high detection efficiency and low dark count rate are desirable. The detection efficiency is the product of the external quantum efficiency and the breakdown probability P_b, which rises as the bias voltage is increased above breakdown, eventually approaching unity. Since the dark count rate also increases with bias voltage, a rapid rise in P_b with bias is desirable, both to improve detection efficiency and also to keep the dark count rate to a minimum. Oldham *et al.* [5] and McIntyre [6] have shown that the breakdown probability due to pure electron injection rises faster with bias when the hole to electron ionization coefficient ratio $\beta/\alpha = k$ is small. Hence, commercial Si SPADs, with small k, provide high detection efficiency when electrons are injected to initiate the avalanche process. Moreover, they exhibit low dark count rates.

For detecting photons with wavelengths longer than $1\,\mu$m, InGaAs/InP SPADs [7] are considered a better option because of the stronger absorption coefficient of InGaAs in this region. However, they suffer from higher dark count rates [8]. Moreover, in the InP avalanche region, where holes are injected as the primary carriers since $1/k = \alpha/\beta < 1$ at low fields, this ratio rises to approach unity at high fields [9]. The dark count rate can be reduced by cooling or by limiting the timing window for photon detection. However, the statistical spread in the time taken to reach breakdown, known as jitter, sets a lower limit to the width of this window. This jitter also determines the timing resolution in time-correlated photon counting applications.

Spinelli and Lacaita [10] have investigated the timing resolution of a Si SPAD and concluded that it is dominated by the statistics of the ionization events at low current values and by diffusion-assisted carrier spreading at high currents. They also concluded that the dead space, whose significance increases as the avalanche region width falls, does not affect the timing characteristics of SPADs. The latter conclusion is surprising because simulations show that dead space effects reduce the speed of avalanche photodiodes operating below breakdown [11], [12].

Si SPADs increasingly employ narrow avalanche region widths (typically $<1\,\mu$m), where dead space effects become significant, in order to improve their avalanche timing performance [10]. It is, therefore, of interest to reexamine the effects of dead space on timing characteristics and also to study the effects of ionization coefficient ratio, which are not well understood. Furthermore, the carrier transit time falls with reducing avalanche width [13], and this may reduce the time to breakdown, although the dependence of avalanche timing statistics on avalanche width has not been examined. Since timing characteristics are crucial to system performance, knowledge of the fundamental limits imposed by the ionization characteristics will improve our understanding of SPAD operation and assist device design.

In this paper, we investigate, using a random path length (RPL) model [12], [14], the effects of avalanche width, ionization coefficient ratio, and dead space on avalanche breakdown timing performance, characterized by the mean time taken to reach breakdown and the associated standard deviation.

II. Model

In this paper, we assume that carriers always travel with constant velocities, a reasonable assumption when the avalanche region is wide. In narrow avalanche regions, velocity enhancement effects are predicted [15]–[18], and may affect timing statistics. However, this enhancement effect has not been demonstrated experimentally, so we discuss it only briefly, later. We also assume that the electric field in the avalanche multiplication region is uniform. While uniform electric fields, corresponding to ideal p-i-n diodes structures, do not represent those of actual SPAD structures, this simple assumption allows straightforward comparisons to be made and the prediction of general trends.

Since RPL is a Monte Carlo technique, it is well suited to study avalanche breakdown statistics because both the spatial and temporal information associated with each trial can be recorded. The random ionization path length of an electron x_e is described by its ionization path length probability density

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function (pdf), $h_e(x_e)$, and values of x_e are obtained by selecting random numbers, evenly distributed between 0 and 1, to assign values to the ionization probability, $P_e(x_e) = \int_0^{x_e} h_e(x)\,dx$. In this paper, we assume $h_e(x_e)$ to be of the form

$$h_e(x_e) = \begin{cases} 0, & x_e < d_e. \\ \alpha^* \exp[-\alpha^*(x_e - d_e)], & x_e \geq d_e \end{cases}$$

where d_e is the electron dead space and α^* is the enabled [19] electron ionization coefficient. A similar expression for holes is obtained by replacing d_e and α^* with d_h and β^*, respectively. The variable k is hereafter taken to refer to the ratio of enabled ionization coefficients of the secondary and primary carriers, β^*/α^* for pure electron injection, and α^*/β^* for pure hole injection. For the purpose of simulation, we have assumed an avalanche region width $w = 1\ \mu$m, and a constant saturated drift velocity for both electrons and holes of $v_s = 10^5$ m·s^{-1}, so that the current carried by a carrier within the multiplication region is given by $I = qv_s/w$ [20].

