This is a repository copy of A theoretical comparison of the breakdown behavior of In0.52Al0.48As and InP near-infrared single-photon avalanche photodiodes.

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/8731/

**Article:**
Mun, S.C.L.T., Tan, C.H., Dimler, S.J. et al. (4 more authors) (2009) A theoretical comparison of the breakdown behavior of In0.52Al0.48As and InP near-infrared single-photon avalanche photodiodes. IEEE Journal of Quantum Electronics, 45 (5-6). pp. 566-571. ISSN 0018-9197

https://doi.org/10.1109/JQE.2009.2013094

**Reuse**
Unless indicated otherwise, fulltext items are protected by copyright with all rights reserved. The copyright exception in section 29 of the Copyright, Designs and Patents Act 1988 allows the making of a single copy solely for the purpose of non-commercial research or private study within the limits of fair dealing. The publisher or other rights-holder may allow further reproduction and re-use of this version - refer to the White Rose Research Online record for this item. Where records identify the publisher as the copyright holder, users can verify any specific terms of use on the publisher's website.

**Takedown**
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.
A Theoretical Comparison of the Breakdown Behavior of In$_{0.52}$Al$_{0.48}$As and InP Near-Infrared Single-Photon Avalanche Photodiodes

Souye Cheong Liew Tat Mun, Chee Hing Tan, Member, IEEE, Simon J. Dimlter, Lionel J. J. Tan, Jo Shien Ng, Member, IEEE, Yu Ling Goh, Student Member, IEEE, and John P. R. David, Senior Member, IEEE

Abstract—We study the breakdown characteristics and timing statistics of InP and In$_{0.52}$Al$_{0.48}$As single-photon avalanche photodiodes (SPADs) with avalanche widths ranging from 0.2 to 1.0 $\mu$m at room temperature using a random ionization path-length model. Our results show that, for a given avalanche width, the breakdown probability of In$_{0.52}$Al$_{0.48}$As SPADs increases faster with overbias than InP SPADs. When we compared their timing statistics, we observed that, for a given breakdown probability, InP requires a shorter time to reach breakdown and exhibits a smaller timing jitter than In$_{0.52}$Al$_{0.48}$As. However, due to the lower dark count probability and faster rise in breakdown probability with overbias, In$_{0.52}$Al$_{0.48}$As SPADs with avalanche widths $\lesssim 0.5$ $\mu$m are more suitable for single-photon detection at telecommunication wavelengths than InP SPADs. Moreover, we predict that, in InP SPADs with avalanche widths $\lesssim 0.3$ $\mu$m and In$_{0.52}$Al$_{0.48}$As SPADs with avalanche widths $\lesssim 0.2$ $\mu$m, the dark count probability is higher than the photon count probability for all applied biases.

Index Terms—Avalanche breakdown, InP, In$_{0.52}$Al$_{0.48}$As, single-photon avalanche photodiodes (SPADs), timing statistics.

I. INTRODUCTION

EIGER-MODE avalanche photodiodes (APDs), commonly known as single-photon avalanche diodes (SPADs), have recently emerged as a key technology for applications requiring single-photon detection such as in quantum key distribution systems [1], in time-of-flight laser ranging applications [2], and in time-resolved photon counting [3]. While linear-mode InP and In$_{0.52}$Al$_{0.48}$As-based APDs have been characterized extensively [4]–[9] for applications at the telecommunication wavelength of 1.55 $\mu$m, their performance in geiger-mode has not yet been fully optimized. Since the early studies by Oldham et al. [10] and by McIntyre [11] on the breakdown characteristics of SPADs, several works have significantly contributed to the understanding of the dynamics in SPADs.

