Low Avalanche Noise Characteristics in Thin InP p^+-i-n^+ Diodes with Electron Initiated Multiplication

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***Abstract*— We have performed electron initiated avalanche noise measurements on a range of homojunction InP p^+-i-n^+ diodes with "i" region widths, w ranging from 2.40 to 0.24 μm. In contrast to McIntyre's noise model a significant reduction in the excess noise factor is observed with decreasing w at a constant multiplication in spite of α, the electron ionization coefficient being less than β, the hole ionization coefficient. In the $w = 0.24$ μm structure an effective β/α ratio of approximately 0.4 is deduced from the excess noise factor even when electrons initiate multiplication, suggesting that hole initiated multiplication is not always necessary for the lowest avalanche noise in InP-based avalanche photodiodes.**

***Index Terms*—APD, avalanche multiplication, avalanche noise, avalanche photodetector, impact ionization, InP.**

I. INTRODUCTION

THE InGaAs–InP separate absorption and multiplication avalanche photodiodes (SAM-APD's) offer higher sensitivity detection in long wavelength optical communication receivers compared to conventional InGaAs p-i-n diodes because of the internal gain provided by impact ionization. Such SAM-APD's use InGaAs for the photon absorption material and the wider bandgap InP for the avalanching region to obtain a device with high gain and low dark current [1]. Two main problems limit the performance of SAM APD's; first even with very low dark currents the sensitivity of an APD is ultimately limited by multiplication noise due to the stochastic nature of the impact ionization process, and second the avalanche buildup time limits the speed. Avalanche noise is commonly described by McIntyre's [2] avalanche noise model which predicts that for a material to exhibit low noise the ratio $k = \beta/\alpha$ of the hole to electron ionization coefficients, β and α, respectively, must be either much smaller or much greater than unity and the more readily ionizing carrier must initiate multiplication.

In InP, k is approximately 4 at electric fields of 240 kV/cm and decreases to 1.3 at 770 kV/cm [3]–[5]. In commercial SAM-APD's holes initiate the multiplication process in the typically 1 – 1.5-μm-long InP multiplication region and operate at electric fields of ~400 kV/cm, for which k is approximately 2. To obtain a larger k value and thus lower noise in these structures very thick avalanche regions with lower operating fields are needed. However, this would not be practical because of the high operating voltages required for multiplication and also because of the longer avalanche response time [6]. Alternatively multiquantum-well (MQW) avalanche regions have been implemented as a way of obtaining an enhanced k [11]. However, these structures also required high operating voltages and only electrons can initiate multiplication for low avalanche noise. We have shown recently [7] that GaAs p^+-i-n^+ and n^+-i-p^+ diodes with thin (<1 μm) avalanche regions operating at high electric fields can also exhibit low excess noise, independent of the initiating carrier, despite the fact that $k \approx 1$ at these fields. This low noise was explained by a model which took account of the increased influence of the dead space, d (the minimum distance a carrier must travel in the electric field to initiate an ionization event) in these thinner avalanching structures. The dead space narrows the probability distribution for ionization path length and so makes the multiplication more deterministic [8].

In this letter, we report measurements of the electron initiated multiplication and associated avalanche noise in a series of InP p^+-i-n^+ diodes with avalanche widths, w, ranging from 2.40 to 0.24 μm. In thick devices ($w = 2.40$ μm), the avalanche noise follows McIntyre's analysis, but in the thinner devices ($w < 1$ μm) the avalanche noise is significantly lower than predicted by this model. In addition, we perform electron initiated multiplication on a commercial InGaAs–InP Fujitsu SAM-APD for comparison.

II. GROWTH AND FABRICATION OF p^+-i-n^+ DIODES

The InP p^+-i-n^+ structures were grown by conventional metal–organic vapor phase epitaxy (MOVPE) on n^+ (100) InP substrates and comprised an n^+ InP buffer, 0.50 μm of n^+ (Si) InP, an undoped InP avalanche region of width w and finally a 0.60-μm InP p^+ (Zn) layer. Circular mesa diodes of 50–200-μm radius with annular top contacts for optical access were fabricated from these layers. Current versus voltage (I–V) characteristics were measured in the dark using a picoammeter and all layers showed a clearly defined sharp breakdown voltage. The p^+-i-n^+ diodes had i-region widths of $w = 2.40$, 0.90, 0.48, 0.33, and 0.24 μm, as determined

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Manuscript received October 6, 1998; revised November 23, 1998. This work was supported by the EPSRC (U.K.) under Grant GR/L71674.

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Publisher Item Identifier S 1041-1135(99)01863-7.

