Optimization of InP APDs for High-Speed Lightwave Systems

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***Abstract*—Calculations are carried out to optimize the width of the InP avalanche region in high speed APD-based optical receivers. The model includes the effects of intersymbol interference, tunneling current, avalanche noise and its correlation with the stochastic avalanche duration. A minimum sensitivity of ~-28.8 dBm is predicted at an optimal width of ~180 nm and an optimal gain of 10, assuming a Johnson-noise level of 500 noise electrons per bit.**

Keywords- avalanche photodiodes; receiver sensitivity; noise; impact ionization; intersymbol interference; avalanche duration

I. Introduction

InP avalanche photodiodes (APDs) have become the photodetectors of choice in present-day high-speed lightwave communication systems. Compared to PIN photodetectors, telecom APDs offer bias-controllable optoelectronic gain, generated by carrier impact ionizations in the InP avalanche region, which amplifies the photocurrent. This amplification suppresses Johnson noise and ultimately improves the receiver sensitivity. However, the problem of selecting the best avalanche region width and the associated bias is quite complex. There are three main competing factors that govern the sensitivity of APD-based optical receivers at high speeds: (i) the avalanche noise of the APD, represented by the excess noise factor, F, which governs the penalty brought about by the stochastic nature of the impact-ionization process; (ii) the stochastic avalanche duration (or buildup time), which is strongly correlated with gain and governs the APD's speed and ultimately the level of intersymbol interference (ISI); and (iii) APD's dark current, which is typically dominated by tunneling in the avalanche region.

Generally, as the gain increases, so do the excess noise factor and the avalanche buildup time. Thus, there is an optimal sensitivity-minimizing gain that offers a balance between suppressing Johnson noise while keeping the excess noise factor and ISI under acceptable levels. More importantly, changing the width of the avalanche region strongly affects the receiver sensitivity as all of the aforementioned three factors change. On the one hand, reducing the thickness of the avalanche region serves to reduce the excess noise factor (due to the so-called dead space effect) and minimize ISI via reducing carrier transit times across the avalanche region. On the other hand, the increase in the field in narrow regions accentuates tunneling current at exponential rates. To the best of our knowledge, no rigorous model has been available heretofore for optimizing the sensitivity of APD-based receivers over the width of the avalanche region while taking into consideration all of the performance-determining factors. This work reports such optimization for the first time, thereby enabling device engineers to identify the optimal InP-based APD and the associated operation bias for use at a prescribed digital transmission speed.

II. Model

Recently, a rigorous model was developed in [1] for the performance of high-speed APD-based integrate-and-dump receivers. The model includes the effects of ISI, nonlocalized ionization, also known as the dead-space effect, as well as the stochastic correlation between the gain and the avalanche duration. This model allows us to determine the receiver sensitivity (for a bit error rate of $< 10^{-9}$), for a fixed APD, as a function of the transmission speed. In addition, an accurate un-multiplied tunneling-current model in thin InP avalanche regions was recently reported in [2] based upon a systematic experimental study. In this paper we extend the work in [1] to include tunneling current based on [2] and solve the optimization problem associated with the selection of the width of the InP avalanche region. Here, the probability distribution function of the gain and avalanche duration that the model in [1] requires is obtained from the Random Path Length model [3], which offers a simpler alternative to the recursive analytical method reported in [1]. The field-dependent nonlocalized ionization coefficients and the ionization threshold energies for InP, are obtained from [2]. A Johnson-noise level of 500 noise electrons per bit was assumed.

III. Results

The receiver sensitivity was calculated for a series of avalanche-region widths, w (0.08μm to 0.5μm), as function of gain for an NRZ transmission speed of 10Gb/s. Note that for avalanche regions narrower than 0.2μm, the operating electric field exceeds the field range covered by [2], requiring extrapolations of the expressions given in [2]. The results are compared in Fig. 1. As expected, for a given avalanche region width, there exists an optimum gain to achieve best sensitivity.

The optimum sensitivity, S_{opt}, and its corresponding gain of Fig. 1 are plotted against avalanche region width in Fig. 2. We observe an optimum avalanche width of ~ 0.18μm for a 10Gb/s system, yielding S_{opt} of ~ -28.8 dBm. Results obtained without tunneling current are also shown in Fig. 2.