Using a history-dependent analytical model, Wang et al. [12] suggested that a faster increase in breakdown probability with overbias, $P_b(V_{over})$, can be achieved in In$_{0.52}$Al$_{0.48}$As diodes than in InP diodes while Ng et al. studied the effects of deadspace [13] and field dependences of ionization coefficient ratio [14] on the rate at which $P_b(V_{over})$ increases using a hard deadspace model. In [13] and [14], these authors found that a large dead-space-to-avalanche-width ratio and a large ionization coefficient ratio leads to faster increase in $P_b(V_{over})$. Ramirez et al. [15] investigated a set of design parameters using the recursive deadspace multiplication model [16] and showed that a larger increase in $P_b(V_{over})$ is achieved using InP and In$_{0.52}$Al$_{0.48}$As SPADs with thicker avalanche width. Interestingly, they also found the single-photon quantum efficiency (SPQE), a figure of merit incorporating the dark count probability, the photon count probability, and the probability that there is at least one photon during the gated time, to be higher in InP SPADs than in In$_{0.52}$Al$_{0.48}$As SPADs for a given avalanche width. However, these works [12]–[15] relied on ionization coefficients derived using limited experimental data. Moreover, their analysis omitted timing statistics which are critical in applications where the timing resolution can be the limiting factor to the photon detector’s performance.

When APDs are biased to a metastable condition, a single absorbed photon can initiate breakdown, and the time taken for the avalanche current to build up to the circuit threshold current depends on the ionization process. This process is stochastic in nature, hence, creating a spread in the time taken to breakdown, commonly termed as the timing jitter. Spinelli et al. [17] investigated the timing statistics of Si SPADs and they concluded that diffusion-assisted process dominates the timing statistics. Using a random path length (RPL) model, Tan et al. [18] later demonstrated that these timing statistics are also affected by deadspace and ionization coefficient ratios. They showed that, in materials with similar ionization coefficients and having low deadspace contribution, the time taken to reach breakdown is low and the timing jitter is small.

In this study, we compare the timing statistics of InP and In$_{0.52}$Al$_{0.48}$As SPADs at room temperature using a RPL model that employs ionization coefficients derived from a wide range of devices for these two materials and that is similar to the model used in [18]. We also study the competing effects of the increase in dark count due to tunneling current and photon count whilst the timing jitter decreases as the avalanche width is reduced. This model has been shown to be accurate in modeling the avalanche breakdown voltage of APDs [19] and is equivalent.
to models based on solving the recurrence equations as demonstrated in [18]. Moreover, the model has been demonstrated to give comparable avalanche breakdown current features to those calculated in full band Monte Carlo model [20].

II. MODEL

The RPL model uses the ionization path-length probability density functions (PDFs) as input parameters to calculate the ionization probability. Under constant electric fields, these electron PDFs can be described analytically as

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

where $d_e$ represents the electron deadspace, $\alpha^e$ is the enabled electron ionization coefficient, and $x_e$ represents the electron ionization path length. A similar expression for the hole PDFs is obtained by replacing $d_e$, $\alpha^e$, and $x_e$ with $d_h$, $\beta^e$, and $x_h$, respectively. Further details on the RPL model can be found in [18]–[20]. In our calculations, we used In$_{0.52}$Al$_{0.48}$As and InP ionization coefficients and threshold energies published in [7] and [9], respectively, as these parameters were derived using multiplication and excess noise factors measured on a series of devices covering a wide range of electric fields using pure electron and pure hole injection. Hence, we believe that [7] and [9] provide the most reliable ionization coefficients and parameters to date.

To calculate the avalanche current $I$, we used Ramo’s theorem [21], which is given by $I = q_n w$, where $q$ is the electronic charge, $w$ is the avalanche width, and $v_n$ is the saturated velocity. We assumed $v_n$ values of $1.0 \times 10^7$ ms$^{-1}$ for electrons and $6.0 \times 10^4$ ms$^{-1}$ for holes for both InP and In$_{0.52}$Al$_{0.48}$As. As a result, the timing statistics obtained was solely functions of $w$, ionization coefficient ratio, and deadspace. In our simulation, the circuit threshold current was set to 50 $\mu$A, the breakdown probability $P_b$ was calculated as the ratio of the number of carriers triggering breakdown to the number of injected carriers, the mean time to breakdown $t_b$ was taken as the mean time required for the avalanche current to reach the circuit threshold current, and the timing jitter $\sigma$ was taken as the standard deviation of the mean time to breakdown. Interestingly, we found that using higher threshold current does not affect $\sigma$ obtained for a given $w$ but merely increases $t_b$ as previously observed by Groves et al. [22]. To achieve convergence of our results, $6 \times 10^4$ particles were simulated. In this study, the electric field was assumed to remain constant as the avalanche current builds up.

