# Avalanche Noise Characteristics of Single $Al_xGa_{1-x}As(0.3 < x < 0.6)$–GaAs Heterojunction APDs

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***Abstract*—Avalanche multiplication and excess noise have been measured on a series of $Al_xGa_{1-x}As$–GaAs and GaAs–$Al_xGa_{1-x}As$ ($x = 0.3, 0.45$, and $0.6$) single heterojunction $p^+$-i-$n^+$ diodes. In some devices excess noise is lower than in equivalent homojunction devices with avalanche regions composed of either of the constituent materials, the heterojunction with $x = 0.3$ showing the greatest improvement. Excess noise deteriorates with higher values of $x$ because of the associated increase in hole ionization in the $Al_xGa_{1-x}As$ layer. It also depends critically upon the carrier injection conditions and Monte Carlo simulations show that this dependence results from the variation in the degree of noisy feedback processes on the position of the injected carriers.**

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

## I. Introduction

Avalanche photodiodes (APDs) are key components of optical datacommunications systems because of their high sensitivity which results from their internal avalanche gain. However, this internal gain is provided via the stochastic process of impact ionization and therefore contributes its own excess noise.

It is well known that excess avalanche noise can be reduced below the level predicted by the local model of McIntyre [1] by reducing the avalanche region width $w$. This is because the dead space, the distance travelled by carriers before their ionization coefficient reaches equilibrium with the electric field, becomes a larger fraction of their mean ionization path lengths. The associated reduced uncertainty in ionization position reduces the fluctuations in multiplication and hence in excess noise.

The use of heterojunctions in avalanche regions as a means of reducing excess noise was first proposed by Chin *et al.* [2], who argued that that an electron (hole) which gains energy from a band-edge discontinuity would ionise with an enhanced ionization coefficient $\alpha(\beta)$. Choice of the layer heterostructure could therefore influence the value of $k = \beta/\alpha$ which controls the degree of noisy feedback processes [1]. Subsequent experiments by numerous authors variously supported [3]–[7] or disagreed [8]–[15] with these predictions. However, the most compelling evidence comes from Chia *et al.* [16], [17], who compared multiplication in both homojunction and single heterojunction $Al_xGa_{1-x}As$–GaAs $p^+$-i-$n^+$ diodes and found that the multiplication in heterojunction diodes, and hence the ionization coefficients, were not enhanced over those of corresponding homojunction diodes.

Herbert *et al.* [18] suggested that low avalanche noise might be achieved in a Si–SiGe MQW APD because of the localization of the ionization process by the heterostructure interfaces and the associated reduction in multiplication fluctuations. Campbell *et al.* [19]–[23] measured avalanche noise in submicron III-V heterojunctions and demonstrated impressive reductions in excess noise, in one case achieving an excess noise factor as low as $F = 1.5$ at a multiplication, $M = 10$ [19]. Modeling by Hayat *et al.* [24] later suggested that low noise could be achieved in heterojunction APDs without invoking the heterojunction-enhanced ionization coefficients proposed by Chin *et al.* [2], in agreement with Herbert *et al.* [18] and Campbell *et al.* [19]–[23].

However, the excess noise characteristics of heterojunction APDs have not shown sustained improvement after successive iterations of device design [19]–[23], despite the improved understanding of their behavior [24], [25]. This is partly because few experimental data exist to support design optimization. The purpose of the present work is to improve understanding of the excess noise behavior of heterojunction APDs by measuring excess noise in a systematic series of single heterojunction $Al_xGa_{1-x}As$–GaAs $p^+$-i-$n^+$ diodes with $x = 0.3, 0.45$, and $0.6$. Both type A heterojunctions, where the electrons are injected from the wider bandgap material, and type B heterojunctions, where electrons are injected the other way, are studied.

We also discuss why the simple Monte Carlo (SMC) model [25], and also the even simpler modified hard dead space model (MHDSM) of Hayat *et al.* [24] perform so well in predicting ionization behavior of heterojunction devices.