At high avalanche currents, space charge will also affect the multiplication process. However, since our objective here is to understand the separate roles of avalanche width, ionization coefficient ratio, and dead space, we have ignored space charge effects in our simulations. A threshold current of 1 mA (corresponding to the simultaneous presence of $\sim 6 \times 10^4$ carriers in the multiplication region) was used as a practical criterion for avalanche breakdown in this paper. The chosen threshold current value is not dissimilar from those typically used in experiments. The breakdown probability is taken as the fraction of trials resulting in breakdown.

III. Results

In order to assess the accuracy of the RPL model in studying avalanche breakdown statistics, we first used it to simulate breakdown probability. Fig. 1 shows the breakdown probability simulated for pure electron injection with $k = 0.1$, 0.5, and 1.0 when $\alpha^* w$ is increased by up to 100% above its value at breakdown. The breakdown probability increases faster with $\alpha^* w$ for smaller k. The results are indistinguishable from those calculated using the recurrence technique described by McIntyre [6], confirming both that the threshold current of 1 mA, chosen to represent breakdown, is sufficiently large and that the RPL technique can be used to calculate avalanche breakdown statistics reliably.

In the following, we consider separately the effects of ionization coefficient ratio, dead space, and avalanche region width on most important statistics of the timing characteristics of avalanche breakdown, namely the mean time to breakdown $\langle t_b \rangle$ and its standard deviation $\sigma = \sqrt{\langle t_b^2 \rangle - \langle t_b \rangle^2}$, referred to here as breakdown time and jitter. Small breakdown time and jitter are desirable in time-correlated photon counting applications. It was shown in [21, Fig. 5] that while the breakdown time asymptotically increases logarithmically with the chosen threshold current, the jitter is asymptotically independent of the threshold current.

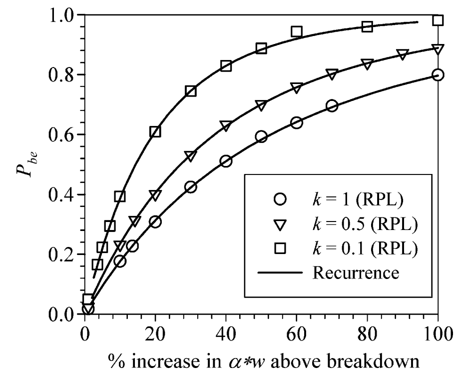

Fig. 1. Breakdown probability due to pure electron injection simulated using the RPL technique (symbols) and the recurrence technique [6] (lines) for $k = 1$, 0.5, and 0.1 with zero dead space.

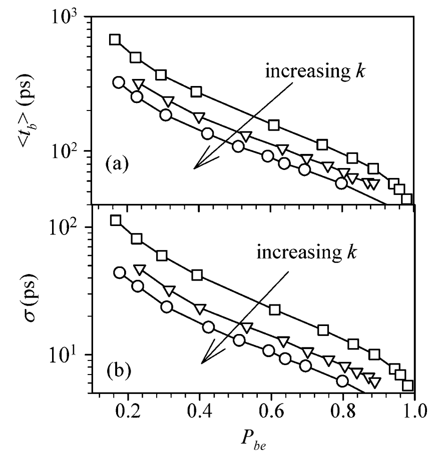

Fig. 2. (a) $\langle t_b \rangle$ and (b) σ resulting from pure electron injection versus breakdown probability for $k = 1.0$ (○), 0.5 (▽), and 0.1 (□), assuming zero dead space.

Breakdown time and jitter, calculated by RPL, are plotted in Fig. 2 against breakdown probability (varied by adjusting $\alpha^* w$) for pure electron injection and for a range of values of k. Dead space was set equal to zero in these calculations to reveal more clearly the effects due to varying k. Both breakdown time and jitter decrease with breakdown probability, and for a fixed value of breakdown probability, they also decrease with k.

The time dependence of the mean avalanche current for $k = 0.1$ and 1.0 is shown in Fig. 3, where it is apparent that current rises faster when k is large, consistent with the results in Fig. 2(a). The results of some of the individual simulation trials, one of which failed to reach the 1 mA threshold, are also plotted to illustrate the widely disparate possible evolutions of avalanche current, resulting from the random nature of the impact ionization process.