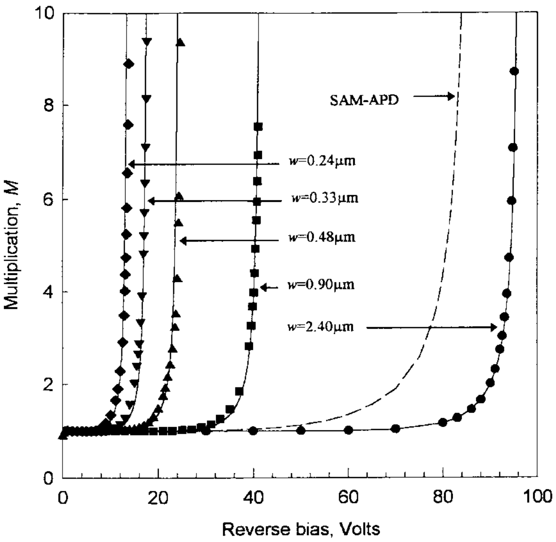

Fig. 1. Measured electron initiated multiplication (symbols) dependence on reverse bias, for a range of InP p^+-i-n^+'s and the commercial SAM-APD (broken line). Solid lines are the predicted multiplication characteristics from (1) using the ionization coefficients of Amiento [3] with avalanche widths: $w = 0.24$ μm (♦), 0.33 μm (▼), 0.48 μm (▲), 0.90 μm (■), and 2.40 μm (●).

both by capacitance voltage (C–V) measurements and from their multiplication characteristics, as described below.

III. DEVICE CHARACTERIZATION

Avalanche multiplication measurements were performed using a noise measurement system with a center frequency of 10 MHz and a noise effective bandwidth of 4.2 MHz [7]. Two lock-in amplifiers were used to distinguish unambiguously the photocurrent and multiplication noise from the system noise and dark current noise. Optical injection was provided by a 633-nm He–Ne laser focused to a spot onto the top p^+ InP cladding layer. At this wavelength the absorption coefficient of doped InP is $\sim 63 \times 10^3$ cm^{-1} [14] and <2% of the light reaches the high field through the 0.6-μm p^+ capping layer. To determine the dependence of multiplication on reverse bias a reference for $M = 1$ was deduced by linearly extrapolating the gradient of the bias dependence of photocurrent at fields below the onset of multiplication. Although this gradient was small in all structures the extrapolation serves to compensate for the increase in collection efficiency of the high field region resulting from cladding layer depletion. The excess noise factor, F, was determined from the noise power measurements using the method described previously [7] and calculated using $F = i_{\mathrm{eq}}/M^2 i_p$, where i_{eq} is the equivalent photocurrent of the silicon p-i-n diode that produces the same noise power as the device under test (DUT), M is the average multiplication of the DUT, and i_p the unmultiplied primary photocurrent.

IV. RESULTS

The dependence of multiplication on reverse bias for the p^+-i-n^+ diodes and the SAM-APD are shown in Fig. 1. In the p^+-i-n^+ diodes electron initiated multiplication measurements were performed using 542- and 633-nm wavelength light which produced identical multiplication characteristics confirming pure electron injection had been achieved. All devices attain a multiplication of at least $M = 7$. As expected the thinner avalanche regions require higher electric fields to achieve the same multiplication and they break down at a lower reverse bias.

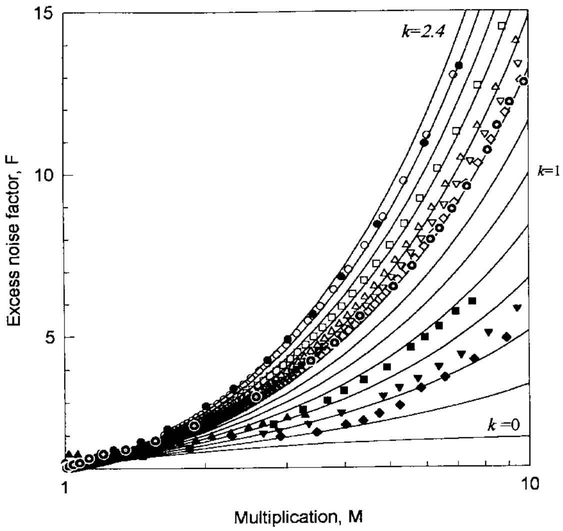

Fig. 2. Excess noise factor dependence on multiplication, for the SAM-APD (○) and a range of InP p^+-i-n^+ structures with nominal avalanche widths: $w = 2.40$ μm (●, ○), 0.90 μm (■, □), 0.48 μm (▲, △), 0.33 μm (▼, ▽), and 0.24 μm (♦, ◇). Solid symbols represent experimental results while, open symbols are predicted using McIntyre's noise model and the ionization coefficients of Amiento [3]. Solid lines are McIntyre's predictions with k increasing from 0 to 2.4 in steps of 0.2. Excess noise measurements were only performed up to $M \approx 3$ on the $w = 0.48$-μm device because excessive reverse leakage currents saturated the measurement system.