## II. Experimental Details

The devices used in this investigation were grown on GaAs substrates using MBE. Figs. 1 and 2 show the layer structure for type A and B devices, which were grown with $w = 0.1$ $\mu$m in all cases. Both the $Al_xGa_{1-x}As$ and GaAs layers were grown as 0.05 $\mu$m thick in all cases so as to examine the effects

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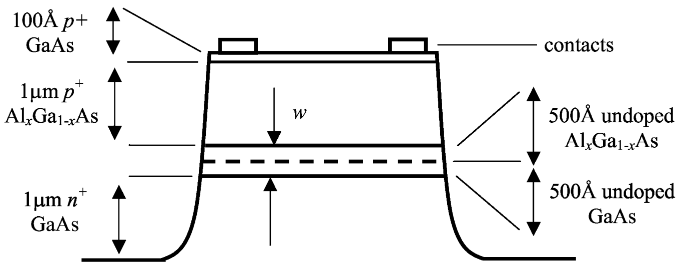


Fig. 1. Device structure for a type A, $Al_xGa_{1-x}As$–GaAs single heterojunction $p^+$-i-$n^+$ diode.

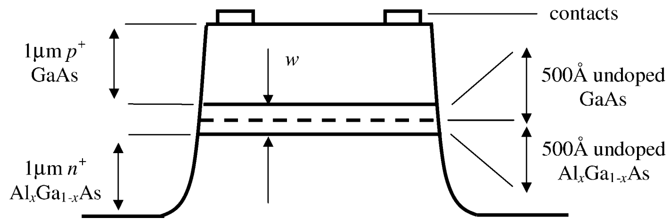


Fig. 2. Device structure for a type B, GaAs–$Al_xGa_{1-x}As$ single heterojunction $p^+$-i-$n^+$ diode.

of changing materials and injection conditions on roughly similar device designs. As the devices used in this work were designed for a systematic investigation, they are not expected to show optimal excess noise characteristics, which have been shown to be very sensitive to the layer structure [24], [25]. The layers were subsequently etched into mesa diodes of radius 50–400 $\mu$m using standard wet chemical etching. Annular top contacts were deposited to allow optical access.

The avalanche region thickness was estimated from capacitance–voltage (*CV*) measurements, and in some cases by SIMS measurements. The thickness of the undoped $Al_xGa_{1-x}As$ and GaAs layers in the avalanche region and also the aluminum mole fraction, $x$ were also estimated by X-ray diffraction spectroscopy. The results of these analyzes are summarized in Table I. Good agreement between *CV* and X-ray measurements was achieved in all cases. Device dimensions determined by X-ray diffraction spectrometry are used in preference here since *CV* analysis is rather insensitive to small changes in device structure. All devices showed sharp breakdown, indicating low defect density in the avalanche region. Breakdown voltage was measured on several devices from the same layer and was found to vary by less than 0.1 V, indicating good avalanche region uniformity.

Laser light of various wavelengths incident on the $p^+$ surface of the mesa generated photomultiplication characteristics corresponding to pure electron, mixed carrier, and, in some cases, pure hole injection, designated $M_e$, $M_{\rm mix}$, and $M_h$, respectively. The degree of optical absorption in the 1-$\mu$m $p^+$- cladding layer was estimated using the optical absorption coefficients of Monemar *et al.* [26]. The laser light was chopped mechanically and the resulting ac photocurrent was detected using a lock in amplifier in order to reject dc leakage currents. The increase in photocurrent with bias due to the increasing collection efficiency of the widening depletion region was corrected for by using a linear expression, after Woods *et al.* [27]

Table I
AVALANCHE REGION PARAMETERS DETERMINED BY X-RAY ROCKING DIFFRACTION SPECTROSCOPY AND *CV* MEASUREMENTS

| | X Ray | | | CV |
|---|---|---|---|---|
| **Device** | **$Al_xGa_{1-x}As$ Å** | **GaAs Å** | **Alloy composition, $x$** | **$w$ μm** |
| $x$ = 0.3, A | 480 | 495 | 0.29 | 0.099 |
| $x$ = 0.3, B | 452 | 500 | 0.29 | 0.102 |
| $x$ = 0.45, A | 520 | 500 | 0.45 | 0.098 |
| $x$ = 0.45, B | 490 | 505 | 0.47 | 0.107 |
| $x$ = 0.6, A | 548 | 500 | 0.6 | 0.106 |
| $x$ = 0.6, B | 524 | 429 | 0.64 | 0.106 |

Multiplication and noise measurements were performed simultaneously using a lock-in noise measurement system, operating at a center frequency of 10 MHz and with a bandwidth of 4.2 MHz, as used by Li *et al.* [28]. The excess noise factor $F$ was calculated from

$$F = \frac{i_{\rm eq}}{M^2 i_p} \tag{1}$$

after Bulman *et al.* [29], where $i_p$ is the unmultiplied primary photocurrent and $i_{\rm eq}$ is the photocurrent which flows in a Si $p^+$-i-$n^+$ diode operating below avalanche which produces the same noise power as the device under test. Measurements of both multiplication and noise were made on at least three devices for each structure to ensure reproducibility. Optical intensity was varied in some cases to check that device heating was not affecting the results.

