Extremely low noise, low voltage InAs Avalanche Photodiodes

A.R.J.Marshall, C.H.Tan, J.P.R.David
Department of Electronic and Electrical Engineering,
The University Of Sheffield,
Mappin Street, Sheffield, S1 3JD

Abstract

We report on studies of avalanche multiplication in InAs avalanche photodiodes (APDs). The results of multiplication measurements show that the electron ionisation coefficient (α) is much greater than the hole ionisation coefficient (β), in contradiction to the only earlier published experimental result. Furthermore measurements of the excess noise associated with the electron initiated avalanche multiplication in InAs APDs showed it to be extremely low, comparable with that measured on so called electron APDs fabricated from HgCdTe. These characteristics, combined with a low operating voltage, make InAs an interesting option for the fabrication of high sensitivity APD focal plane arrays in the III-V material system, potentially offering a lower cost alternative to HgCdTe APDs in some ranging, targeting and imaging applications.

Introduction

Making use of avalanche photodiodes instead of simple unity gain pin photodiodes can improve the overall sensitivity of a light detecting system, such as a laser range finder or an active imaging camera. This is achieved by providing gain to optically generated carriers at the point of detection within the APD and hence increasing the photocurrent supplied to the connecting circuitry. The extent to which this gain can be usefully exploited is limited, in most applications, by the associated rapid increase in the primary photocurrent's shot noise, which results from the statistics of the pseudo random impact ionisation process providing the avalanche gain. The increase in the shot noise is dependant on the operational gain M and an excess noise factor F, which itself depends on the statistics of the impact ionisation process. The total noise current is given by $I_n^2 = 2qI_0M^2FB$ where q is the electron charge, I_0 is the primary photocurrent and B is the bandwidth.

McIntyre developed the local model of impact ionisation [1], which defines a dependence of the excess noise factor on the ionisation coefficient ratio, k=α/β for hole initiated multiplication (M_h), or k=β/α for electron initiated multiplication (M_e). Therefore for pure electron injection the excess noise factor is give by the equation shown below.

$$F_e = kM_e + (1-k)\left(2 - \frac{1}{M_e}\right)$$

The local model shows that to minimise the excess noise factor, and hence the undesirable increase in the APDs noise current, the ionisation coefficients of electrons and holes should be as disparate as possible, minimising k. The optimum case being when either α or β is equal to zero, when the excess noise factor will tend towards a maximum of 2 at high gains.

Physically this equates to only a single carrier type undergoing impact ionisation.

To date characterisation of impact ionisation in III-V materials has shown that, relative to Silicon, they have similar ionisation coefficients, with α/β ratios between 1 and 10 at the most. For this reason they are usually considered to have high excess noise factors and offer limited opportunity to exploit avalanche gain before the associated avalanche noise starts to dominate the system noise. Indeed the use of III-V APDs has been limited to applications where Silicon can not be used, such as detection of the 1.55μm telecomunications wavelength. When targeting focal plane array (FPA) applications, the operational voltage of the APD must also be considered due to the restrictions imposed by the read out IC (ROIC). III-V APDs typically require 20V or more, making them difficult to interface to ROICs.

HgCdTe, a material which has been developed almost exclusively for defence sensing applications, has been shown to demonstrate an ideal multiplication characteristic for a number of compositions. In the results published to date it has been shown that the multiplication is dominated by electrons, and excess noise factors of between 2 and 1 have been reported at high gains [2 Beck/Kinch]. This would suggest that HgCdTe is an ideal material from which to fabricate high sensitivity APDs, and indeed a HgCdTe FPA using APDs has been demonstrated and shown to facilitate high sensitivity detection [3 Baker].

