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Excess Noise Characteristics of $Al_{0.8}Ga_{0.2}As$ Avalanche Photodiodes

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***Abstract*—The avalanche noise characteristics of $Al_{0.8}Ga_{0.2}As$ have been measured in a range of p-i-n and n-i-p diodes with i-region widths w varying from 1.02 to 0.02 μm. While thick bulk diodes exhibit low excess noise from electron initiated multiplication, owing to the large α/β ratio $(1/k)$, the excess noise of diodes with $w < 0.31$ μm were found to be greatly reduced by the effects of dead space. The thinnest diodes exhibit very low excess noise, corresponding to $k = 0.08$, up to a multiplication value of 90. In contrast to most III–V materials, it was found that both thick and thin $Al_{0.8}Ga_{0.2}As$ multiplication layers can give very low excess noise and that electrons must initiate multiplication to minimize excess noise, even in thin structures.**

***Index Terms*—$Al_{0.8}Ga_{0.2}As$, APD, avalanche excess noise, avalanche multiplication, impact ionization, indirect band gap.**

I. INTRODUCTION

THE ADVANTAGE of avalanche photodiodes (APDs) lies in their internal current gain mechanism which can improve the signal-to-noise ratio of photodetection systems [1]. However, this advantage also carries the penalty of excess noise arising from the stochastic nature of the avalanche process. The conventional local noise model [2] relates the avalanche noise of a material to its multiplication factor M, and the ratio of its hole to electron ionization coefficients $k = \beta/\alpha$. This model indicates that low excess noise can only be achieved in materials with very disparate ionization coefficients and that the carrier type with the larger ionization coefficient should be used to initiate multiplication. This is, however, only true for thick bulk structures and recent work [3]–[7] has shown that thin devices can also exhibit low excess noise, regardless of the initiating carrier type, owing to nonlocal effects.

APDs for use at the telecommunication wavelengths of 1.3 and 1.55 μm are InP-based, where InP and InGaAs are used as the multiplication and absorption media, respectively. GaAs-based APDs operating at these wavelengths are also now possible by using GaInAsN [8], which can absorb telecommunications wavelength light and is lattice-matched to GaAs. However, GaAs-based APDs operating at such long wavelengths will also necessarily require a separate avalanche region comprising the wider band gap GaAs or $Al_xGa_{1-x}As$ to reduce tunneling currents. We have recently shown that bulk $Al_{0.8}Ga_{0.2}As$ [9] has a large α/β ratio and exhibits low excess noise. Measurements carried out by Zheng *et al.* [10] also showed that the excess noise from electron initiated multiplication in $Al_{0.8}Ga_{0.2}As$ diodes with i-region thicknesses of 0.65 and 0.15 μm is lower than that from devices of similar thickness, but with aluminum compositions $x \leq 0.6$. These results suggest that $Al_{0.8}Ga_{0.2}As$ may constitute a suitable avalanche material. However, APD designs using $Al_{0.8}Ga_{0.2}As$ as the avalanche medium will require a better knowledge of the excess noise behavior of this material.

In this letter, we report measurements of the excess avalanche noise of a series of $Al_{0.8}Ga_{0.2}As$ homojunction p-i-n/n-i-p diodes with i-region thicknesses ranging from 1.02 to 0.02 μm. Excess noise characteristics under both electron and hole injection conditions from the same diode have also been measured using a heterojunction p-i-n structure. The excess avalanche noise behavior of $Al_{0.8}Ga_{0.2}As$ as a function of the carrier injection type and avalanche width are presented and discussed.

II. NOISE MEASUREMENT

The diodes in this work have been reported in [11]. The i–region thicknesses w of the homojunction p-i-n and n-i-p diodes are $w = 1.02, 0.31, 0.10, 0.03, 0.02\,\mu$m and $w = 1.01, 0.09\mu$m, respectively, while the heterojunction p-i-n structure has $w = 0.82\,\mu$m. The avalanche multiplication and excess noise were measured using the method described previously by Li *et al.* [4]. Photogenerated carriers were injected into the high field region of the diodes by focusing modulated light from a laser to a small spot onto the optical access windows. The noise measurement system utilizes two lock-in amplifiers to measure independently the photocurrent and the avalanche noise power of a diode. This phase-sensitive detection technique allows us to distinguish unambiguously the photocurrent and multiplication noise power from the components not arising from the modulated injection. The avalanche excess noise of the diodes was measured at a center frequency of 10 MHz and a noise effective bandwidth of 4.2 MHz.