## III. RESULTS

Measurements of $M_e$ on our diodes have been reported previously by Chia *et al.* [16], [17], and so only the results are summarized here; good agreement between the present measurements and those of Chia *et al.* [16], [17] are obtained in all cases.

Fig. 3 shows $M_e, M_{\rm mix}$, and $M_h$ for the type A, $x = 0.45$ diode resulting from excitation by laser light at wavelengths $\lambda = 442, 542$, and 633 nm, of which >98%, 83%, and 0% (i.e., absorbed in the GaAs layers), respectively, was estimated to be absorbed in the 1-$\mu$m $p^+$ $Al_{0.45}Ga_{0.55}As$ top cladding layer. Also shown is $M_e$ for the type B, $x = 0.45$ device resulting from laser light excitation at $\lambda = 542$ nm which was estimated to be >98% absorbed in the 1-$\mu$m $p^+$ GaAs cladding layer. Multiplication is plotted as $M - 1$ on a log scale to emphasise small values of multiplication.

At values of $M_e < 2$ the multiplication characteristic of the heterojunction device resembles that of a homojunction device composed of the material in the latter half of the avalanche region, in agreement with Chia *et al.* [16], [17]. These authors argued that this was because primary carrier ionization is postponed until the latter half of the avalanche region by the dead space, and that these carriers thereafter ionise at a rate corresponding to the local material. Later, detailed Monte Carlo simulations by Groves *et al.* [25] qualitatively supported these ar-

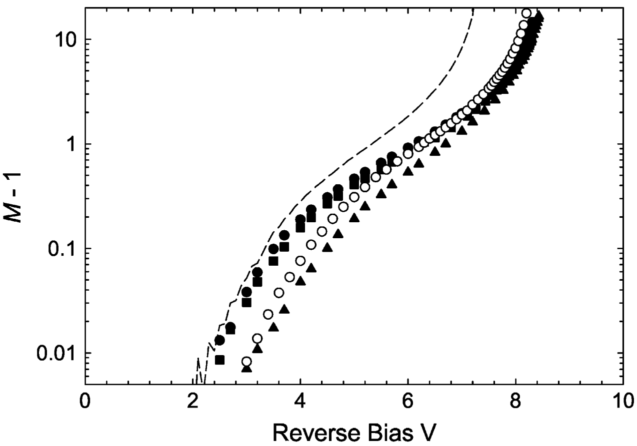


Fig. 3. $M_e$ (circles) and $M_{\rm mix}$ corresponding to 83% (squares) and 0% (triangles) optical absorption in the p$^+$ cap layer for the $x = 0.45$ type A device (solid) and also $M_e$ for the $x = 0.45$ type B (open circles) device. Also shown is $M_e$ for a $w = 0.1$ $\mu$m GaAs homojunction (dashed line).

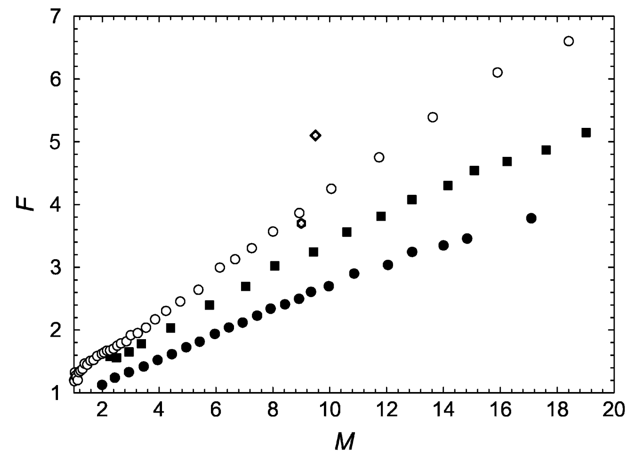


Fig. 4. $F_e$ (circles) and $F_{\rm mix}$ (squares), corresponding to 83% optical absorption of in the 1-$\mu$m cladding layer for type A (solid) and B (open) $x = 0.3$ devices. Also shown is $F_e$ when $M_e = 9$ and 9.5 for a $w = 0.1$ $\mu$m GaAs (hexagon) and $Al_{0.3}Ga_{0.7}As$ (diamond) homojunction p$^+$-i-n$^+$ diodes from Li *et al.* [28].