Next, the effects of dead space on breakdown time and jitter were investigated. These were calculated as functions of breakdown probability for various values of k and of dead space, and the results are presented in Fig. 4. Both breakdown time and jitter are predicted to increase with dead space, contrary to the predictions of [10]. These detrimental effects of dead space are evident at all values of k. Figs 2 and 4 also show that increasing

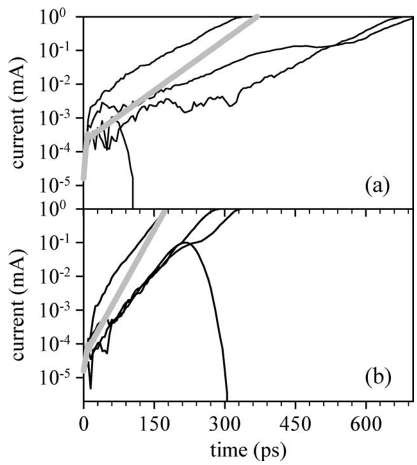

Fig. 3. Mean avalanche current versus time (thick gray lines) due to pure electron injection. (a) $k = 0.1$. (b) $k = 1$. Avalanche currents from selected simulation trials are also plotted (black lines).

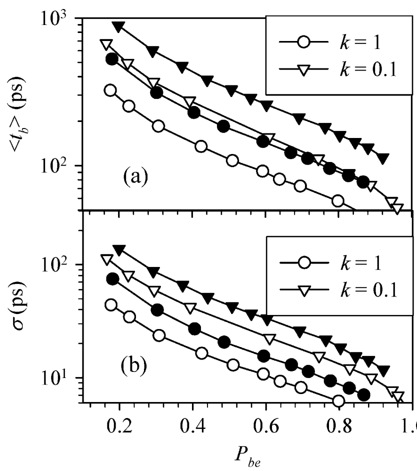

Fig. 4. (a) $\langle t_b \rangle$ and (b) σ from pure electron injection versus breakdown probability resulting for $k = 1$ (○) and 0.1 (▽), with zero dead space (open symbols) and $d_e/w = d_h/w = 0.1$ (closed symbols).

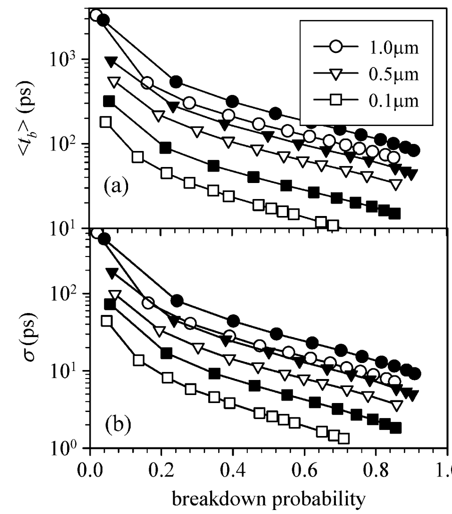

Fig. 5. (a) $\langle t_b \rangle$ and (b) σ resulting from pure electron injection versus breakdown probability for Si SPADs (closed symbols) and from pure hole injection for InP SPADs (open symbols), with $w = 1.0$, 0.5, and 0.1 μm.

k serves to reduce breakdown time and jitter, regardless of the significance of dead space.

It is also of interest to examine how breakdown time and jitter vary with avalanche width w, since SPADs with small w must operate at high electric fields. In such devices, k increases toward unity as w is reduced, which is expected to reduce breakdown time and jitter. However, the dead space also becomes more significant, which should have the opposite effect.

We, therefore, simulated breakdown time and jitter using the ionization characteristics of Si [22], [23] and InP [9], [24] in SPADs with uniform electric fields. Published values of local electron ionization coefficient α and electron ionization threshold energy E_{the} were used to calculate electron dead space $d_e = E_{\mathrm{the}}/e\,\Im$, where $\Im$ is the electric field, and enabled electron ionization coefficient $\alpha^* = [(1/\alpha) - d_e]^{-1}$ [19]. β^* and d_h were obtained in a similar manner.

Fig. 5 compares breakdown time and jitter calculated for SPADs of different avalanche region widths, composed of Si and InP, resulting, respectively, from injection of primary electrons and holes. It is clear that in both materials, both breakdown time and jitter fall with decreasing avalanche region width, as expected from the reduction in carrier transit time. Nevertheless, for a given avalanche region width, both breakdown time and jitter are smaller for InP SPADs than for Si SPADs because k is larger in InP than in Si.

We find that breakdown time in InP SPADs is proportional to w over the range of values of w studied. These observations suggest that, as w is reduced in InP SPADs, the favorable effect of increasing k just balances the increasingly detrimental effect of dead space on the timing characteristics. For Si SPADs, decreasing w to 0.1 μm does not produce the same reduction in breakdown time and jitter because, in this material, the increased effects of dead space win out over those of increasing k.

