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Ng, J.S., Tan, C.H., David, J.P.R. et al. (1 more author) (2005) Effect of impact ionization in the InGaAs absorber on excess noise of avalanche photodiodes. IEEE Journal of Quantum Electronics, 41 (8). pp. 1092-1096. ISSN 0018-9197

https://doi.org/10.1109/JQE.2005.850700

Effect of Impact Ionization in the InGaAs Absorber on Excess Noise of Avalanche Photodiodes

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***Abstract*—The effects of impact ionization in the InGaAs absorption layer on the multiplication, excess noise and breakdown voltage are modeled for avalanche photodiodes (APDs), both with InP and with InAlAs multiplication regions. The calculations allow for dead space effects and for the low field electron ionization observed in InGaAs. The results confirm that impact ionization in the InGaAs absorption layer increases the excess noise in InP APDs and that the effect imposes tight constraints on the doping of the charge control layer if avalanche noise is to be minimized. However, the excess noise of InAlAs APDs is predicted to be reduced by impact ionization in the InGaAs layer. Furthermore the breakdown voltage of InAlAs APDs is less sensitive to ionization in the InGaAs layer and these results increase tolerance to doping variations in the field control layer.**

***Index Terms*—Avalanche photodiodes, impact ionization, noise.**

I. Introduction

THE DETECTOR of choice for optical fiber communication systems is often an InP-based, near infrared avalanche photodiode (APD) since its internal gain can improve the overall sensitivity of the receiver. The quantum efficiency, frequency response and excess noise of such devices are thus of some interest [1]. The APD consists typically of an undoped InGaAs absorption layer, a doped, thin InP field-control layer, an undoped InP multiplication layer and doped cladding layers. The doping profile is designed so that, under operating bias, the absorption, field control and multiplication layers are fully depleted, while the field across the narrow bandgap InGaAs absorption layer is kept low but finite to minimize tunneling in the InGaAs [2] while ensuring rapid drift of photogenerated carriers to the multiplication region. In recent years devices investigated in the laboratory have favored InAlAs lattice-matched to InP for the multiplication layer [1], however, the structure remains largely the same, except that electrons, the more readily ionizing carriers in InAlAs, are injected into the multiplication layer.

Conventional APD models usually assume that the field across the InGaAs absorption layer is too weak to cause ionization, so that only the InP or InAlAs multiplication and possibly field control layers contribute to the gain and the excess noise and limit the intrinsic avalanche bandwidth. In most III–V semiconductors the ionization coefficients, α for electrons and β for holes, exhibit a strong and approximately exponential dependence on inverse electric field. However, recent work [3], [4] shows that, at low fields, the field dependence of α in InGaAs becomes weaker, resulting in relatively large values, even at fields as low as $\sim$150 kV$\cdot$cm^{-1}, previously thought too low for ionization. This behavior is thought to result from a combination of narrow bandgap and large intervalley separation [5].

The effect of impact ionization in the InGaAs absorption layer on the bandwidth of InGaAs–InAlAs APDs has recently been studied in [6], [7]. Using a local model for ionization, which neglects dead space effect, and measured values of InGaAs ionization coefficients Hollenhorst [8] predicted detrimental effects on excess noise. Theoretical investigations by Shih [9] on an a-Si:H/a-SiC:H superlattice APD predicted that ionization in the a-Si:H absorption layer also increases excess noise.

However, the effects of ionization in the InGaAs absorption layer in InGaAs–InAlAs APDs have not been investigated. In this paper we report a theoretical study of multiplication and excess noise in InP and InAlAs APDs with InGaAs absorption layers, allowing for nonlocal ionization, by including the effects of dead space in the multiplication layer, and using the most recent and accurate measurements of ionization coefficients in InGaAs covering the low fields.

