2-15-2011

Sensitivity of High-Speed Lightwave System Receivers Using InAlAs Avalanche Photodiodes

Daniel S.G. Ong

Majeed M. Hayat

John P.R. David

Jo Shien Ng

IEEE Photonics Technology Letters, Vol. 23, No. 4 (February 15 2011) : 233-235. DOI. This article is © Institute of Electrical and Electronic Engineers (IEEE) and permission has been granted for this version to appear in e-Publications@Marquette. Institute of Electrical and Electronic Engineers (IEEE) does not grant permission for this article to be further copied/distributed or hosted elsewhere without the express permission from Institute of Electrical and Electronic Engineers (IEEE).

Sensitivity of High-Speed Lightwave System Receivers Using InAlAs Avalanche Photodiodes

Daniel S. G. Ong
Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield, U.K.
Majeed M. Hayat
Department of Electrical and Computer Engineering and Center for High Technology Materials, University of New Mexico, Albuquerque, NM, USA
John P. R. David
Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield, U.K.
Jo Shien Ng
Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield, U.K.

Abstract:

Calculations based on a rigorous analytical model are carried out to compare the sensitivity of optical receivers that use InP and $In_{0.52}Al_{0.48}As$ avalanche photodiodes (APDs). The model includes the effects of intersymbol interference, tunneling current, avalanche noise and its correlation with the stochastic avalanche duration, dead space, and transimpedance amplifier noise. For a 10-Gb/s system with a bit-error rate of 10^{-12}, the optimum receiver sensitivity predicted for $In_{0.52}Al_{0.48}As$ and InP APDs is -28.6 and -28.1 dBm, respectively, corresponding to a reduction of 11% in optical signal power for receivers using $In_{0.52}Al_{0.48}As$ APDs. Thus, considering overall receiver sensitivity, the improvement offered by $In_{0.52}Al_{0.48}As$ APDs over InP is modest.

SECTION I. Introduction

Indium phosphide (InP) avalanche photodiodes (APDs) are widely used in receivers for high-speed direct-detection lightwave communication systems. The internal gain, G, resulted from carrier impact ionization in the InP avalanche region in the APD, amplifies the signal (the photocurrent). This amplification reduces the significance of Johnson noise, leading to improved receiver sensitivity, since the APD adds only a small amount of avalanche noise (from the carrier impact ionization, which has a stochastic nature).

For a given avalanche region material, the performance of the APD is strongly influenced by the avalanche-region width, w, through the following factors. They are the (i) avalanche noise, which is characterized by the excess noise factor, (ii) stochastic avalanche duration (also known as the avalanche buildup time), and (iii) dark current, which is usually dominated by tunneling current in the avalanche region. As the receiver operation speed increases, the stochastic avalanche duration becomes increasingly important since it eventually determines the level of intersymbol interference (ISI) present in the receiver. In addition, the receiver output is also influenced by noise from the transimpedance amplifier (TIA), which follows the APD. Thus it is common to assess the receiver performance through the receiver sensitivity, which is the minimum average optical power in each bit required to produce a bit-error-rate (BER) of 10^{-12}.

Models for calculating sensitivity and BER have been improving in their accuracy through gradually taking into account the above three factors [1]–[2][3][4][5][6] at different levels of sophistication. Using the joint-probability distribution function (PDF) of gain and avalanche duration generated by the Random Path Length model [7], the most complete model so far includes ISI, avalanche noise, stochastic avalanche duration, tunneling current and TIA noise [6]. An optimum w (of 0.18 μm) was also established for InP APDs in 10 Gb/s receivers [6].

The material $In_{0.52}Al_{0.48}As$ (referred hereafter as InAlAs) is considered as an avalanche material superior to InP due to lower excess noise factors in InAlAs than that in InP [8], [9]. APDs using InAlAs avalanche region have thus been researched widely. However, as mentioned earlier, to rigorously assess the performance of an APD, we should evaluate the receiver sensitivity at a certain BER, instead of relying on a single APD performance parameter. Comparing experimental sensitivity data from receivers with different APDs is unfortunately not straightforward because often different TIAs were used in the receivers.