In real SPADs, the timing jitter can arise as a result of the random position of the absorbed photon in the absorption layer and from the random impact ionization events occurring during avalanche breakdown. As both InP and In$_{0.52}$Al$_{0.48}$As SPADs have InGaAs as their absorption layer, the timing jitter resulting from the former process is expected to be similar in both SPADs for a given InGaAs absorption layer. Thus, to compare the timing statistics occurring due to the ionization events in InP and In$_{0.52}$Al$_{0.48}$As multiplication layers, we simulated breakdown events in ideal $p^- - i - n^+$ and $n^- - i - p^+$ structures with $w = 0.20$, 0.30, 0.40, 0.50 and 1.0 $\mu$m. Due to the different majority ionizing carriers in these materials, pure electrons were injected into the $p^+$ side of the multiplication layer for In$_{0.52}$Al$_{0.48}$As while pure holes were injected into the $n^+$ side of the multiplication layer for InP. As for the dark carriers, we assumed that they are generated uniformly and randomly in the avalanche region during the gated time.

III. RESULTS AND DISCUSSION

Fig. 1 shows the calculated breakdown probability as a function of overbias ratio, defined as $V_{\text{over}} = (V - V_{\text{BR}})/V_{\text{BR}}$, where $V$ is the applied bias and $V_{\text{BR}}$ is the breakdown voltage, assumed to be the voltage that yields a breakdown probability of 0.001. At a given overbias ratio, the thickest diode produces the largest breakdown probability. Our results also show that In$_{0.52}$Al$_{0.48}$As diodes exhibit a larger increase in $P_b(V_{\text{over}})$ than InP diodes for a given $w$, confirming the trend obtained by Wang et al. [12] and Ramirez et al. [15] despite the different ionization coefficients and threshold energies used.

McIntyre [11] showed that $P_b(V_{\text{over}})$ rises more rapidly in diodes with large ionization coefficient ratio while Ng et al. [13] demonstrated, and later confirmed by Tan et al. [20], that larger deadspace also leads to a more rapid rise in $P_b(V_{\text{over}})$. Thus, to assess the dominant effect that is causing the more rapid rise in $P_b(V_{\text{over}})$ in In$_{0.52}$Al$_{0.48}$As diodes, we compared the ionization coefficient ratio of InP and In$_{0.52}$Al$_{0.48}$As as a function of breakdown probability in Fig. 2. For a given $w$, it is evident that the electron-to-hole ionization coefficient ratio in In$_{0.52}$Al$_{0.48}$As is larger than the hole-to-electron ionization coefficient ratio in InP. As expected, in the thinnest diode and at high breakdown probabilities, the difference between the two ratios reduces as a result of the convergence of ionization coefficients at high electric fields. We then assessed the ratio of deadspace $d$ calculated as $d = E_{\text{th}}/\varepsilon$ where $E_{\text{th}}$ is the threshold energy and $\varepsilon$ the electric field, to $w$ for each diode. As pure electrons were injected for In$_{0.52}$Al$_{0.48}$As SPADs and pure holes for InP SPADs, Fig. 3 compares the calculated
of the ionization coefficient ratio and deadspace, as previously discussed by Tan et al. [18]. These authors showed analytically that the lowest $t_h$ is obtained in thin diodes having similar electron and hole ionization coefficients and small deadspace effect. As shown earlier, for a given breakdown probability, InP has a smaller ionization coefficient ratio and similar $d/w$ when compared with In$_{0.52}$Al$_{0.48}$As, resulting in the smaller $t_h$ for InP SPADs. Moreover, the values of $t_h$ recorded for In$_{0.52}$Al$_{0.48}$As SPADs is found to be approximately 12% longer than those recorded for InP SPADs for a given $w$. However, the exact difference between the values of $t_h$ for real diodes will not only be dependent on the saturation velocities, ionization coefficients ratio, and deadspace contribution but also on the effect of the enhanced velocity occurring in early ionizing carriers [18] and on the space charge effect [17].