II. Model

APD designs for high speed reported in [6] and [7] were used and the structures modeled here are summarized in Tables I and II, where positive and negative doping densities indicate p-type and n-type layers, respectively. Field profiles were evaluated using a one-dimensional Poisson solver. The doping density in the field-control layer was varied to modify the electric field in the InGaAs layer and the corresponding devices are labeled APD1, APD2, and APD3. The peak fields (kept below 200 kV$\cdot$cm^{-1} to avoid significant tunneling current) in InGaAs absorber are shown in Tables I and II at biases corresponding to multiplication factors of $\sim$20, including the effects of impact ionization in the InGaAs layer.

Recurrence equations [10] were used to calculate multiplication M and excess noise factor F as functions of reverse bias V. The calculations require knowledge of the probability density function of the carrier's ionization path length $h(x,x')$, where x and x' are its positions of ionization and generation, respectively [10]. For electrons, we used [10]

$$h(x,x') = \begin{cases} 0, & x-x' < d_e(x') \\ \alpha*(x)\exp\left[-\int_{x' d_e(x')}^{x} \alpha*(\xi)d\xi\right], & x-x' \geq d_e(x') \end{cases} \tag{1}$$

Manuscript received January 28, 2005; revised March 29, 2005. This work was supported in part by the U.K. Engineering and Physical Sciences Research Council and the Electromagnetic Remote Sensing Defence Technology Centre and in part by the Electro Magnetic Remote Sensing Defence Technology Centre, U.K., and Engineering and Physical Sciences Research Council, U.K.

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Digital Object Identifier 10.1109/JQE.2005.850700

TABLE I
STRUCTURE OF THE InP APDs MODELED

Purpose	Material	Thickness (nm)	Doping density (cm^{-3})	Peak field in InGaAs ($kVcm^{-1}$)
p-cladding	InP	1000	2×10^{18}	
Avalanche	InP	200	-10^{15}	
Field-control	InP	100	-3.0×10^{17} (APD1) -3.6×10^{17} (APD2) -4.0×10^{17} (APD3)	~205 ~155 ~115
Absorption	InGaAs	1500	-10^{15}	
n-cladding	InP	1000	-2×10^{18}	

TABLE II
STRUCTURE OF THE InAlAs APDs MODELED

Purpose	Material	Thickness (nm)	Doping density (cm^{-3})	Peak field in InGaAs ($kVcm^{-1}$)
p-cladding	InAlAs	1000	2×10^{18}	
Absorption	InGaAs	1500	10^{15}	
Field-control	InAlAs	100	4.0×10^{17} (APD1) 4.5×10^{17} (APD2) 5.0×10^{17} (APD3)	~200 ~140 ~80
Avalanche	InAlAs	200	10^{15}	
n-cladding	InAlAs	1000	-2×10^{18}	

where d_e and α^* are the dead space and the "activated" ionization coefficient for electrons. The dead space is related to the ionization threshold energy, $E_{\mathrm{the}}(x') = q\int_{x'}^{x'+d_e} \Im(\xi)d\xi$, where q is the electron charge and $\Im$ is the electric field. α^* is deduced from the local ionization coefficient, α, using $1/\alpha = 1/\alpha^* + d$ [11]. Holes are treated similarly. Bandgap discontinuities were not considered in the model.

Light of wavelength 1.55 μm enters the structure from the top of the InGaAs absorption layer and its absorption is characterized by a coefficient of 0.7×10^4 cm^{-1} [12]. Electrons and holes are assumed to have the same ionization threshold energy of 2.2 eV ($\sim$1.5 $\times$ bandgap) for both InP and InAlAs. The local ionization coefficients of [13] and [14] were used for InP and InAlAs, respectively. For InAlAs [14]

$$\alpha(\Im)(\mathrm{cm}^{-1}) = 3.14 \times 10^6 \exp(-2.71 \times 10^6/\Im) \quad (2)$$

$$\beta(\Im)(\mathrm{cm}^{-1}) = 4.29 \times 10^6 \exp(-3.80 \times 10^6/\Im) \quad (3)$$

where $\Im$ is in V$\cdot$cm^{-1}. The field dependences of α and β in InGaAs were taken from [4] and the ionization threshold energy was taken as zero in this material since dead space effects are expected to be less important in the thick absorption layer.