In this letter, we use the model reported in [6] to carry out sensitivity calculations for InAlAs APDs of varying w, establishing an optimum avalanche region and associated best sensitivity for 10 Gb/s systems. This enables straightforward comparisons to be made between optimized InAlAs APDs and InP APDs.

SECTION II. Model

Since the BER model used in this work was described fully in [2] and [6], we present only a brief description here. The model takes into account that the receiver output is conditional on the state of the present bit and the entire past bit stream. In [6] we began with computing such pattern-specific BER, repeating the process for all possible past bit patterns. An overall average BER was then given by

$$\mathrm{BER} = \frac{1}{2^L}\sum_{j=1}^{2^L} \mathrm{BER}(I_j)\,, \quad (1)$$

where I_j is the past bit pattern of length L bits. The value of L should be sufficiently large to capture all significant ISI terms; in our calculations we have found $L = 10$ to be adequate. The pattern-specific BER is approximated by [6]

$$\mathrm{BER}(I_j) \approx \frac{1}{4}\left[\mathrm{erfc}\left(\frac{\theta-\mu_0(I_j)}{\sqrt{2}\sigma_0(I_j)}\right) + \mathrm{erfc}\left(\frac{\mu_1(I_j)-\theta}{\sqrt{2}\sigma_1(I_j)}\right)\right], \qquad (2)$$

where $\mu_0(I_j)$ and $\sigma_0^2(I_j)$ denote the mean and variance for the receiver's output conditional upon the present bit (i.e., the information bit corresponding to the receiver's present integration period) being ‘0,’ and μ1(Ij) and $\sigma_1^2(I_j)$ are similar quantities conditional on the present bit being ‘1.’ The expressions for $\mu_0(I_j), \sigma_0^2(I_j), \mu_1(I_j)$ and $\sigma_1^2(I_j)$ are equations (16), (18), (10) and (12), respectively in [6]. The decision threshold, θ, is taken as $\theta = (\mu_0\sigma_1 + \mu_1\sigma_0)/(\sigma_0 + \sigma_1)$, which is a convenient albeit accurate approximation to the optimal decision threshold that minimizes the BER [1], [10].

As in [6], we use the Random Path Length (RPL) model, described in [7], to provide the joint PDF of gain and avalanche duration required by the BER model. Impact ionization coefficients and threshold energies for InP and InAlAs are obtained from [11] and [9], respectively. Due to differences in impact ionization properties, pure hole injection and pure electron injection were used for InP and InAlAs, respectively, when generating joint PDF of gain and avalanche duration statistics using the RPL model. The un-multiplied tunneling currents in the avalanche regions are given by Forrest et al. [12], with the value of tunneling fitting parameter for InP and InAlAs taken from [11] and [13], respectively. The Johnson noise due to the TIA in the receiver was assumed to be 636 electrons per bit, corresponding to an input noise current density, i_n, of 10.7 pA/Hz$^{1/2}$—an average from a number of commercial TIA modules at the speed of 10 Gb/s, as described in [6].

SECTION III. Results

Calculations were performed for a series of InP and InAlAs APDs, with active area diameter of $30\ \mu$m and w ranging from 0.1 to 0.5 μm. Compared to the $50\ \mu$m used in [6], the smaller diameter was chosen to reflect the trend of smaller APDs for lower dark currents and higher speed. An ideal electric-field profile (negligible depletion into the p- and n-claddings, and a constant electric field across the i region) was assumed. The system speed was assumed to be 10 Gb/s.

