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Extremely Low Excess Noise in InAs Electron Avalanche Photodiodes

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***Abstract*—Measurements of the avalanche multiplication noise in InAs p-i-n and n-i-p diodes at room temperature demonstrate unambiguously that the avalanche multiplication process is dominated by impact ionization of electrons. This results in the excess noise factor for electron initiated multiplication asymptotically approaching a maximum value just less than two and becoming virtually gain-independent for higher gains. Measurements for predominantly hole initiated multiplication show corresponding high excess noise factors suggesting the electron to hole ionization coefficient ratios are comparable to those reported for $Hg_{1-x}Cd_xTe$ electron avalanche photodiodes.**

***Index Terms*—Avalanche photodiodes (APDs), impact ionization.**

I. Introduction

PREVIOUS characterization of III–V semiconductors has shown that in general these materials are not ideally suited to high performance avalanche photodiode (APD) applications. An APD's avalanche gain is accompanied by an increase in noise, characterized by the gain-dependent excess noise factor F. Under the local model of impact ionization [1] to minimize F the ionization coefficients for electrons (α) and holes (β) should be as disparate as possible. Ideally either α or β should be equal to zero, such that the ionization coefficient ratio $k = \alpha/\beta$ or $k = \beta/\alpha$ also becomes zero, resulting in $F \sim 2$ at high gains. Unfortunately, most III–V materials exhibit an ionization coefficient ratio in the range $0.2 < k < 1$ for the field range in which practical APDs have been demonstrated [2], [3].

Extremely low excess noise, close to the lower limit predicted by the local model when only one carrier type undergoes impact ionization, has been observed in $Hg_{1-x}Cd_xTe$ diodes made from both short-wave infrared and mid-wave infrared sensitive compositions [4]. It would be useful if similar low noise behavior could also be found in the more widely used III–V material system. The first indication that this might be possible came from recent photomultiplication measurements which showed that avalanche gain in the III–V material InAs is dominated by electron impact ionization, with holes playing almost no part in the avalanche process [5]. The band structure of InAs has some similarities to that of $Hg_{1-x}Cd_xTe$ at the compositions for which low noise has been reported, with the first conduction band intervalley separations being two or more times the bandgap energy. This letter reports on a systematic study of excess noise undertaken on InAs diodes.

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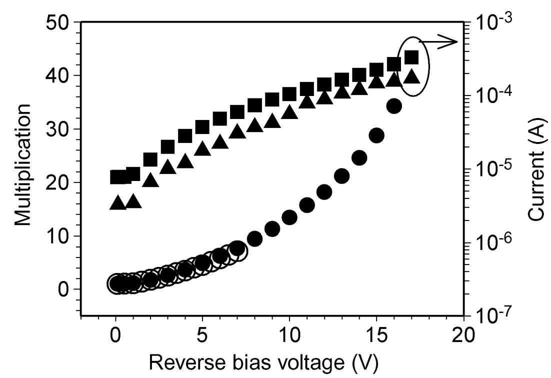

Fig. 1. Multiplication (●), reverse leakage current (▲), and photocurrent (■) measured on a 50-μm diameter P2 diode, under top illumination during noise measurement. Reported M_e (○) [5].

II. Experimental Detail and Results

InAs p-i-n and n-i-p diode structures were grown by molecular beam epitaxy and processed into mesa diodes as described in earlier work [5], [6]. Measurement results are reported for two p-i-n diodes with intrinsic region widths of 2.0 μm (P1) and 3.5 μm (P2) and a n-i-p diode with a 2.0-μm intrinsic region width (N1). The reverse leakage characteristics were strongly influenced by the fabrication process and in some cases revealed the presence of a significant surface component; however, the total leakage remained sufficiently low for the noise to be measured on P1, P2, and N1 diodes of 50- and 100-μm diameters and P2 diodes of 200-μm diameter. An example of the leakage current and photocurrent measured on a 50-μm diameter P2 diode is shown in Fig. 1. The noise power was measured using the custom built setup described by Lau *et al.* [7] capable of employing phase sensitive detection (PSD) to differentiate both the photocurrent from the leakage current and the photocurrent noise from the leakage current noise. The use of PSD enabled the measurement of multiplied photocurrent noise at room temperature, removing the complication of cooling to reduce the leakage current. This setup has been used successfully in the measurement of excess noise in other III–V materials in the presence of high leakage currents [8].