The values of $\sigma$ calculated for InP and In$_{0.52}$Al$_{0.48}$As SPADs are shown in Fig. 5. As expected, we observed that diodes having the smallest $w$ produce the lowest $\sigma$ for a given avalanche material, which is consistent with the findings of [18]. When the two materials were compared, InP shows a smaller $\sigma$ than In$_{0.52}$Al$_{0.48}$As for a given $w$ due to the smaller ionization coefficients ratio in InP. Moreover, we obtained the difference in $\sigma$ values between InP and In$_{0.52}$Al$_{0.48}$As SPADs to be approximately equal to 18% for all $w$. However, as commercially available time-to-amplitude converter (TAC) equipment [23] has at best, a timing resolution of 7 ps, the smaller $\sigma$ in InP SPADs does not always provide significant timing advantages. As the timing jitter of the SPAD and the timing resolution of the TAC $\sigma_{TAC}$ are independent of each other, the combined timing jitter $\sigma_t$ would be measured as $\sigma_t^2 = \sigma_e^2 + \sigma_{TAC}^2$. For instance, in SPADs with $w = 0.2 \, \mu m$ and operating at a breakdown probability of 0.5, InP and In$_{0.52}$Al$_{0.48}$As SPADs exhibit $\sigma$ values of 9.8 and 11.5 ps, which would yield $\sigma_t$ values of 12.0 and 13.5 ps, respectively. Therefore, the difference in $\sigma$ between the two materials decreases from 18.0% to 12.5% for these SPADs, suggesting that the difference could become

$d_e/w$ for In$_{0.52}$Al$_{0.48}$As and $d_h/w$ for InP as a function of the breakdown probability. Interestingly, we can observe that, in SPADs with $w \leq 0.3 \, \mu m$, the contribution of deadspace is more significant in In$_{0.52}$Al$_{0.48}$As than in InP but, as $w$ increases, an opposite behavior is observed; the deadspace becomes more significant in InP than in In$_{0.52}$Al$_{0.48}$As. However, as the difference in $d/w$ values between InP and In$_{0.52}$Al$_{0.48}$As is not significant for a given breakdown probability, our results therefore suggest that the steeper rise in $F(V_{CM})$ observed for In$_{0.52}$Al$_{0.48}$As is caused by the more pronounced effect of the larger ionization coefficient ratio than that of the deadspace effect.

When the values of $t_h$ calculated for InP and In$_{0.52}$Al$_{0.48}$As SPADs were compared in Fig. 4, we observed smaller values in InP than in In$_{0.52}$Al$_{0.48}$As for a given $w$. Moreover, the lowest $t_h$ was obtained in the thinnest diodes. These timing results can be explained by the shorter transit time combined with the effects
As (closed symbols) as a function of \( w \) of 0.20, 0.50, and 1.00 \( \mu m \). The results for SPADs with \( w \) of 0.30 and 0.40 \( \mu m \) are not shown for clarity.

Fig. 6. Tunneling current calculated for circular SPADs with radius of 10 \( \mu m \) for InP (open symbols) and In\(_{0.52}\)Al\(_{0.48}\)As (closed symbols) as a function of breakdown probability for SPADs with \( w \) of 0.20 (\( \square \)), 0.30 (\( \diamond \)), and 0.50 \( \mu m \) (\( \triangle \)). The results for SPADs with \( w \) of 0.40 \( \mu m \) are not shown for clarity.

Fig. 7. Dark count probability calculated as a function of photon count probability for InP (open symbols) and In\(_{0.52}\)Al\(_{0.48}\)As (closed symbols) SPADs with \( w \) of 0.20 (\( \square \)), 0.30 (\( \diamond \)), 0.40 (\( \nabla \)), and 0.50 \( \mu m \) (\( \triangle \)). Lines associated with the symbols are plotted to assist visualization. The line (\( \bullet \bullet \bullet \)) shows the condition where the dark count probability is equal to the photon count probability.

less significant depending on the applications and limitations of existing measuring apparatus.