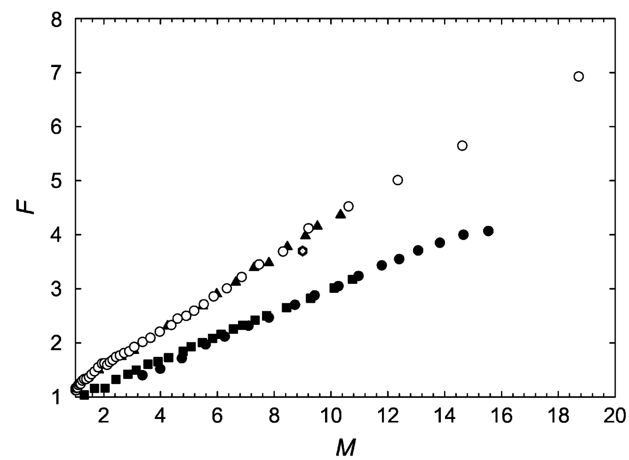


Fig. 5. $F_e$ (circles) and $F_{\rm mix}$ corresponding to 83% (squares) and 0% (triangles) for type A (solid) $x = 0.45$ device and $F_e$ corresponding to the type B $x = 0.45$ device (open circles). Same symbols as in Fig. 3. Also shown is $F_e$ when $M_e = 9$ for a $w = 0.1$ $\mu$m GaAs homojunction p$^+$-i-n$^+$ diode (hexagon) from Li *et al.* [28].

guments. As the field is increased, secondary carrier ionization sets in across the whole of the avalanche region at a rate corresponding approximately to that of the local material, so that the multiplication characteristic converges to an average of those for the corresponding devices formed from its constituent materials.

Multiplication in the type A device is seen to fall with decreasing purity of electron injection. This is because under conditions of pure electron (hole) injection, a portion of the large (small) bandgap $Al_{0.45}Ga_{0.55}As$ (GaAs) layer is unavailable for primary ionization, because of the effects of dead space. Consequently, with pure electron injection, injected electrons injected only miss out on the low ionization coefficient in the $Al_{0.45}Ga_{0.55}As$ layer, whereas under pure hole injection, holes injected from the bottom miss out on the higher ionization coefficient in the GaAs, yielding lower multiplication. This behavior of $M_e$ and $M_{\rm mix}$ seen in a type A devices and of $M_e$ in type B devices, shown in Fig. 3 for $x = 0.45$, was observed for all $x$.

Excess noise characteristics for single heterojunction $Al_xGa_{1-x}As$ GaAs, $x = 0.3, 0.45$, and 0.6 devices are shown in Figs. 4–6. The claims by Chin *et al.* [2], and by others [3]–[7] that heterojunctions could be used in avalanche regions to reduce excess noise by tailoring the ratio $k$ via the band-edge discontinuity, have not been borne out [8]–[17]. Indeed, increasing the aluminum fraction above $x = 0.3$ and hence band-edge discontinuity actually increases excess noise, as shown in Figs. 4–6.

Figs. 4–6 also show that pure electron injection yields lower excess noise for a type A structure than for a type B device. The reason for this is examined with the help of the Monte Carlo model used previously by Groves *et al.* [25]. The multiplication and noise characteristics for $Al_{0.6}Ga_{0.4}As$ GaAs type A and B diodes corresponding to the measured devices are simulated and the resulting noise characteristics are shown in Fig. 6. The simulations correctly predict higher noise for pure electron injection in the type B than in the type A structure. Qualitative fits to measured multiplication characteristics (not shown) were also achieved. It should be noted that the fits to excess noise would have been better had an ideal p$^+$-i-n$^+$ profile not been assumed. In reality, the depletion region extends into the heavily doped cladding layers [31], which effectively widens the depletion region and thus increases excess noise [32]. We make this simplifying assumption, as our aim is only to show qualitatively why the excess noise characteristics for these devices are different.