A primary aim of this work was to measure the excess noise in InAs under the two extreme conditions of pure electron initiated multiplication and pure hole initiated multiplication, F_e and F_h, respectively. For large area diodes, these conditions can be achieved using focused p-side illumination of p-i-n diodes and n-side illumination of n-i-p diodes, respectively, as described earlier [5]. In this work, laser wavelengths of 633 and 1150 nm were used to ensure absorption was, confined to the top p- and n-type cladding layers with the shorter wavelength being required where the cladding layer was thinner. However, to maintain the expected transimpedance amplifier gain response from the measurement circuit a lower limit was imposed on the acceptable dynamic resistance of the device under test, restricting the maximum size of diode which could be measured. This in turn made it difficult to constrain the laser spot on the mesa top, resulting in some illumination of the mesa sidewall and base.

The minority electron diffusion length in the p-type cladding layer of the p-i-n diodes characterized is expected to be greater than the cladding thickness [9]. Hence, when the p-i-n diodes were illuminated by a wavelength of light almost entirely absorbed in the p-type cladding layer, a substantial fraction of the photogenerated electrons would have diffused to the depletion region, giving the desired pure electron injection primary photocurrent. Indeed this was confirmed by the measurement of unity gain external quantum efficiencies (QEs) $\sim$15% under such conditions on large area P1 and P2 diodes, with the spot well focused on the mesa top. During the noise measurements on small area p-i-n diodes, some contamination of the intended electron injection will have occurred from carriers generated by light falling on the mesa sidewall and around the base. However, in relation to the substantial electron injection from the p-type cladding layer, the level of contamination was not thought to be significant. This expectation is supported by the similarity between the multiplication measured during noise measurements on small area p-i-n diodes and the multiplication due to pure electron injection (M_e) measured previously on large area diodes [5], as shown in Fig. 1.

In contrast to these results on p-i-n diodes, when large area n-i-p diodes were illuminated by a wavelength of light almost entirely absorbed in the n-type cladding layer the measured unity gain external QE was only $\sim$1%. This is thought to be due to the photogenerated minority holes having a short diffusion length in relation to the cladding thickness, so that only a small fraction reached the depletion region. In relation to this low level pure hole injection the contamination resulting from light falling on the mesa sidewall would have been more significant than for p-i-n diodes. Furthermore, minority electrons generated by light falling around the mesa base would have been collected through diffusion from a much larger volume than the corresponding holes were in p-i-n diodes. Hence a relatively higher degree of electron contamination, of the desired hole injection, was expected during the measurements on n-i-p diodes. This is confirmed by comparing the multiplication measured during noise measurements on small area n-i-p diodes with the multiplication due to pure hole injection (M_h) measured previously on large area diodes [5], as shown in Fig. 2. The higher multiplication factors measured at any given bias on the smaller diodes are regarded as evidence of contaminated injection, since with $\beta \sim 0$ there must have been significant levels of electron injection to initiate this multiplication.

The excess noise measured on InAs p-i-n diodes is shown in Fig. 3. The results are near, or a little below, the level predicted by the local model for $k = 0$. This confirms that avalanche multiplication in InAs is dominated by electron impact ionization, in the electric field range exercised, as was predicted

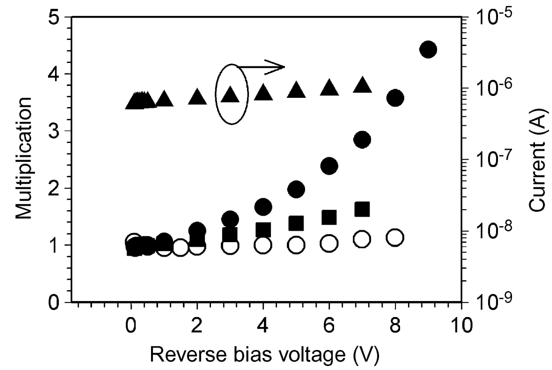

Fig. 2. Multiplication measured on 100-μm (■) and 50-μm (•) diameter N1 diodes and photocurrent (▲) measured on a 100-μm diameter N1 diode, under top illumination during noise measurement. Reported M_h (○) [5].

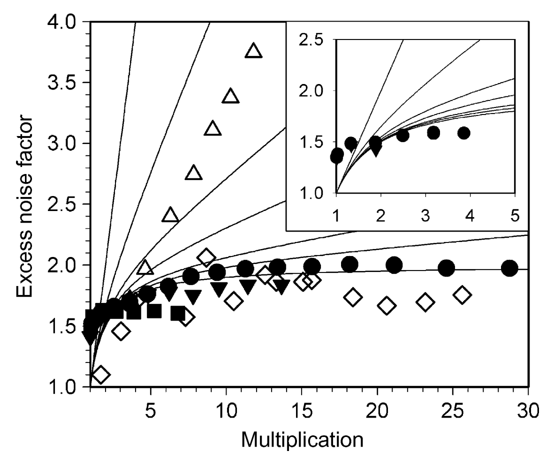

Fig. 3. Excess noise measured on P1 (inset) and P2 diodes with 50-μm (•), 100-μm (▼), and 200-μm (■) diameters under top illumination. F_e measured on an $Al_{0.48}In_{0.52}As$ $p-i-n$ APD with a 0.29-μm intrinsic width (△) and F_e reported by Beck [4] for a $Hg_{1-x}Cd_xTe$ APD (◇). Reference lines from the local model [1] with $k = 0, 0.01, 0.02, 0.05, 0.1, 0.3$, and 1.