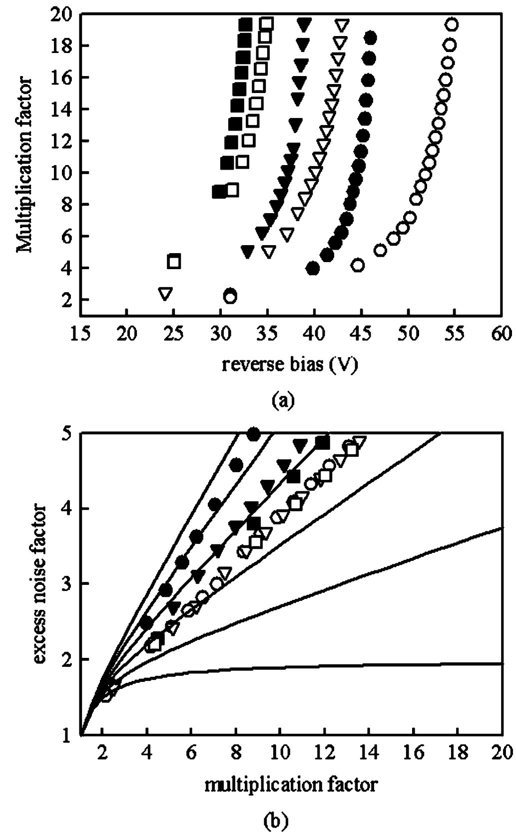

Fig. 1. (a) Multiplication factors of InP APD1 1 (●), 2 (▼), and 3 (■) as functions of reverse bias calculated with (solid symbols) and without (open symbols) impact ionization in the InGaAs layer. (b) The corresponding $F(M)$ results. $F(M)$ given by local model for fixed values of k from 0 to 0.5 in steps of 0.1 are also shown (solid lines) for comparison.

III. RESULTS

The multiplication and excess noise curves predicted for the InP APDs are shown in Fig. 1, both excluding and including the effects of ionization in the InGaAs. Similar results for the InAlAs APDs are shown in Fig. 2. $F(M)$ given by local model for fixed values of α/β (for Fig. 1) or β/α (for Fig. 2) from 0 to 0.5 in steps of 0.1 are also shown for comparison.

Of the three InP APD designs considered the InP APD1 structure has the highest field across the InGaAs layer. Consequently it has the highest breakdown voltage, since for a given bias the field in the multiplication region is correspondingly reduced and the bias must be increased to compensate. However, the excess noise characteristics for the three InP APD designs, calculated excluding ionization in the InGaAs layer, coincide, since the multiplication and excess noise are generated only in the InP layers. It is evident from Fig. 1(a) that ionization in the InGaAs layer significantly increases the multiplication, with the most dramatic increase predicted in the device with the highest field across this layer. Hence, taking this mechanism into account reduces the breakdown voltages of the InP APDs, especially that of APD1.

The excess noise in the InP devices also increases with increasing InGaAs layer field, as shown in Fig. 1(b), in agreement with the findings of [8]. In fact the comparison shows that small variations in the doping level of the field control layer can give