The binary III-V alloy InAs has remained unexploited for APD applications, with only one published experimental measurement of avalanche multiplication in InAs [4 Mikhailova]. In earlier work [5 DTC 06] the authors have shown that the band structure of InAs, which is quite unlike that of the well characterised wider bandgap III-V alloys, can be exploited to achieve high avalanche gain at low reverse bias. Such low voltage gain would allow InAs APD FPAs to be driven from existing ROICs. Furthermore as a binary III-V material InAs can also be grown and fabricated with relatively low costs, making it an attractive material from which to manufacture low cost, low voltage avalanche photodiodes (APDs). Indeed based on our early multiplication results we predicted that InAs had the potential to matching some of the desirable performance characteristics of HgCdTe with the relative ease of working within the III-V material system. In particular compositional uniformity over the areas required for FPA applications is not an issue with InAs which could make it a cheaper and hence attractive alternative.

Here we report on the characterisation of impact ionisation and the avalanche multiplication process in InAs. We also report the first measurement of excess multiplication noise in InAs APDs, demonstrating for the first time extremely low noise multiplication in an APD made from a III-V material.

A range of pin and nip diode structures have been grown epitaxial on InAs substrates by MBE[6 DTC 07]. The layers have been processed using wet chemical etching to form mesa etched diodes, for characterisation[7 Me SPIE 07].

Measurement of Avalanche Multiplication in InAs APDs

The main challenge involved in accurately measuring avalanche multiplication in InAs APDs at room temperature is distinguishing between the dark leakage current and the photocurrent. In order to achieve this distinction the fabricated diodes were reverse biased and illuminated with light from a chopped laser, the resulting photocurrent and its bias dependence was measured using phase sensitive detection. With this technique it was possible to accurately differentiate the photocurrent

from the dark current which was in the worst cases as much as several orders of magnitude greater at the highest reverse biases. The set-up used is shown in figure 1 below.

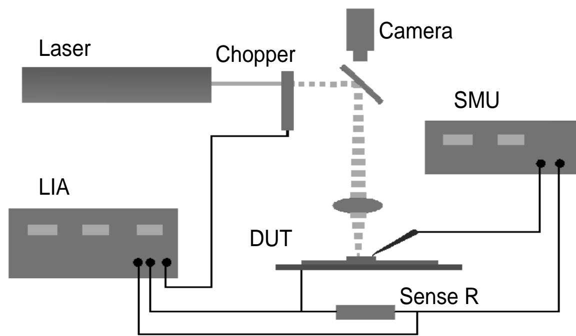

Figure 1: Set-up used for measuring avalanche multiplication

In order to identify the relative magnitude of the ionisation coefficients α and β, it was necessary to obtain pure electron and pure hole injection into the depleted region in which the gain took place. Pure electron injection into the depletion region was obtained by focused p-side illumination of pin APDs, with a laser of an appropriate wavelength to ensure that all the light was absorbed in the p-type layer. In this case only electrons were able to diffuse to and enter the high field depletion region, while holes will recombine or diffuse to the p-type contact. Likewise pure hole injection into the depletion region was obtained by similar n-side illumination of nip APDs.

To provide further confirmation of the results and trends identified a 3.39µm laser was used to acheive mixed injection into the depletion region for both pin and nip APDs. The weaker absorption of this longer wavelength, near the cut-off of InAs, led to the creation of photo-generated carriers in all three layers of the structure, and hence mixed injection into the high field depletion region.

The graph in figure 2 below shows the typical multiplication measured on a nip APD, for both pure hole injection (M_h) and mixed injection (M_{mixed}). Similarly the graph in figure 3 shows the typical multiplication measured on a pin APD for pure electron injection (M_e) and mixed injection (M_{mixed}).