Electrons (holes) are injected into the high field region of the homojunction p-i-n (n-i-p) diodes by illuminating the top p^+ (n^+) cladding with 442-nm wavelength light, which is strongly absorbed [12] in the 1-μm-thick top cladding. In the case of the heterojunction p-i-n structure, both pure electron and hole initiated multiplication are measured on the same diode by illuminating it from the top with 442- and 633-nm light, respectively. Measurements were also performed using 542-nm wavelength light [12] to investigate the multiplication characteristics under mixed carrier injection conditions.

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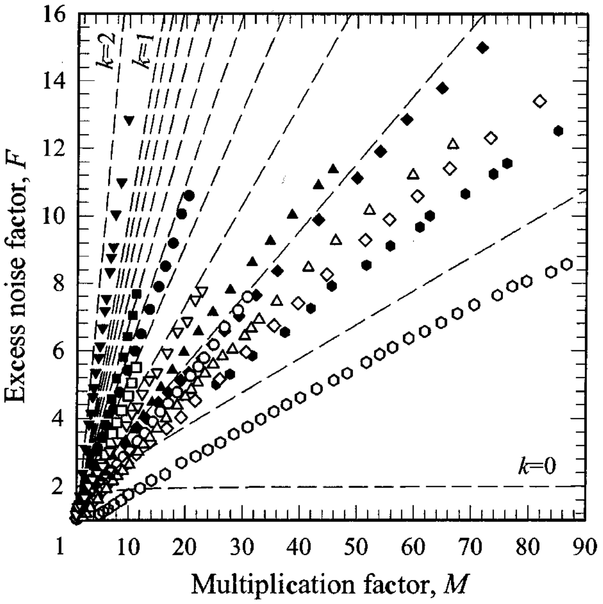

Fig. 1. Excess noise factor (F) versus multiplication factor (M) measured in $Al_{0.8}Ga_{0.2}As$ p-i-n diodes with measured w of 1.02 μm (○, ●), 0.82 μm (▽, ▼), 0.31 μm (□, ■), 0.10 μm (△, ▲), 0.03 μm (◇, ◆) and 0.02 μm (hexagons). Open and closed symbols are results obtained from pure electron and mixed carrier injection with 442- and 542-nm wavelength light respectively. Dashed lines are predictions from McIntyre's local model for $k = 0$ to 1 in steps of 0.1 and $k = 2$.

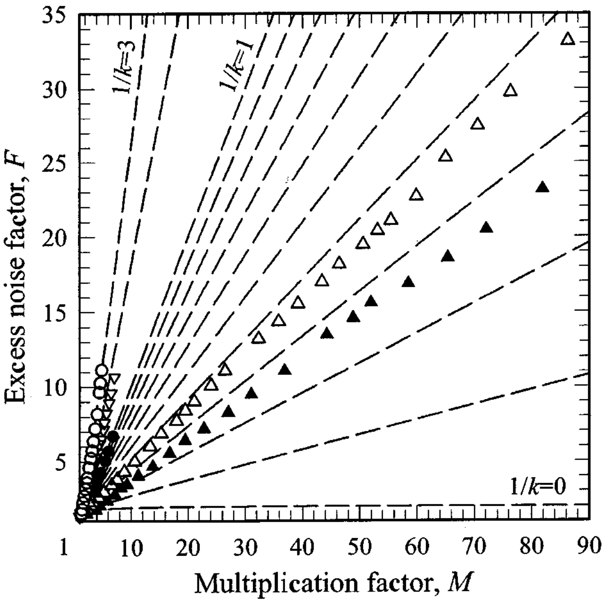

Fig. 2. Excess noise factor (F) versus multiplication factor (M) measured in $Al_{0.8}Ga_{0.2}As$ n-i-p diodes with nominal w of 1.01 μm (○, ●) and 0.09 μm (△, ▲). Open and closed symbols of the homojunction structures are results obtained from pure hole and mixed carrier injection with 442- and 542-nm wavelength light respectively. Excess noise from pure hole injection in the heterojunction structure with $w = 0.82$ μm (▽) was obtained with 633-nm light. Dashed lines are predictions from McIntyre's local model for $1/k = 0$ to 1 in steps of 0.1, $1/k = 2$ and $1/k = 3$.

