Breakdown Characteristics of $In_{0.52}Al_{0.48}As$–InP Heterojunction APDs

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The breakdown characteristics of an avalanche photodiode (APD) are generally assessed by examining the steepness of the breakdown-probability curve as a function of the normalized excess breakdown voltage, $\Delta V/V_{BR}$, which is the voltage beyond the breakdown voltage, V_{BR}, normalized by the breakdown voltage. This metric indicates how quickly the transition from stable operation (finite gain) to breakdown (infinite gain) occurs. For photon counting, it is most desirable to have the transition take place with as little excess voltage as possible. It is also desirable to have a low operational breakdown voltage. Unfortunately, homojunction APDs that have good breakdown characteristics are those that are thick ($>$ 400nm) requiring high breakdown voltages [1,2].

Recently, we have demonstrated by means of analytical modeling that the breakdown-probability characteristics of $Al_{0.6}Ga_{0.4}As$–GaAs electron-injection heterojunction APDs can be optimized when the APD is operated in Geiger mode [3]. The optimization strategy is based on maximizing the benefits of the dead-space effect through the initial-energy and heterojunction-boundary effects [4,5]. In this paper we extend our results to hole-injection $In_{0.52}Al_{0.48}As$–InP heterojunction APDs. $In_{0.52}Al_{0.48}As$ and InP are lattice-matched with $In_{0.48}Ga_{0.52}As$, which is suitable for the wavelengths used in telecommunications (i.e., $\lambda = 1.3$ μm and 1.55 μm). In our structure, $In_{0.52}Al_{0.48}As$ is used as a buildup layer for injected and offspring holes, allowing them to heat up prior to entering the InP layer while denying them ionization. This is due to the wide bandgap of $In_{0.52}Al_{0.48}As$, its high ionization threshold energy, and its relatively low ionization coefficients. On the other hand, the energized holes that enter the InP layer require a significantly reduced dead space before impact ionizing, thereby enhancing the breakdown probability [3].

We consider a separate-absorption-multiplication (SAM) APD structure in our calculations, as shown schematically as the inset in Fig. 1. We also consider the fact that the $In_{0.52}Al_{0.48}As$-buildup layer is a part of the multiplication layer, implying that carriers in this layer are in principle capable of impact ionization as long as they acquire sufficient energy. We intentionally make the electric field in the $In_{0.52}Al_{0.48}As$-buildup-layer smaller (about a half) than in that in the InP-multiplication-layer in order to suppress undesired ionization taking place therein.

To characterize the breakdown probability, we use the recurrence technique developed by Hayat *et al.* [6], which generalized McIntyre's history-dependent theory for the breakdown probability [7] to heterostructure multiplication regions. First, we compute the breakdown probability of a 100-nm InP homojunction APD. Since the ionization rate for holes is higher than that for electrons in InP, we consider hole injection. Then, we incrementally add the $In_{0.52}Al_{0.48}As$-buildup layer to the 100-nm InP layer and compute the corresponding breakdown probabilities for the resulting heterojunction APD. Finally, we plot the normalized excess voltage at the probability P of 0.9 (viz., the steepness) as a function of $In_{0.52}Al_{0.48}As$ layer width, as shown in Fig. 2. As shown in the figure, the excess breakdown voltage decreases as the width of $In_{0.52}Al_{0.48}As$ layer increases until it reaches 50 nm, and it increases afterwards. This clearly shows the existence of an optimal width for the $In_{0.52}Al_{0.48}As$ buildup layer. The breakdown probability of a 100-nm InP homojunction APD (thick solid) and the optimized heterojunction (50-nm $In_{0.52}Al_{0.48}As$–100-nm-InP, thick dashed) APD are presented in Fig. 1. Indeed, the calculated curve for the heterojunction APD is steeper than that for the homojunction APD by approximately 25% at $P = 0.9$. It also shows that the characteristics of the optimized heterojunction APD matches those for a 500-nm homojunction $In_{0.52}Al_{0.48}As$ (shown as "$\circ$"). Thus, the optimization of heterostructure multiplication regions benefits achieving the steep breakdown characteristics that a thick multiplication region exhibits while restraining the breakdown voltage (and possibly the dark current). The breakdown probability of a 100-nm $In_{0.52}Al_{0.48}As$ homojunction APD (thick dashed-dotted) are also calculated as a reference. The $In_{0.52}Al_{0.48}As$ homojunction APD exhibits steeper breakdown probability curve than InP homojunction APD, which is consistent with Wang *et al.* [1]. On the other hand, the optimized heterojunction APD exhibits improved breakdown characteristic. It should be mentioned that carrier trapping at the heterojunction interface, which we have not taken into account in our calculations, may add to dark counts.

We also calculated the breakdown characteristics triggered by dark counts resulting from thermal generation or trapped carriers (possibly due to after-pulsing) in the multiplication region. This is the breakdown probability averaged over all possible locations of the random birthplaces of the dark carriers [3]. In Fig. 1, curves in the lower part are these average breakdown probabilities. The average breakdown probability also increases in the optimized heterojunction APD compared to the same multiplication-width of the homojunction APD. However, the rate of increase is smaller than the breakdown probability due to injected carriers. This is deduced from the observation that the steepness of the average breakdown probability for the optimized heterojunction APD is smaller than the that for the 500-nm homojunction APD.

Finally, we attempted to further improve the breakdown probabilities by considering multi-stage heterojunction APDs (e.g., InAlAs–InP–InAlAs–InP). Unfortunately, we discovered very little improvement in the steepness (approximately 3% at $P = 0.9$). Thus, there is no evidence of significant improvement rendered by a multi-stage heterojunction APD, which is also very sensitive to the accuracy of the widths. This work was supported by the National Science Foundation (awards ECS-0334813 and ECS-0196569).

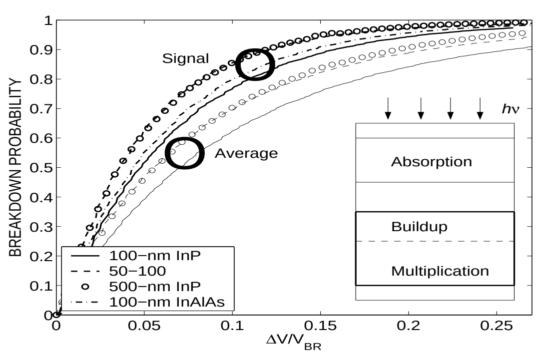

Figure 1. Breakdown probability as a function of normalized excess voltage ($\Delta V/V_{BR}$). The inset depicts the schematic of the proposed structure.

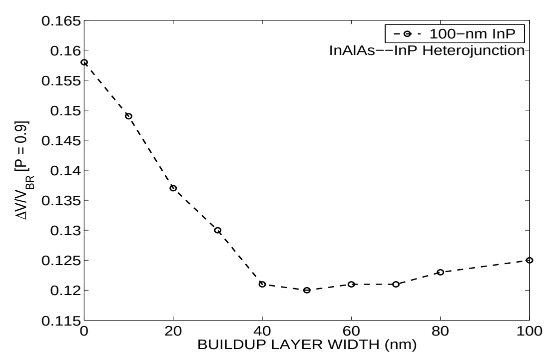

Figure 2. Normalized excess voltage when the breakdown probability is 0.9 as a function of $In_{0.52}Al_{0.48}As$-buildup-layer width.

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