It is perhaps not surprising that the SMC model gives reasonable agreement despite its simplicity and our additional simplifying assumption. The model gives good agreement with the ionization path length pdf calculated from a full band model [33] and so can accurately reproduce multiplication and noise in homojunction structures [34]. Since this model gives quantitative predictions of the ionization properties of homojunction devices for each component material it can also be expected to work in heterojunction structures, provided the physics of the heterojunction is treated suitably. Ma *et al.* [21] used a three-valley Monte Carlo model to show that heterojunction APD performance was relatively insensitive to effects quantum mechanical tunnelling and the band line-up scheme at the heterojunction interface.

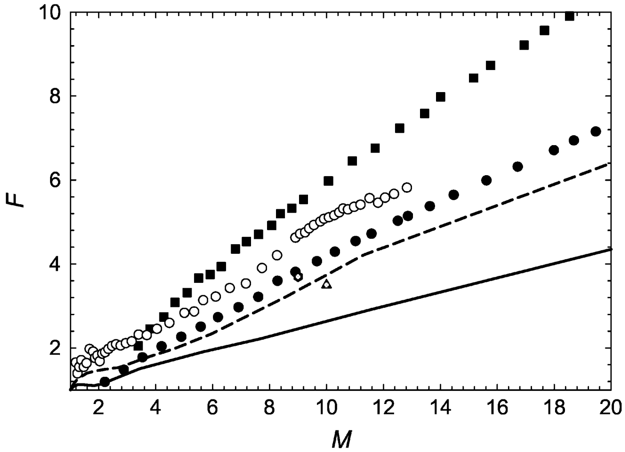


Fig. 6. Measured (symbols) $F_e$ (circles) and $F_{\rm mix}$ (squares), estimated to correspond to 80% optical absorption in the 1-$\mu$m cladding layer, for type A (solid) and B (open) $x = 0.6$ devices. Also shown are simulated (lines) $F_e$ for type A (solid) and B (dashed) devices, together with $F_e$ when $M_e = 9$ for $w = 0.1$ $\mu$m GaAs (hexagon) from Li *et al.* [28] and $M_e = 10$ for $w = 0.09$ $\mu$m $Al_{0.6}Ga_{0.4}As$ (triangle) homojunction p$^+$-i-n$^+$ diodes from Tan *et al.* [30].

The MHDSM of Hayat *et al.* [24] was also used to predict the multiplication and excess noise characteristics of the type A and B $Al_{0.6}Ga_{0.4}As$–GaAs structures measured here using modeling parameters deduced from Groves *et al.* [25]. The MHDSM employs a displaced exponential model for ionization path length pdf in a recurrence equation technique to calculate multiplication and noise. The exponential decay in the pdf is characterized by the enabled ionization coefficient in the local material and is displaced from the origin by a dead space. This is calculated as the distance required to reach the local hard threshold by ballistic transport in the electric field and band edge structure encountered on the way to ionization. The excess noise characteristics (not shown here) show a similar quality of fit to experiment as the SMC model, with slight variations depending on how the model parameters for GaAs or $Al_{0.6}Ga_{0.4}As$ are calculated (the SL and LD parameters in [25]). The quality of fit is surprisingly good, considering the simplicity of the model, which ignores diffusion in both position and energy and also energy losses due to phonon scattering. This is because the pdf for ionization equilibrates to the local material value quickly after crossing a heterojunction, as shown in Figs. 4 and 5 in [25]. Hence, the assumption of Hayat *et al.* [24] that the enabled ionization coefficient [35] depends only upon the local material and electric field is substantially correct, at least in the case of $Al_{0.6}Ga_{0.4}As$–GaAs heterojunctions. The soft ionization path length pdf resultant from diffusion in energy can be imitated within the MHDSM by softening the ionization threshold energy, although this has been shown to have little effect upon the model predictions [36], [37].