The excess noise factor F was determined from the measured noise power using $F = i_{\mathrm{eq}}/M^2 i_{\mathrm{pr}}$, where i_{eq} is the equivalent photocurrent of a reference Si p-i-n diode that gives the same noise power as the diode measured and i_{pr} is the unmultiplied primary photocurrent [4]. The value of i_{pr} used was varied between 5 nA–1 μA to ensure that the circuit was not saturated during measurement. Several diodes across each layer were also measured and the results were found to be consistent and reproducible.

III. RESULTS

Figs. 1 and 2 show the measured F versus M of the p-i-n and n-i-p diodes under different injection conditions. The excess noise predictions from McIntyre's local model [2] are also plotted in these figures for comparison. These local noise predictions are given by

$$F(M) = k_{\mathrm{eff}}M + \left(2 - \frac{1}{M}\right)(1 - k_{\mathrm{eff}}) \qquad (1)$$

where $k_{\mathrm{eff}} = k$ for electron initiated multiplication and $k_{\mathrm{eff}} = 1/k$ for hole initiated multiplication. Hereafter, we use this k_{eff} (which may not correspond to the actual β/α ratio) as an indicator to represent approximately the measured excess noise behavior of a diode with M in order to enable a direct comparison between the excess noise of different diodes.

In Fig. 1, the excess noise for electron initiated multiplication in the p-i-n diodes increases from $k_{\mathrm{eff}} = 0.19$ to $k_{\mathrm{eff}} = 0.38$ when w is decreased from 1.02 to 0.31 μm. On the other hand, decreasing w further from 0.31 to 0.02 μm causes the k_{eff} to decrease from 0.38 to a very low value of 0.08. The excess noise in the thinner structures has been measured up to a multiplication of 90, as depicted in Fig. 1. In addition, the excess noise in the thinnest diode is, to the best of our knowledge, the lowest reported to date for III–V materials. The high multiplication values also show that the dark currents in the thin structures are very low, even when they are biased near V_{bd}. Mixed carrier injection using 542-nm wavelength light on the p-i-n diodes resulted in a larger excess noise for all thicknesses. In the thinnest diode with $w = 0.02$ μm, the excess noise increased by ~50%, with k_{eff} increasing from 0.08 to 0.13, when 542-nm light is used.

For hole initiated multiplication, the excess noise is reduced from $k_{\mathrm{eff}} = 2.76$ to $k_{\mathrm{eff}} = 1.69$ when w decreases from 1.01 to 0.82 μm, as shown in Fig. 2. The excess noise was further reduced for the $w = 0.09$-μm n-i-p diode, and is found to lie significantly below the $1/k = 1$ curve. Similar to the thinner p-i-n diodes, the excess noise in the thin n-i-p diode was also measured up to a multiplication of 90. When 542-nm light is used on the n-i-p structures, the excess noise decreases to $k_{\mathrm{eff}} = 0.87$ for the $w = 1.01$ μm diodes and $k_{\mathrm{eff}} = 0.26$ for the $w = 0.09$ μm diodes.

IV. DISCUSSION

Multiplication measurements indicate that the β/α ratio of $Al_{0.8}Ga_{0.2}As$ converges to 1 as the electric field increases [9], [11]. The excess noise characteristics of diodes with $w \geq 0.31$ μm are in qualitative agreement with the local noise model and reflect the converging β/α ratio in $Al_{0.8}Ga_{0.2}As$. In contrast, the excess noise in thinner diodes ($w < 0.31$ μm) reduces with decreasing w, regardless of the initiating carrier type. Furthermore, the measured excess noise corresponding to $1/k < 1$ obtained from hole injection (the carrier with the lower ionization