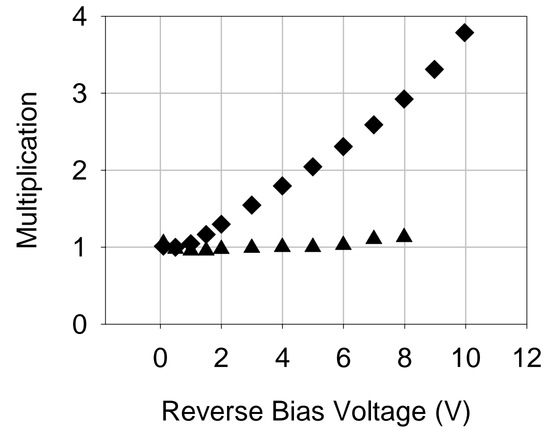

Figure 2: Multiplication results M_h (▲) and M_{mixed} (◆) for a nip APD with a 2µm thick intrinsic region

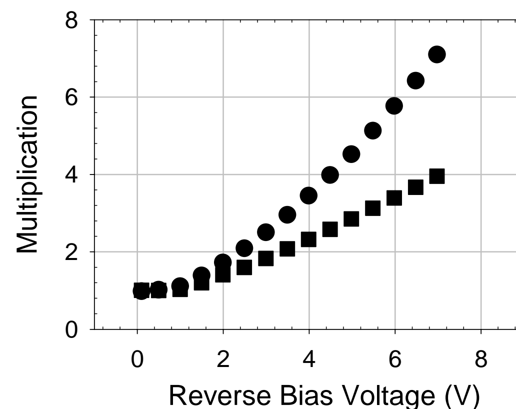

Figure 3: Multiplication results M_e (●) and M_{mixed} (■) for a pin APD with a 3.5µm thick intrinsic region

These are the first results to be reported showing room temperature multiplication in InAs pin and nip APDs. They clearly illustrate, from the near unity value of Mh in figure 2 for all biases, that the hole ionisation coefficient β is very low within the electric field range exercised during the measurement. For pure hole injection any multiplication must be initiated by impact ionisation of holes, and from the very low

multiplication measured it is clear that there is very little taking place. For the case of mixed injection in a nip APD however the measured multiplication is not near unity, indicating that electrons are able to impact ionise and give rise to multiplication. The results from a pin APD shown in figure 3 further confirm this trend, with moderate multiplication measured for the mixed injection condition, but the highest multiplication seen when the injection into the high field region is purely of electrons. This trend, seen on a range of pin and nip APDs indicates that α is much greater than β in InAs. It should be noted that this result is in contradiction to the only previously published experimental measurement of avalanche multiplication in InAs from Mikhailova et al., who reported that β was much greater than α at 77K [4].

The finding that α>>β is a significant one, as in III-V materials α is usually similar to β giving rise to high excess noise. This indicates that InAs is unique among the characterised III-V materials, being the only one to have one ionisation coefficient near zero (β) while the other (α) has a significant value. This is a highly desirable characteristic, similar to that reported for HgCdTe, and promises low excess noise in InAs APDs.

The multiplication measurements on pin APDs show another unique characteristic. In silicon and III-V APDs the width of the high field multiplication region must be reduced to increase the APD gain for a given applied reverse bias. Reducing the multiplication width has the effect of increasing the electric field, for a given bias, and hence because α and β are strongly dependant on the electric field, increasing the gain. An undesirable side-effect of increasing the electric field is a rise in the tunnelling current, which ultimately places a lower limit on the multiplication region width which can be used in practical APDs. The ionisation coefficients also converge as the electric field is increased, giving rise to an increase in the excess noise. In InAs pin APDs however a different relationship between the gain at a given reverse bias and the multiplication width was seen. This relationship can be seen in figure 4, which shows the multiplication measured for pure electron injection into three pin APDs, with different intrinsic region widths and hence different high field multiplication region widths. Here it can be seen that the multiplication is higher for a given bias in the APD with the largest multiplication width. This is thought to be a result of the single carrier nature of the multiplication and a weak dependence of α on the electric field. The relationship is expected to hold for thicker multiplication regions that those measured during this work, so long as the multiplication region has a low enough background doping concentration to be fully depleted.