The distributions of electron initiated and hole initiated ionization events in the type A and B $Al_{0.6}Ga_{0.4}As$–GaAs devices simulated using SMC at $M_e \approx 10$ are shown in Figs. 7 and 8, respectively. It can be seen that there is more hole initiated ionization in the type B device than in the type A device simply because the accumulated holes drift toward the lower bandgap GaAs layer, while corresponding converse arguments apply for electrons. Consequently, there is more reliance on noisy feedback ionization in the type B structure to provide multiplication. Fig. 9 shows the distribution of multiplication values for

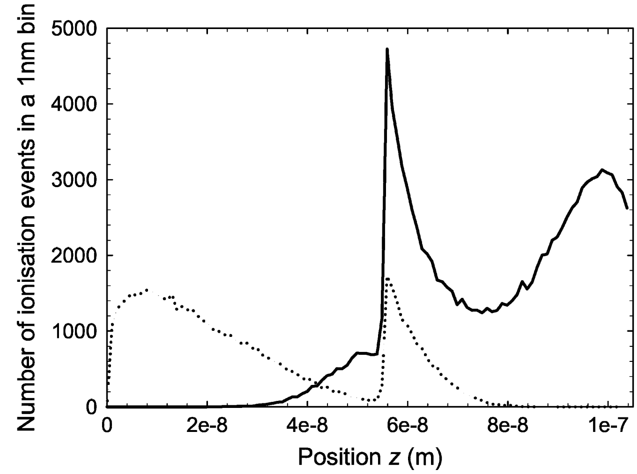


Fig. 7. Ionization position distribution at $M_e \approx 10$ for electron (solid) and hole (dotted) initiated ionization events after 20 000 trials in a type A $Al_{0.6}Ga_{0.4}As$–GaAs diode simulated by SMC. Electrons are injected at $z = 0$, the heterojunction is at $z = 0.0548$ $\mu$m and $w = 0.1048$ $\mu$m.

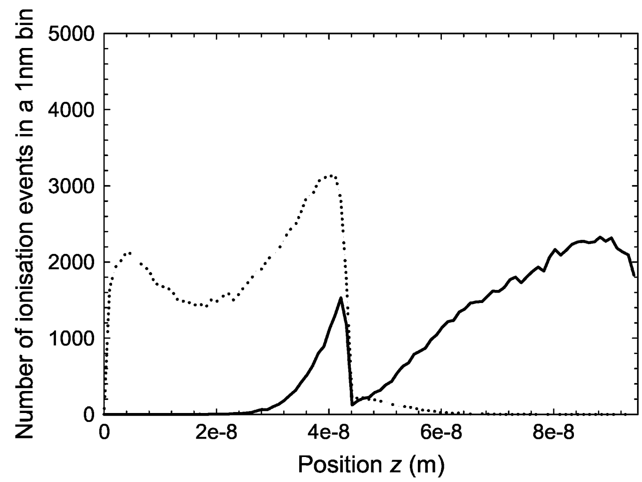


Fig. 8. Ionization position distribution at $M_e \approx 10$ for electron (solid) and hole (dotted) initiated ionization events in a type B $Al_{0.6}Ga_{0.4}As$–GaAs diode simulated by SMC. Electrons are injected at $z = 0$, the heterojunction is at $z = 0.0429$ $\mu$m and $w = 0.0953$ $\mu$m.

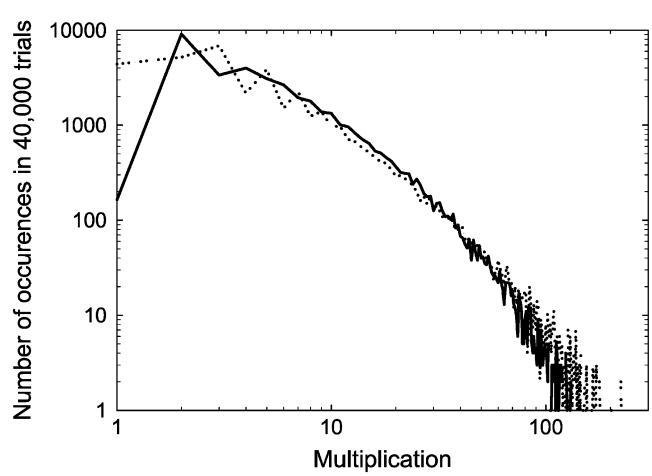


Fig. 9. Multiplication distribution logged from 40 000 trials for a type A (solid) and B (dotted) $Al_{0.6}Ga_{0.4}As$–GaAs devices at $M_e \approx 10$.

the type A and B $Al_{0.6}Ga_{0.4}As$–GaAs structures at a mean multiplication, $M_e \approx 10$ for 40 000 trials. The increased reliance on feedback events for the type B device clearly results in more long multiplication chains than in the type A device. Further simulations, not reported here, show that the multiplication distributions shown in Fig. 9 and corresponding noise figures are not sensitive to variations in the thickness of the layers within the avalanche region, such as are normally encountered in the growth process.