In SPADs, besides \( P_d \), \( \eta \), and \( \sigma \), it is also crucial to analyze the dark counts. As Karve et al. [24] suggested, band-to-band tunneling in the multiplication layer of thin SPADs can contribute to the majority of dark counts. Thus, in order to assess the dark count rates of InP and In\(_{0.52}\)Al\(_{0.48}\)As, we analyzed the tunneling currents of SPADs having \( w \leq 0.5 \mu m \). In our calculation, the band-to-band tunneling current \( I_{\text{tun}} \) was calculated using experimentally derived tunneling parameters for In\(_{0.52}\)Al\(_{0.48}\)As [6] and InP [9] for diodes having circular mesas and radius of 10 \( \mu m \). As shown in Fig. 6, InP exhibits higher tunneling current than In\(_{0.52}\)Al\(_{0.48}\)As for a given breakdown probability, suggesting a higher number of dark carriers in InP. Interestingly, this observation is in contradiction to that predicted by Ramirez et al. [15] who approximated the tunneling current of InP using parameters derived for In\(_{0.52}\)Al\(_{0.48}\)As. As a result, these authors underestimated the tunneling current in InP SPADs.

For most single-photon detection applications, low dark count and high photon count are desirable. Thus, we calculated the photon count probability and the dark count probability in InP and In\(_{0.52}\)Al\(_{0.48}\)As SPADs with \( w \leq 0.5 \mu m \) using Poissonian statistics for a given set of conditions. The dark count probability was calculated as \( 1 - \exp(-N_d P_d) \) [25], where \( P_d \) is the breakdown probability of dark carriers generated randomly in the avalanche region and \( N_d \) is the number of dark carriers within the gated time given as \( N_d = I_{\text{tun}} t_{\text{gated}} / \eta \) where \( t_{\text{gated}} \) is the gated time and taken as 2 ns in this study. As for the photon count probability, we assumed that all carriers generated by photons absorbed in the absorption layer reach the multiplication layer. Therefore, the photon count probability was calculated as \( 1 - \exp(-\eta N_C P_E) \), where \( \eta \) is the quantum efficiency taken as 0.5 and \( N_C \) is the number of photon per pulse taken as 1. As shown in Fig. 7, In\(_{0.52}\)Al\(_{0.48}\)As has a lower dark count probability than InP for a given photon count probability. Interestingly, we also observed that, in InP SPADs with \( w \leq 0.3 \mu m \) and In\(_{0.52}\)Al\(_{0.48}\)As SPADs \( w \leq 0.2 \mu m \), the dark count probability is always larger than the photon count probability, suggesting that these diodes would be impractical for most single-photon applications. These observations are consistent with those reported by Ramirez et al. [15]. Moreover, as \( w \) increases, the range over which the probability of achieving higher photon count than dark count also increases. For instance, in InP SPADs with \( w = 0.4 \) and 0.5 \( \mu m \), we obtained equal dark and photon count probabilities at photon count probabilities of 0.25 and 0.34, which correspond to overbias ratios of around 0.06 and 0.12, respectively. As for In\(_{0.52}\)Al\(_{0.48}\)As SPADs with \( w = 0.4 \) and 0.5 \( \mu m \), equal dark count and photon count probabilities were obtained for photon count probabilities of 0.32 and 0.37, which correspond to overbias ratios of around 0.07 and 0.13, respectively. These results
therefore suggest that, due to the lower dark count probability for a given photon count probability and the larger increase in $P_d(V_{th})$ in In$_{0.52}$Al$_{0.48}$As SPADs, these diodes would outperform InP SPADs for applications at the telecommunication wavelength despite their poorer timing statistics.