The optimum avalanche width observed in Fig. 2 is caused by competing tunneling current and excess noise characteristics as the avalanche width varies. As the avalanche region width decreases, the operating electric field increases, resulting in increasing tunneling current density, as shown in Fig. 3. On the other hand, as dead-space effects becomes more significant in narrower avalanche regions, the excess noise factor for a given gain decreases, resulting in decreasing k_{eff} (a parameter commonly used to describe excess noise characteristics) [2], [4]. The k_{eff} dependence on avalanche width is also plotted in Fig. 3.

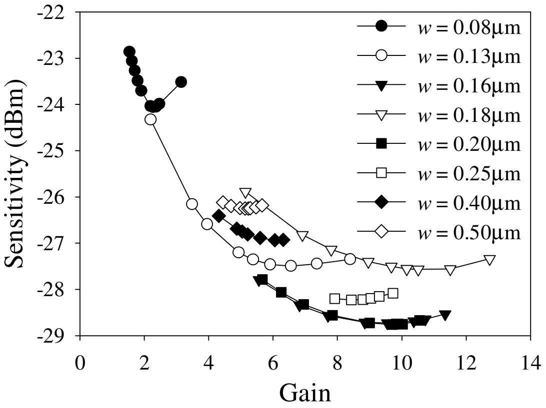

Figure 1. Sensitivity versus gain for InP APDs with different avalanche widths at a transmission speed of 10Gb/s.

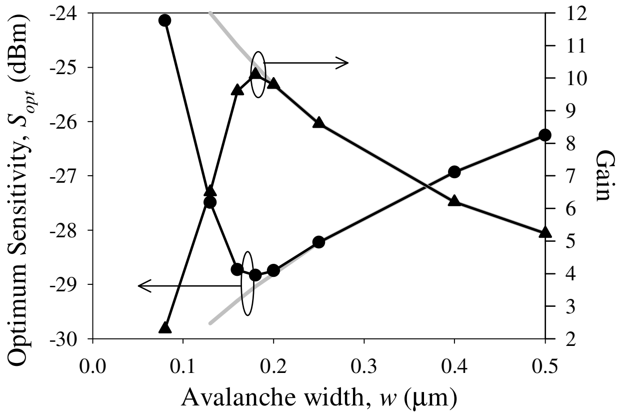

Figure 2. Optimum sensitivity (●, left axis) and its corresponding gain (▲, right axis) versus avalanche width of the InP APDs at a transmission speed of 10Gb/s. Grey lines are results without tunneling current.

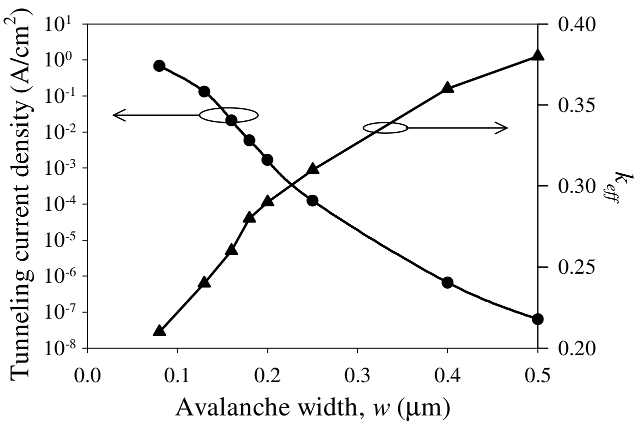

Figure 3. Dark current density (●, left axis) and k_{eff} (▲, right axis) as a function of avalanche width of the InP APDs at a transmission speed of 10Gb/s.

The optimum avalanche width for InP APDs of this work is similar to that reported in [5], which included tunneling current in the analyses but ignored ISI. The agreement suggests that effects of ISI on sensitivity are not significant at the transmission speed of 10Gb/s. However we expect the significance of ISI to increase when studying APDs for 40Gb/s transmission speed, which is ongoing.

IV. CONCLUSIONS

We have extended the model in [1] to include tunneling current in optimization of avalanche region width for best receiver sensitivity at 10Gb/s. An optimal width of ~180 nm was predicted yielding a minimum sensitivity of ~-28.8 at an optimal gain of 10, assuming a Johnson-noise level of 500 noise electrons per bit.

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