Indeed, the type B structure operates in a manner converse to that of the low noise, type A devices reported in the literature [24], [25]. In type A structures, the high bandgap layer serves two purposes, to inject the electrons hot from the high bandgap into the low bandgap layer and to suppress feedback hole ionization, both of which reduce noise. In the type B device, hole feedback ionization occurs freely in the small bandgap GaAs injector layer and, furthermore, primary electron ionization is suppressed when these carriers reach the large bandgap $Al_{0.6}Ga_{0.4}As$ layer.

Excess noise characteristics resulting from mixed injection in the $x = 0.3$ and $0.45$ type A devices are intermediate between those of pure injection in the type A and type B devices. The excess noise for the $x = 0.6$ type B device, shown in Fig. 6, is lower than that for mixed injection in the type A device. However, this may be because the type B device is thinner and so will show more pronounced dead space effects. The progressive increase in the excess noise with $x$ may also be due to the device design becoming less optimal.

It is also useful to ask whether the excess noise in heterojunction APDs is lower than in a homojunction device of similar width composed of either of the constituent materials. The excess noise results for other $w = 0.1$ $\mu$m $x = 0, 0.3$, and $0.6$ homojunction diodes taken from the literature are also shown in Figs. 4–6. Evidently, in some cases heterojunction devices do indeed give excess noise lower than for an equivalent homojunction. The improvement is greatest for the $x = 0.3$ device and deteriorates with increasing $x$ until $x = 0.6$, when the heterojunction and homojunction excess noise characteristics are broadly similar (note that the $Al_{0.6}Ga_{0.4}As$ homojunction has a multiplication region width $w = 0.09$ and so is slightly more subject to dead space effects).

The increase in noise with aluminum mole fraction can be explained in terms of hole ionization in the $Al_xGa_{1-x}As$, whose ionization coefficient was calculated for the type A devices using the results of Plimmer *et al.* [37] at the field required to obtain $M_e = 10$, and is found to increase by 12% as $x$ increases from 0.3 to 0.6. This increase in $\beta$ is counter-intuitive, since ionization coefficients at a fixed field are known to decrease with $x$ [37]. However, the electric field must be increased as $x$ increases to maintain the same value of $M$ and moreover the electric field difference between the $Al_xGa_{1-x}As$ and GaAs layers also increases with $x$, resulting in a net increase in $\beta$. Since the likelihood of noisy feedback processes increases with $\beta$ it follows that the noise performance of the type A $Al_xGa_{1-x}As$–GaAs heterojunction devices deteriorates with increasing $x$ for the device design considered here. It appears that optimal low noise single heterojunction APDs contain a smaller amount of $Al_xGa_{1-x}As$ as $x$ is increased, since this reduces the operating field and consequently the degree of hole ionization occurring in the $Al_xGa_{1-x}As$ layer [25]. Type A $Al_{0.6}Ga_{0.4}As$–GaAs heterojunction APDs with smaller proportions of $Al_{0.6}Ga_{0.4}As$ in their avalanche regions than the present devices have been modeled and are predicted to give even lower noise [24], [25].

## IV. Conclusion

Excess noise and multiplication have been measured on a systematic series of $w = 0.1$ $\mu$m $Al_xGa_{1-x}As$–GaAs type A and B heterojunction $p^+$-i-$n^+$ diodes with $x = 0.3, 0.45$, and $0.6$.

The noise characteristics of the heterojunction APDs were found to depend critically upon the injection conditions, with lowest noise corresponding to pure electron injection into a type A device for all values of $x$. Monte Carlo modeling showed that the increased importance of feedback ionization in the type B structures served to increase the noise.

In some cases the excess noise of the heterojunction devices was lower than for homojunction devices composed of either of the constituent materials. Noise was shown to increase with increasing aluminum mole fraction, in disagreement with the arguments of Chin *et al.* [2]. The increase in noise is explained in terms of an increase in hole ionization in the $Al_xGa_{1-x}As$, which in turn leads to increased feedback and consequently to higher noise.

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