For a given combination of avalanche width and material, the calculations yielded an optimum sensitivity and corresponding mean gain. Results for the different combinations are summarized in Fig. 1, which plots optimum sensitivity (optimized over the mean gain) and its corresponding mean gain from the InP and InAlAs calculations against the avalanche region width. Our calculations predict an optimum w of 0.15 μm, with sensitivity of -28.6 dBm and gain of 15, for InAlAs APDs in a 10 Gb/s system. For InP APDs, the optimum w is $0.18\ \mu$m, with sensitivity of -28.1 dBm and gain of 13. It is interesting to note that at the optimal width, the corresponding optimal mean gain (whose value is selected to maximize the sensitivity at each width) is also maximized. Our results were benchmarked against published experimental reports. In [14], an optimum sensitivity of -26.8 dBm at 10 Gb/s was reported for an InP APD ($w = 0.5\ \mu$m) receiver system, in agreement with our results in Fig. 1. For InAlAs APD-based receiver systems. Yagyu et al. [15] and Levine et al. [16] reported optimum sensitivity values of -29.9 ($w = 0.2\ \mu$m) and -29.0 dBm ($w = 0.13\ \mu$m), respectively. Although these are better than our results, the difference may be due to the system's TIA (not specified in either paper).

Reducing in from 10.7 to 6.5 pA/Hz$^{1/2}$, which is still reasonable for a 10 Gb/s TIA, we obtained results in agreement with [15] and [16].

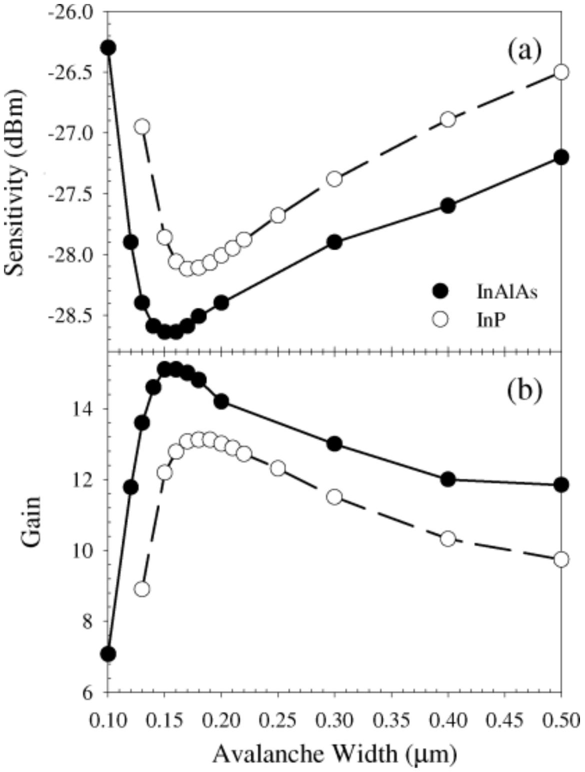

Fig. 1. (a) Optimum sensitivity and (b) the corresponding mean gain versus device avalanche width for a 10-Gb/s system using InAlAs (closed symbols) and InP (open symbols) APDs. Lines are drawn to aid visualization.

For a given width, InAlAs provides better (lower) sensitivity than InP. However, at their respective optimum avalanche widths, the difference in receiver sensitivities is only 0.5 dBm, corresponding to a reduction of 11% in optical signal power at the receiver input. The improvement brought on by replacing InP with InAlAs for avalanche material is therefore modest. The modesty in this improvement is partly due to a diminishing advantage, as w decreases, in excess-noise characteristics in InAlAs over InP, as shown in Fig. 2(a) in the form of effective ionization coefficient ratio, k_{eff}. At the optimum avalanche widths, the values for k_{eff} are 0.21 and 0.29, for InAlAs (at 0.15 μm) and InP (at 0.18 μm), respectively. Another factor is the slightly higher gain-bandwidth product in InAlAs compared to InP, 220 and 180 GHz, respectively, at their optimum widths, as shown in Fig. 2(b). The slightly lower tunneling current in InAlAs APDs compared to those in InP APDs (expected from the slightly larger bandgap of InAlAs), as shown in Fig. 2(c), also contributes slightly to the improvement in receiver sensitivity. These results have not taken into account device fabrication variations, which may worsen receiver sensitivity performance.