from photomultiplication measurements [5]. Such an optimal excess noise characteristic has previously only been reported for $Hg_{1-x}Cd_xTe$ APDs and Fig. 3 includes one such result [4], also measured at room temperature. In contrast, the F_e characteristic for an $Al_{0.48}In_{0.52}As$ APD, also shown in Fig. 3 and broadly representative of state of the art telecommunications APDs, continues to rise with increasing gain in common with other reported III–V APDs.

Due to the significant electron contamination to the hole injection obtained in small diameter N1 diodes, the excess noise shown in Fig. 4 is not that due to pure hole injection, but rather that due to device diameter-dependent levels of mixed electron and hole injection. This is evident from the excess noise being significantly lower for the 50-μm diameter diodes than for the 100-μm diameter diodes. Were the purity of the hole injection to be improved, it would be expected that the excess noise would increase towards the local model prediction for $k = \infty$ in complement to the $k \sim 0$ characteristic for electron initiated multiplication. However, with pure hole injection unachievable, the $k \sim 0$ characteristics measured on the p-i-n diodes are most clearly corroborated by measurements on N1 diodes when the laser spot was positioned on the mesa sidewall and at its base,

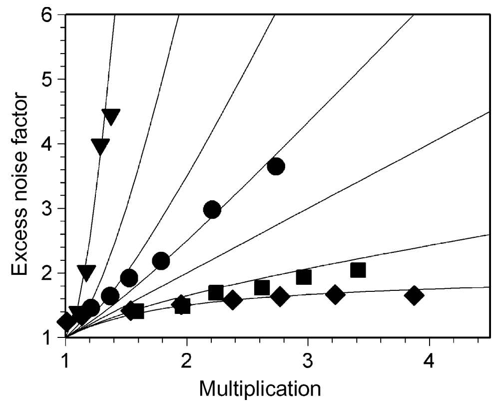

Fig. 4. Excess noise measured on N1 diodes with 50-μm (●) and 100-μm (▼) diameters under top illumination and on 50-μm diameter diodes for illumination on the mesa sidewall (■) and on the substrate next to it (⧫). Reference lines from the local model [1] with $k = 0, 0.3, 1, 2, 4, 10$, and 40.

the excess noise results for which are also shown in Fig. 4. Under these conditions the photocurrent injected into the depletion region contained a high proportion of electrons and the excess noise was again very low.

III. Discussion

It is evident that the excess noise results for InAs p-i-n diodes depend to a degree on the diameter of the measured diode with smaller diodes showing higher noise. This suggests that truly pure electron injection was not achieved on all diodes. Since the noise power is proportional to the square of the gain, the effects of low level contamination to the injected photocurrent are more pronounced in the excess noise than the photomultiplication. It follows that the excess noise F_e, to be expected with truly pure electron injection, is equal to or less than that measured on the largest diodes. In this case, it is necessary to offer an explanation as to how F_e for InAs APDs can fall below the lower boundary condition for excess noise in the local model, usually considered to be approximately accurate for APDs like P2 with thick multiplication regions. It has been shown [10] that where α and β have similar magnitudes, the local model is reasonable because the deadspace (d), not taken into account by the local model and equal to the distance traveled by a carrier while it obtains the threshold energy required before it can potentially undergo impact ionization, is relatively small compared with the mean ionization path length α^{-1}. Since there is less than one ionization event on average per carrier transit of the multiplication region in such cases below breakdown, the deadspace introduces little determinism into the ionization probability distribution within the multiplication width and hence has little effect on the excess noise. However, as k approaches zero, the injected carriers of the ionizing type must, for gains greater than two, traverse a deadspace and undergo impact ionization multiple times in a single transit of the multiplication region. In this case, α^{-1} must reduce to a fraction of the total multiplication region width and it is proposed that d can become sufficiently significant with respect to it in order to account for the sublocal model noise measured. An indication of the d to α^{-1} ratio required to reduce the excess noise when $k = 0$ can be found in the work of Saleh *et al.* [11], who showed that F asymptotically approaches 1.7 if $\alpha d = 0.1$.

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