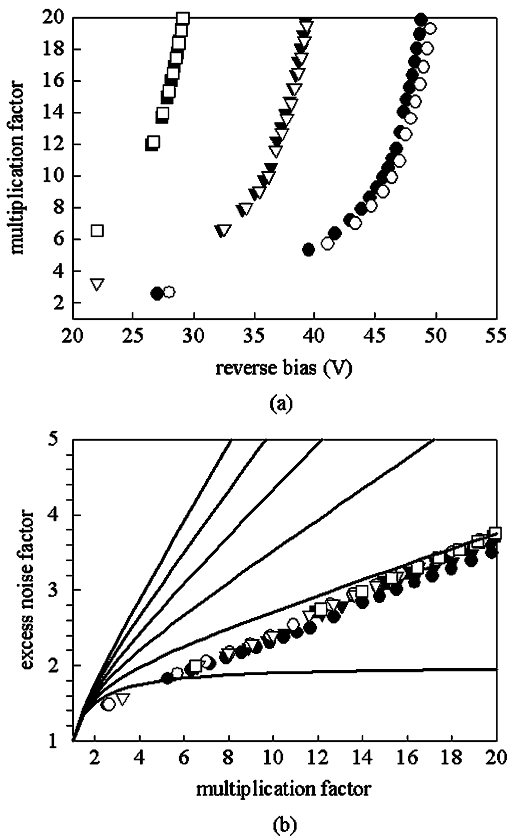

Fig. 2. (a) Multiplication factors of InAlAs APD 1 (●), 2 (▼)), and 3 (■) as functions of reverse bias calculated with (solid symbols) and without (open symbols) impact ionization in the InGaAs layer. (b) The corresponding $F(M)$ results. $F(M)$ given by local model for fixed values of k from 0 to 0.5 in steps of 0.1 are also shown (solid lines) for comparison.

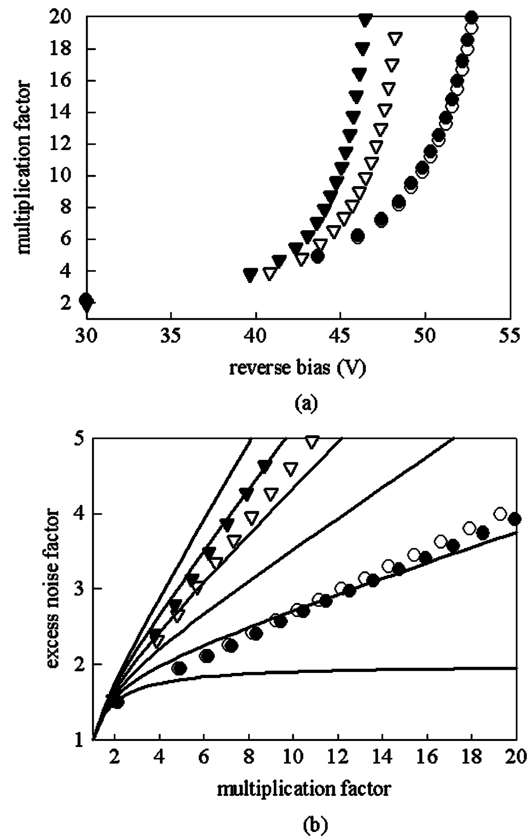

Fig. 3. (a) Multiplication factors of InP APD (▼) and InAlAs APD (●) with 0.5-μm-thick multiplication layer as functions of reverse bias calculated with (solid symbols) and without (open symbols) impact ionization in the InGaAs layer. (b) The corresponding $F(M)$ results. $F(M)$ given by local model for fixed values of k from 0 to 0.5 in steps of 0.1 are also shown (solid lines) for comparison.

quite different values of excess noise. Moreover, fields as weak as $\sim$120 kV$\cdot$cm^{-1} in the absorption layer are still not weak enough to avoid detrimental effects on excess noise, suggesting a lower limit on field across the InGaAs layer than that imposed by band-to-band tunneling. It appears to be vital to achieve a depleted InGaAs layer but with an extremely low field, demanding tight tolerances on InP APD wafer growth.

On the other hand, it appears that ionization in the InGaAs affects the multiplication factors and the breakdown voltages of InAlAs APDs only marginally, as shown in Fig. 2(a). More significantly, Fig. 2(b) shows that the excess noise is reduced when ionization in the InGaAs layer is included. By contrast with the prediction of increased excess noise in InP APDs, the InAlAs APDs are predicted to achieve lower noise as the field across the InGaAs layer is increased, with the InAlAs APD1 structure having the lowest noise of the three structures simulated.

Multiplication and noise characteristics were also calculated for other InP and InAlAs APD structures with 0.5-μm-thick multiplication layers and suitably doped field control layers (other layers remaining unchanged). The fields across the InGaAs layer for $M \sim 20$ are $\sim$90 kV$\cdot$cm^{-1} and $\sim$120 kV$\cdot$cm^{-1}, respectively. The multiplication and excess noise curves for these APDs are compared in Fig. 3(a) and (b). The results also show that ionization in the InGaAs results in respectively higher and lower excess noise factors for InP and InAlAs APDs, reflecting the behavior shown in Fig. 1(b) and Fig. 2(b).