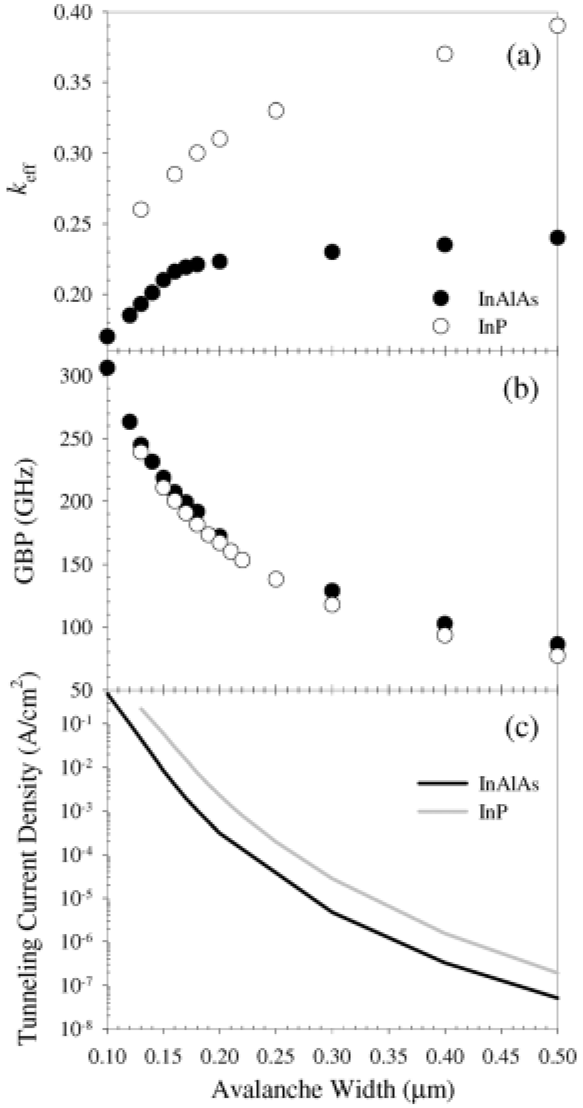

Fig. 2. (a) Effective ionization coefficient ratio (k_{eff}), (b) gain-bandwidth product, and (c) tunneling current density, all functions of the avalanche width for a 10-Gb/s transmission system using InAlAs (closed symbols; black line) and InP (open symbols; gray line).

SECTION IV. Conclusion

Using the APD-based receiver model for BER in [6], which includes effects of ISI, avalanche noise, stochastic avalanche duration, tunneling current in APDs, and Johnson noise from TIA, we have calculated and compared the sensitivities of receivers using InAlAs and InP APDs for a BER of 10−12 at 10 Gb/s. InAlAs APDs are found to bring a modest improvement in sensitivity of ~ 0.5 dBm (from -28.6 to -28.1 dBm) over InP APDs. This enables a reduction of 11% in optical signal power whilst maintaining the BER at 10−12. Our results show that, when considering overall receiver sensitivity, InAlAs APDs are not significantly better than InP APDs.

References

1. M. M. Hayat, B. E. A. Saleh, J. A. Gubner, "Bit-error rates for optical receivers using avalanche photodiodes with dead space", *IEEE Trans. Commun.*, vol. 43, no. 1, pp. 99-106, Jan. 1995.
2. P. Sun, M. M. Hayat, B. E. A. Saleh, M. C. Teich, "Statistical correlation of gain and buildup time in APDs and its effects on receiver performance", *J. Lightw. Technol.*, vol. 24, no. 2, pp. 755-768, Feb. 2006.