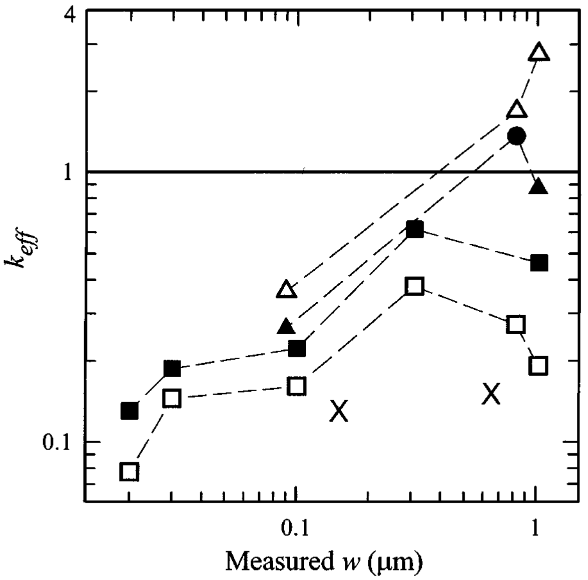

Fig. 3. k_{eff} versus measured w under pure electron (□) and pure hole (△) injection conditions for the range of diodes investigated. The k_{eff} values under mixed carrier injection for the homojunction p-i-n diodes (■), the homojunction n-i-p diodes (▲) and the heterojunction p-i-n diode (•) lay between those from pure carrier injection. The data obtained by Zheng *et al.* (X) [10] are also included for comparison. The dashed lines are drawn to aid visualization.

coefficient in $Al_{0.8}Ga_{0.2}As$) in the thin n-i-p structure cannot be explained in terms of the local noise model. This nonlocal behavior is similar to that observed in other materials [3]–[7], [10] and is attributed to the effect of dead space, the minimum distance a carrier must travel before it gains sufficient energy to impact ionize, becoming dominant.

A summary of the excess noise behavior of $Al_{0.8}Ga_{0.2}As$ is shown in Fig. 3, where the k_{eff} values under different carrier injection conditions are plotted against w. The k_{eff} values under mixed carrier injection were found to lie between those for pure carrier injection. As shown in Fig. 3, the results obtained by Zheng *et al.* [10] for $Al_{0.8}Ga_{0.2}As$ broadly corroborate our measurements. The slight discrepancy may be due to uncertainties in w or doping values. Fig. 3 suggests that, under electron initiated multiplication, an avalanche width of ~0.31 μm gives the highest excess noise and should therefore be avoided.

The change in excess noise for all diodes when the initiating carrier type becomes mixed is consistent with $\alpha > \beta$ and also with multiplication measurements [9], [12]. Unlike GaAs, the excess noise of thin $Al_{0.8}Ga_{0.2}As$ diodes with $w \leq 0.1$ μm changes significantly when injection becomes mixed. It is interesting to note that thin Si diodes [6] also exhibit similar characteristics. This indicates that it is still necessary for electrons to initiate multiplication in thin $Al_{0.8}Ga_{0.2}As$ diodes to minimize excess noise.

Our results suggest that very thin $Al_{0.8}Ga_{0.2}As$ multiplication layers can be used to achieve very high speed APDs [13] without limitation from tunneling current because of the large bandgap. In addition, using a very thin $Al_{0.8}Ga_{0.2}As$ multiplication layer also has the advantages of a very low avalanche excess noise and low voltage operation.

V. CONCLUSION

The avalanche excess noise characteristics of $Al_{0.8}Ga_{0.2}As$ have been determined in a series of p-i-n/n-i-p diodes over a wide range of avalanche widths, varying from 1.02 μm down to 0.02 μm. The thicker structures ($w \geq 0.31$ μm) exhibit excess noise characteristics in qualitative agreement with McIntyre's local model. As the avalanche width reduces below 0.31 μm the excess noise is found to decrease with decreasing w, regardless of initiating carrier type. This reduction in excess noise is attributed to the dead space effect which causes the avalanche process to become more deterministic in thin structures. Similar to Si, the multiplication process in thin $Al_{0.8}Ga_{0.2}As$ APDs must be initiated by electrons to minimize the avalanche excess noise. Our results suggest that very thin $Al_{0.8}Ga_{0.2}As$ avalanche widths can be use to achieve APDs with very high speed and very low excess noise, without the penalty of a large tunneling current.

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