IV. Discussion

It is now well known that to achieve low excess noise it is beneficial to use a material with dissimilar ionization coefficients and significant dead space effects [15] and to inject the carriers with the higher ionization coefficient. For the field ranges typical of those in the InGaAs absorption layer and the InAlAs multiplication layer, the ionization coefficients are more dissimilar in InGaAs ($\alpha/\beta > 20$ at high multiplication factors), leading to lower associated excess noise, than in InAlAs. Even with dead space effect reducing the excess noise in the InAlAs, multiplication in the InGaAs is still less noisy than in the InAlAs. Furthermore, feedback holes generated by ionization in the InAlAs multiplication layer are less likely to initiate ionization in the InGaAs layer because of its low value of β. Hence, allowing for ionization in the InGaAs layer leads to slightly reduced excess noise.

It appears that the multiplication, excess noise and breakdown voltage of InAlAs APDs are less susceptible to variations in the field across the InGaAs layer and hence to variations in doping level of the field control layer. While lowest excess noise would be achieved by designing for ionization in the InGaAs layer, tunneling places a strong upper limit on the electric field there and design tolerances could be uncomfortably tight.

In the InP APD the advantages of ionizing in the InGaAs, where the dissimilar ionization coefficients, $\alpha > \beta$, can be expected to reduce multiplication noise, still apply in principle. However $\alpha < \beta$ in the InP multiplication region and the device is designed so that photogenerated holes are injected from the InGaAs. These holes are unlikely to have ionized in the low field InGaAs absorption layer, where $\alpha > \beta$. However, feedback electrons, generated by ionization in the high field InP, are likely to ionize in the InGaAs, generating more holes, which subsequently enter the high field InP layers and may create more carriers. Such chains of events may increase multiplication, reducing the breakdown voltages as shown in Fig. 1(a). It also leads to photo-generated carriers producing a wider distribution of multiplication factors in the InP APD when ionization is allowed in the InGaAs layer for a given mean value of multiplication, leading to increased excess noise.

Impact ionization in the InP or InAlAs cladding and field-control layers has been included in all the results presented above. Since the accuracy of the recurrence equations has not been tested for structure with rapidly changing field, such as those across the cladding and the field-control layers in the APDs, it was necessary to check that the observations in Figs. 1–3 are not affected by impact ionization taken place in these layers. Ignoring impact ionization in the cladding and field-control layers yields similar observations to those in Figs. 1–3, confirming that ionization in the InGaAs layer increases and reduces the excess noise factors for InP and InAlAs APDs, respectively.

In addition, to check that the predictions are not an artifact of the values chosen for ionization threshold energy the calculations were repeated using values of $E_{\mathrm{th}} = 0$ and 3 eV for both InP and InAlAs APDs. We find the trends described earlier are repeated.

The results in Figs. 1–3, obtained with light entering from the p-cladding side (termed top injection), are also compared to those obtained with light entering from the substrate side (termed back injection). For both InP and InAlAs APDs, top injection resulted in slightly larger multiplication factors than back injection for a given reverse bias, since electrons impact ionize more easily than holes in InGaAs absorber. Excess noise factors are also lower with top injection, compared to back injection.

V. Conclusion

Multiplication and excess noise have been calculated in APDs with InGaAs absorption layers and multiplication layers composed of both InAlAs and InP, allowing for the low field ionization behavior observed in InGaAs. Ionization in the InGaAs increases the excess noise of the InP APDs and the effect becomes more pronounced as the field in InGaAs increases. The design of InP APDs may therefore be as limited by undesirable impact ionization in the InGaAs as by tunneling current. By contrast, the excess noise was reduced in the InAlAs APDs when impact ionization in the InGaAs was included in the model and the reduction increased with the field in the InGaAs. These contrasting effects were explained by the match (for the InAlAs APDs) or mismatch (for the InP APDs) between the ionization coefficient ratio in the InGaAs absorption layer and in the multiplication layers. The calculations also suggest that InAlAs APDs are more tolerant to variations in field across the InGaAs absorption layer resulting from poor control of the doping level in the charge control layer.