3. A. R. J. Marshall, Y. L. Goh, L. J. J. Tan, C. H. Tan, J. S. Ng, J. P. R. David, "A comparison of the lower limit of multiplication noise in InP and InAlAs based APDs for telecommunications receiver applications", *Proc. LEOS*, pp. 789-790, 2006.
4. C. Groves, J. P. R. David, "Effects of ionization velocity and dead space on avalanche photodiode bit error rate", *IEEE Trans. Commun.*, vol. 55, no. 11, pp. 2152-2158, Nov. 2007.
5. P. Sun, M. M. Hayat, A. K. Das, "Bit error rates for ultrafast APD based optical receivers: Exact and large deviation based asymptotic approaches", *IEEE Trans. Commun.*, vol. 57, no. 9, pp. 2763-2770, Sep. 2009.
6. D. S. G. Ong, J. S. Ng, M. M. Hayat, P. Sun, J. P. R. David, "Optimization of InP APDs for high-speed lightwave systems", *J. Lightw. Technol.*, vol. 27, no. 15, pp. 3294-3302, Aug. 2009.
7. J. S. Ng, C. H. Tan, B. K. Ng, P. J. Hambleton, J. P. R. David, G. J. Rees, A. H. You, D. S. Ong, "Effect of dead space on avalanche speed", *IEEE Trans. Electron Devices*, vol. 49, no. 4, pp. 544-549, Apr. 2002.
8. C. Lenox, P. Yuan, H. Nie, O. Baklenov, C. Hansing, J. C. Campbell, A. L. Holmes, B. G. Streetman, "Thin multiplication region InAlAs homojunction avalanche photodiodes", *Appl. Phys. Lett.*, vol. 73, no. 6, pp. 783-784, Aug. 1998.
9. Y. L. Goh, A. R. J. Marshall, D. J. Massey, J. S. Ng, C. H. Tan, M. Hopkinson, J. P. R. David, S. K. Jones, C. C. Button, S. M. Pinches, " Excess avalanche noise in In \$_{0.52}\$ Al \$_{0.48}\$ As ", *IEEE J. Quantum Electron.*, vol. 43, no. 6, pp. 503-507, Jun. 2007.
10. G. P. Agrawal, Fiber-Optic Communication Systems, New York:Wiley, pp. 172, 1997.
11. L. J. J. Tan, J. S. Ng, C. H. Tan, J. P. R. David, "Avalanche noise characteristics in submicron InP diodes", *IEEE J. Quantum Electron.*, vol. 44, no. 34, pp. 378-382, Mar./Apr. 2008.
12. S. R. Forrest, R. F. Leheny, R. E. Nahory, M. A. Pollack, " In \$_{0.53}\$ Ga \$_{0.47}\$ As photodiodes with dark current limited by generation-recombination and tunneling ", *Appl. Phys. Lett.*, vol. 37, no. 3, pp. 322-325, 1980.
13. Y. L. Goh, D. J. Massey, A. R. J. Marshall, J. S. Ng, C. H. Tan, W. K. Ng, G. J. Rees, M. Hopkinson, J. P. R. David, S. K. Jones, "Avalanche multiplication in InAlAs", *IEEE Trans. Electron Devices*, vol. 54, no. 1, pp. 11-17, Jan. 2007.
14. Y. Hirota, Y. Muramoto, T. Takeshita, T. Ito, H. Ito, S. Ando, T. Ishibashi, "Reliable non-Zn-diffused InP/InGaAs avalanche photodiode with buried n-InP layer operated by electron injection mode", *Electron. Lett.*, vol. 40, no. 21, pp. 1378-1380, Oct. 2004.
15. E. Yagyu, E. Ishimura, M. Nakaji, S. Ihara, Y. Mikami, H. Itamoto, T. Aoyagi, K. Yoshiara, Y. Tokuda, "Design and characteristics of guardring-free planar AlInAs avalanche photodiodes", *J. Lightw. Technol.*, vol. 27, no. 8, pp. 1011-1017, Apr. 2009.
16. B. F. Levine, R. N. Sacks, J. Ko, M. Jazwiecki, J. A. Valdmanis, D. Gunther, J. H. Meier, "A new planar InGaAs–InAlAs avalanche photodiode", *IEEE Photon. Technol. Lett.*, vol. 18, no. 18, pp. 1898-1900, Sep. 2006.