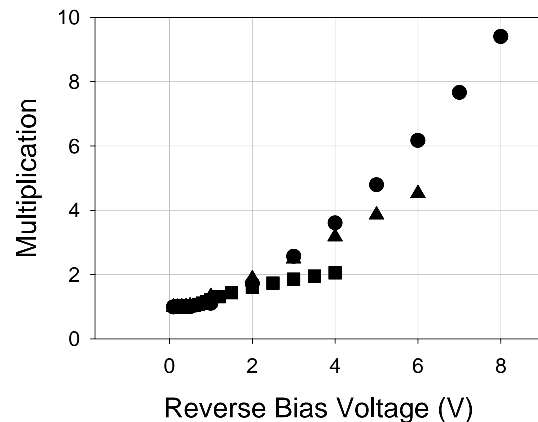

Figure 4: Multiplication results for pin APDs with intrinsic regions which are 3.5µm (●), 2µm (▲) and 1µm (■) thick

This is believed to be the first report of this counter normal dependence between the multiplication width and the APD gain for a given bias. The characteristic can be exploited to make InAs APDs with high gain at low reverse bias, ideal for use in FPAs and integration with ROICs, without the risk of tunnelling currents becoming significant as would usually be the case.

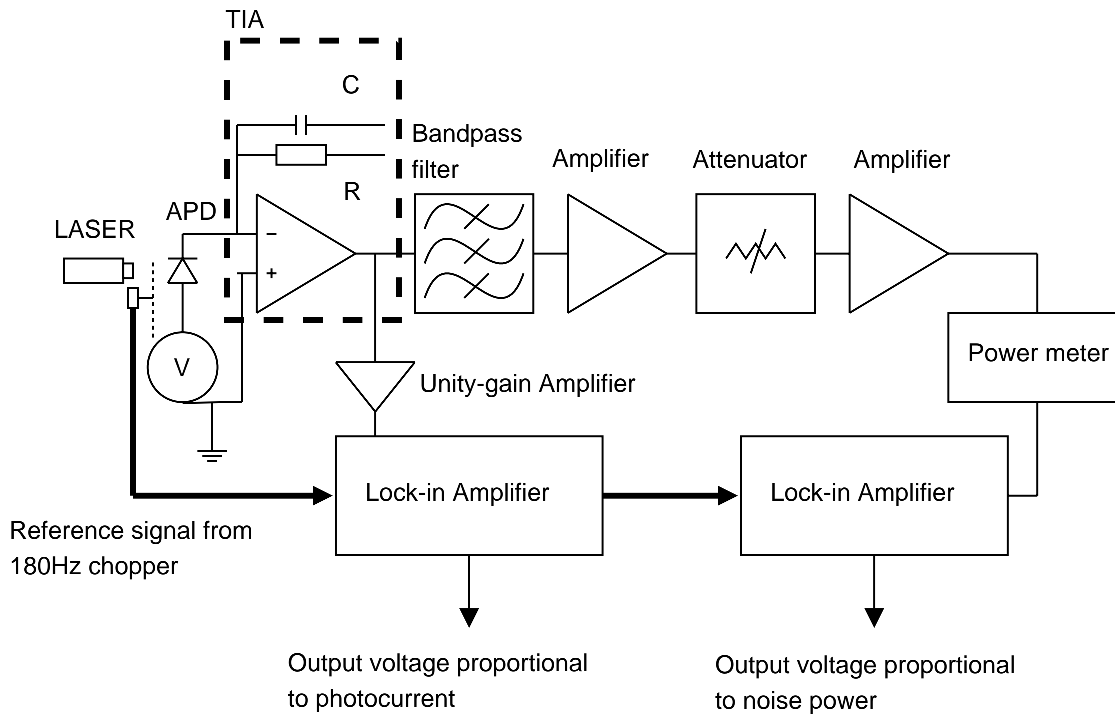

Figure 5: Set-up used for measuring excess multiplication noise

Measurement of Excess Noise in InAs APDs

To accurately measure the excess noise at room temperature a phase sensitive detection technique must again be used to distinguish between photocurrent and leakage current. A custom measurement circuit developed in house was used, this is shown in figure 5. The operation boundaries of this circuit placed a tighter restriction on the maximum tolerable leakage current during the measurement, compared to that for simple multiplication measurements. Due to this leakage current limit the bias range which could be exercised was restricted, and it was not possible to obtain any results from some of the layers.