To study the performance of SPADs with $w$, Fig. 8 shows the dark count probability and $\sigma$ calculated at a breakdown probability of 0.5 for different $w$. It can be seen that, as $w$ increases, the dark count probability decreases. As tunneling current decreases exponentially with electric field, the lower electric field required to achieve a given breakdown probability in thicker SPADs yields smaller tunneling current, resulting in fewer dark carriers and hence smaller dark count probability. However, the same increase in $w$ will cause $t_b$ and $\sigma$ to increase. Thus, as $w$ increases, there exists a trade-off between $\sigma$ and dark count probability for SPADs. A similar trade-off between tunneling current and breakdown probability was also observed by Ramirez et al. [15].

IV. CONCLUSION

We have shown that InP SPADs has better timing characteristics than In$_{0.52}$Al$_{0.48}$As SPADs assuming that these materials have similar saturated velocities. The lower values of $t_b$ and $\sigma$ observed in InP can be explained by the more pronounced effect of the ionization coefficient ratio than the dark count effect. Moreover, we found that In$_{0.52}$Al$_{0.48}$As SPADs with $w \leq 0.2$ $\mu$m and InP SPADs with $w \leq 0.3$ $\mu$m would be unsuitable for applications requiring larger photon count probability than dark count probability. As In$_{0.52}$Al$_{0.48}$As SPADs exhibit a larger increase in $P_d(V_{th})$, lower dark count probability and provide a larger range over which the ratio of photon to dark count probability exceeding 1, they will be more suited than InP SPADs for applications at telecommunication wavelengths despite their poorer timing statistics.

REFERENCES


Souye Cheong Liew Tat Mun received the M.Eng. degree in electronic engineering (computing) from the University of Sheffield, Sheffield, U.K., in 2004, where he is currently working toward the Ph.D. degree in electronic and electrical engineering.

His current research focused on the characterization and optimization of various infrared photodetectors.

Chee Hing Tan (M’05) received the B.Eng. and Ph.D. degrees in electronic engineering from the University of Sheffield, Sheffield, U.K., in 1998 and 2002, respectively. Currently, he is a Senior Lecturer with the Department of Electronic and Electrical Engineering. His research activities include experimental and theoretical investigation of excess noise, breakdown and jitter in APDs and SPADs, design of high-speed APDs and HPTs, and infrared photodetectors.

Simon J. Dimler received the M.Eng. degree in electronic and electrical engineering from the University of Sheffield, Sheffield, U.K., in 2004, where he is currently working toward the Ph.D. degree in electronic and electrical engineering.

His current research focused on developing circuits and measurement setups for the characterization of photodetectors.

Lionel J. J. Tan received the B.Eng. degree in electronic and electrical engineering from the University of Sheffield, Sheffield, U.K., in 2003, where he is currently working toward the Ph.D. degree in electronic and electrical engineering.

His doctoral research focuses on InP-based avalanche photodiodes and Geiger-mode avalanche photodiodes.

Jo Shien Ng (M’99) received the B.Eng. and Ph.D. degrees from University of Sheffield, Sheffield, U.K., in 1999 and 2003, respectively, in electrical and electronic engineering.

From 2003 to 2006, she was with the University of Sheffield and was responsible for characterization within the National Centre for III-V Technologies. She became a Royal Society University Research Fellow in October 2006, and her research interests include avalanche photodiodes, Geiger-mode avalanche photodiodes, and material characterization.

Yu Ling Goh (S’02) received the B.Eng. degree in electronic and electrical engineering from Imperial College, London, U.K., and the M.Eng. Sc. degree from Multimedia University, Malaysia. She is currently working toward the Ph.D. degree in electronic and electrical engineering at the University of Sheffield, Sheffield, U.K.

Her research interests include avalanche photodiodes, infrared detectors, and material characterization.

John P. R. David (SM’96) received the B.Eng. and Ph.D. degrees in electronic engineering from the University of Sheffield, Sheffield, U.K., in 1976 and 1983, respectively.

He joined the Central Facility for III-V Semiconductors, University of Sheffield, in 1985, where he was responsible for the characterization activity. In 2001, he joined Marconi Optical Components (now Bookham Technologies), Devon, U.K., before returning to a Faculty position with the University of Sheffield in September 2002. He has authored or coauthored more than 250 papers published in various journals and conference proceedings, largely in the areas of III-V characterization, impact ionization, and avalanche photodiodes.