Analysis of C–V measurements showed that there was some diffusion of the p^+ zinc into the i-region of the p^+-i-n^+ diodes, effectively reducing the nominal i-region thickness and rounding the electric field profile. To allow comparisons to be made, equivalent ideal p^+-i-n^+ widths w were determined as follows. In an ideal p^+-i-n^+ diode M_e can be expressed as [9]

$$M_e = \left(1 + \frac{\alpha}{\alpha - \beta}(\exp(-(\alpha - \beta)w) - 1)\right)^{-1} \quad (1)$$

where α and β are the ionization coefficients at the uniform operating electric field and w is the avalanche width. Using previously measured ionization coefficients for InP [3] with w as an adjustable parameter, (1) was able to reproduce accurately the measured avalanche multiplication characteristics as shown by the solid lines in Fig. 1. These values of w differed by less than 10% from the maximum depletion values obtained from C–V measurements.

In Fig. 2 the measured dependence of F on M is plotted (filled symbols) and compared with McIntyre's model [2] for $F(M)$, given by

$$F(M) = kM + (2 - 1/M)(1 - k) \quad (2)$$

for various values of k (solid lines). Predictions of $F(M)$ from (2) for the ideal p^+-i-n^+ diodes using k obtained from the bulk ionization coefficients [3] and with electron initiated multiplication are also plotted in Fig. 2 (open symbols). These predictions are insensitive to small variations in w since the β/α ratio is almost constant over a small field range.

For the $w = 2.40$-μm p^+-i-n^+ diode the measured noise figure is consistent with pure electron injection, giving $k \approx$ 2.4, in McIntyre's model which is in good agreement with the previously measured ratio of ionization coefficients [3] at the average operating electric field. This confirms that $\beta > \alpha$ in InP at this field and suggests that holes should be injected to minimize avalanche noise. For the thinner ($w < 1$ μm) devices the $F(M)$ characteristics predicted by the measured β/α [3] show a reduction in F because the β/α ratio approaches unity as the field increases. However, in principle, these predicted characteristics should never fall below the $k = 1$ line since $\beta > \alpha$ even at the highest field encountered in the thinnest device [3]. In contrast, the measured noise characteristic falls to the $k \approx 0.7$ curve for the $w = 0.90$-μm device and decreases further to the $k \approx 0.4$ curve for the $w = 0.24$-μm device. It would be impossible to achieve this low noise characteristic in such a thin structure with any type of injection according to McIntyre's noise model [2]. The commercial SAM-APD is designed to detect 1.3–1.6 μm wavelength light which passes through the p+ InP cap where it is absorbed in a low field InGaAs region resulting in hole initiated multiplication. 633-nm wavelength light however, is absorbed in the p^+ InP capping layer producing electron initiated multiplication corresponding to $k \sim 1.4$ on McIntyre's model. This is expected since hole initiated multiplication gives an excess noise typically corresponding to $1/k = 0.6 - 0.7$. Therefore, electron initiated multiplication in the $w = 0.24$-μm structures is actually quieter than the noise figure for commercial SAM-APD's [12] with hole initiated multiplication.

V. DISCUSSION

Although McIntyre's model [2] is generally used to quantify avalanche noise results, it is only appropriate if w is much greater than the dead space d. The model implicitly assumes that the ionization probability of a carrier is independent of its history and predicts that carrier feedback is the most detrimental mechanism to avalanche noise. For the thinner devices reported here, d becomes an appreciable fraction of w so that the probability distribution function (PDF) for ionization path length narrows, resulting in a more deterministic ionization process and hence a reduced noise, as we have previously shown in thin GaAs diodes [7]. Although only the reduction in noise with electron initiated multiplication is shown here we would expect a similar behavior with hole initiated multiplication since the same mechanism acts to reduce the noise as we have shown in GaAs [7].

It is interesting to note that a reduction in noise below that predicted by McIntyre's model occurs for devices with $w \leq 0.48$ μm due to the effect of dead space. In GaAs p^+-i-n^+ diodes the multiplication characteristic is appreciably affected by dead space only for $w \leq 0.1$ μm [13], while a reduction in noise occurs for $w \leq 0.5$ μm [7]. Noise characteristics thus appear to be more sensitive to dead space than does multiplication, as suggested by our modeling of these quantities using different PDF's for ionization path length [10].

These results suggest that subject to the limitations of tunneling current, the design of low noise SAM-APD's should use thin avalanche regions. From our data, an avalanche region below 0.5 μm is expected to require a lower operating voltage, result in lower noise than a typical $w = 1$–1.5 μm SAM-APD structure, and exhibit a fast pulse response [6].

VI. CONCLUSION

We have shown that in thick InP ($w = 2.40$ μm) p-i-n diodes, electron initiated multiplication exhibits a large avalanche noise as expected, corresponding to $\beta > \alpha$. However, avalanche noise measurements on submicrometer InP diodes show that the excess noise decreases with decreasing avalanche width even when electrons, the carriers with the lower ionization coefficient, initiate multiplication. This reduced noise is attributed to the effect of dead space which results in a more deterministic ionization process. This result has important implications for the design of InP-based SAM-APD's, which can achieve low noise with either hole or electron initiated multiplication provided the multiplication region is thin.

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