The excess noise was measured on APDs fabricated from four layers, two pins and two nips. A typical result from one of the pin APDs layers, which benefited from the lowest leakage current allowing it to be tested across the widest bias range, is shown in figure 6, results obtained from the 3 other layers support this result.

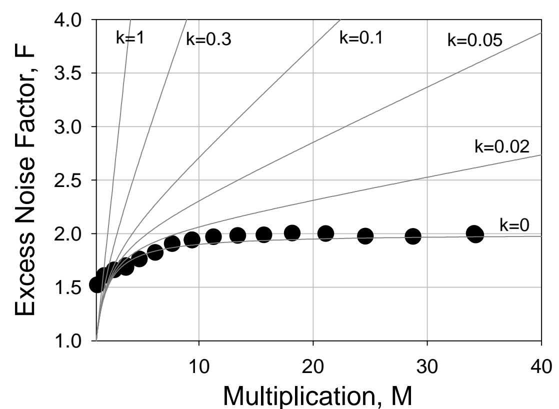

Figure 6: Excess noise result for a pin APD with 3.5µm thick intrinsic region (symbols). Lines show the ideal F vs. M relationships from the local model for different values of k.

As figure 6 shows the excess noise measured for the optimal pure electron

injection case was extremely low. The experimental results almost match the theoretically optimum k=0 case, confirming that β is indeed very low, or approximately equal to zero. This means that this InAs APD is acting in essentially the same way as the HgCdTe 'electron APDs' reported, with only impact ionisation of electrons contributing to the multiplication. This result is believed to be the lowest excess noise measured in a bulk III-V material.

Conclusions

The results from experimental measurements of multiplication and excess noise in InAs pin and nip APDs have been reported. The work presented includes a number of first observations and best performance results for the III-V material system. Of particular significance is the measurement of a single carrier type multiplication characteristic, confirmed by the measurement of excess noise matching the ideal k=0 condition in the local model. Aside from their scientific significance, the results show that InAs has material characteristics which allow excellent APDs to be made from it. Indeed in many aspects InAs APDs can match the theoretically optimal results until now only obtained from HgCdTe 'electron APDs'.

It is important to note that the work reported in this paper is concerned with the fundamental characterisation of a material, which has not until now been used in APDs. As such there remains a significant amount of development work to be carried out before the characteristics identified can be exploited in a commercial application. However the work undertaken has made a start at this development and the material characteristics discovered do indicate that there is the potential to make high performance APDs from InAs. These APDs would be well suited to FPA applications, where the standard III-V manufacturing requirements and good material uniformity would compliment the low voltage, extremely low noise, sensitivity enhancing gain identified here.

References

1. R.J.McIntyre, IEEE Trans. Electron Devices, **ED-13**, 164 (1966).
2. J.D.Beck, C.Wan, M.Kinch, J.Robinson, P. Mitra, R. Scritchfield, F. Ma and J. Campbell, Proceedings of SPIE **5564**, 44 (2004).
3. I.Baker, S.Duncan and J.Copley, Proceddings of SPIE **5406**, 133 (2004).
4. M.P.Mikhailova, M.M.Smirnova and S.V.Slobodchikov, Sov. Phys. Semicond., **10**(5), 509 (1976).
5. A.R.Marshall, C.H.Tan, J.S.Ng, J.P.R.David and M. Hopkinson, EMRS DTC 3rd Annual Conference Proceedings (2006).
6. A.R.Marshall, C.H.Tan, J.P.R.David, M.J.Steer and M. Hopkinson, EMRS DTC 4th Annual Conference Proceedings (2007).
7. A.R.Marshall, C.H.Tan, J.P.R.David, J.S.Ng and M. Hopkinson, Proceddings of SPIE **6740,** 67400H (2007).

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