IV. Discussion

In simulations where the dead space is fixed and the breakdown probability is increased by increasing α^* and β^*, more carriers are generated during each transit. This builds up the avalanche current more rapidly so that the mean time to breakdown falls, as shown in Fig. 2(a). Moreover, this procedure also reduces the spread in the ionization path length pdfs, reducing the randomness in the avalanche process, and hence, reducing the timing jitter, as seen in Fig. 2(b).

Interestingly, increasing k is predicted to improve the timing performance of breakdown, reducing both breakdown time and jitter, as seen in Fig. 2, because this provides the increased carrier feedback needed for breakdown, which consequently increases the avalanche current. Unfortunately, the conditions that optimize the timing statistics are precisely the opposite of those required to maximize the rate of increase of the breakdown probability with overbias [25].

Reducing the avalanche region width also reduces the breakdown time and jitter. Further reductions follow as k increases toward unity in the increased field. However, these improvements

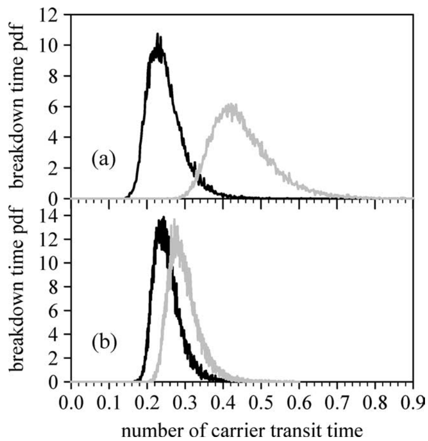

Fig. 6. pdfs of breakdown time versus time normalized to carrier transit time for InP SPADs, with (black lines) and without (gray lines) enhanced velocity for early ionizing carriers. (a) $w = 0.1\,\mu$m. (b) $w = 1.0\,\mu$m.

are tempered by the increased effects of dead space, which tend to have the opposite effects.

It would appear at first sight that our study reaches different conclusions on the effects of dead space on avalanche timing statistics from those of [10]. We, therefore, carefully examine the conditions of the two studies. Our study concludes that dead space is detrimental to timing statistics, from comparisons at a *fixed breakdown probability*, whereas Spinelli and Lacaita [10] found that, for a *fixed relative excess bias*, dead space affects jitter only by a few percent [10]. Since increasing dead space increases breakdown probability at a fixed relative excess bias [25], similar jitter values are to be expected for the cases with dead space (at larger P_b) and without dead space (at smaller P_b). We, therefore, conclude that the two studies are consistent. However, since breakdown probability is crucial in determining quantum efficiency, we argue that it is more appropriate to assess the effects of dead space by comparing timing statistics at fixed values of breakdown probability, as shown in Fig. 4, rather than of relative overbias. Our findings on the effects of ionization coefficients ratio and dead space on breakdown time and timing jitter are also consistent with those reported in [26].

Using a Monte Carlo model, Plimmer *et al.* [15] predicted that carriers ionizing shortly after their ballistic dead space arrive at this ionization event at an average velocity significantly higher than the saturated drift velocity. This enhancement is to be expected, simply because such carriers have undergone less scattering [16]. To calculate breakdown time and jitter in the presence of velocity enhancement, we modified the RPL model so that carrier velocity to ionization position is given by [27, eq.(5)].

The pdfs of breakdown time calculated for InP SPADs with $w = 0.1$ and $1.0\,\mu$m, both with and without the velocity enhancement, are compared in Fig. 6(a) and (b). Velocity enhancement is predicted to decrease both breakdown time and jitter of the $w = 0.1\,\mu$m SPAD, as shown in Fig. 6(a). However, it can be seen from Fig. 6(b) that velocity enhancement has little effect on the avalanche breakdown timing statistics for the $w = 1.0\,\mu$m SPAD. This is because dead space effects, and hence, those of velocity enhancement also, are less pronounced in wider avalanche regions.

V. Conclusion

The RPL technique has been demonstrated to be suitable for calculating breakdown probability, breakdown time, and jitter in SPADs. We find that the breakdown time and jitter fall with increasing breakdown probability, and depend strongly on the avalanche region width and ionization coefficient ratio.

For a given value of breakdown probability, the breakdown time and the jitter decrease as the values of the ionization coefficients become closer. Dead space effects increase both the breakdown time and the jitter, especially at low breakdown probabilities and when k is large.

In materials with similar ionization coefficients and insignificant dead space, breakdown is fast and jitter is small, although the breakdown probability increases more slowly with overbias. Studies of InP and Si SPADs showed that, as the avalanche region width is reduced, the overall effect is to reduce breakdown time and jitter, leading to improved timing performance. In addition, any enhancement of the velocities of carriers that ionize early in their trajectories is expected to decrease breakdown time and jitter.

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