Acknowledgment

The authors would like to thank Dr. C. Groves for proofreading of the manuscript and useful suggestions.

References

[1] J. C. Campbell *et al.*, "Recent advances in avalanche photodiodes," *IEEE J. Sel. Topics Quantum Electron.*, vol. 10, no. 4, pp. 777–787, Jul./Aug. 2004.

[2] S. R. Forrest, R. F. Leheny, R. E. Nahory, and 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, Aug. 1980.

[3] D. Ritter, R. A. Hamm, A. Feygenson, and M. B. Panish, "Anomolous electric field and temperature dependence of collection multiplication in InP/$In_{0.53}Ga_{0.47}As$ heterojunction bipolar transistors," *Appl. Phys. Lett.*, vol. 60, no. 25, pp. 3150–3152, Jun. 1992.

[4] J. S. NG, C. H. Tan, J. P. R. David, G. Hill, and G. J. Rees, "Field dependence of $In_{0.53}Ga_{0.47}As$ impact ionization coefficients," *IEEE Trans. Electron Devices*, vol. 50, no. 4, pp. 901–905, Apr. 2003.

[5] C. H. Tan, G. J. Rees, P. A. Houston, J. S. Ng, W. K. Ng, and J. P. R. David, "Temperature dependence of electron impact ionization in $In_{0.53}Ga_{0.47}As$," *Appl. Phys. Lett.*, vol. 84, no. 13, Mar. 2004.

[6] X. G. Zheng *et al.*, "A 12 × 12 $In_{0.53}Ga_{0.47}As$-$In_{0.52}Al_{0.48}As$ avalanche photodiode array," *IEEE J. Quantum Electron.*, vol. 38, no. 11, pp. 1536–1540, Nov. 2002.

[7] X. G. Zheng *et al.*, "Long-wavelength $In_{0.53}Ga_{0.47}As$-$In_{0.52}Al_{0.48}As$ avalanche photodiodes and arrays," *IEEE J. Quantum Electron.*, vol. 40, no. 8, pp. 1536–1540, Aug. 2004.

[8] J. N. Hollenhorst, "A theory of multiplication noise," *IEEE Trans. Electron Devices*, vol. 37, no. 3, pp. 781–788, Mar. 1990.

[9] N. F. Shih, "Excess noise analysis of separate absorption multiplication region superlattice avalanche photodiode," *IEEE Trans. Electron Devices*, vol. 48, no. 6, pp. 1075–1081, Jun. 2001.

[10] M. M. Hayat, W. L. Sargeant, and B. E. A. Saleh, "Effect of dead space on gain and noise in Si and GaAs avalanche photodiodes," *IEEE J. Quantum Electron.*, vol. 28, no. 5, pp. 1360–1365, May 1992.

[11] A. Spinelli and A. L. Lacaita, "Mean gain of avalanche photodiodes in a dead space model," *IEEE Trans. Electron Devices*, vol. 43, no. 1, pp. 23–30, Jan. 1996.

[12] D. A. Humphreys *et al.*, "Measurement of absorption coefficients of $Ga_{0.47}In_{0.53}As$ over the wavelength range 1.0–1.7 μm," *Electron. Lett.*, vol. 21, no. 25/26, pp. 1187–1189, 1985.

[13] L. W. Cook, G. E. Bulman, and G. E. Stillman, "Electron and hole impact ionization coefficients in InP determined by photomultiplication measurements," *Appl. Phys. Lett.*, vol. 40, no. 7, pp. 589–591, 1982.

[14] J. S. Ng, "Impact ionization measurement and modeling of long wavelength avalanche photodiodes," Ph.D. dissertation, Univ. Sheffield, Sheffield, U.K., Feb. 2003.

[15] G. J. Rees and J. P. R. David, "Why small avalanche photodiodes are beautiful," *Proc. SPIE Quantum Sensing: Evolution and Revolution from Past to Future*, vol. 4999, pp. 349–362, 2003.

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