Avalanche Multiplication Noise in GaN p–n Junctions Grown on Native GaN Substrates

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GaN p–n junction diodes grown on native GaN substrates have been fabricated and characterized. The devices exhibit a positive temperature coefficient of breakdown obtained from variable temperature current–voltage measurements, confirming the impact ionization avalanche. The low-frequency noise characteristics of these devices have been measured under forward and reverse bias conditions. The forward bias noise spectra are dominated by the 1/f noise, and the current spectral density is proportional to $I^{1.6}$. Under reverse bias, the noise spectra show 1/f noise at reverse biases below the avalanche threshold. However, at reverse biases in the avalanche regime, the multiplication noise overpowers the 1/f noise, resulting in a white noise spectrum. To further characterize the avalanche process, the excess noise factor, $F$, is obtained from the measured noise spectra of diodes biased in reverse avalanche. For the case of pure hole injection (achieved by incorporating a thin pseudomorphic In$_{0.07}$Ga$_{0.93}$N layer at the cathode of the device and illuminating with 390 nm UV light), a low excess noise factor is achieved. The impact ionization ratio $\alpha/\beta$ extracted from the multiplication noise ranges from 0.07 to 0.38 over the electric field ranging from 2.8 to 3.7 MV cm$^{-1}$, consistent with the impact ionization coefficients reported previously using the photomultiplication method.

1. Introduction

GaN is attractive for high-power and high-frequency applications because of its high critical electric field and high electron saturation velocity. The critical electric field is related to the onset of avalanche breakdown due to impact ionization, which puts an upper limit on the reverse blocking voltage. Recent p–n diode results on bulk GaN substrates have shown the performance approaching material limits. Detailed impact ionization data in low defect density GaN is needed for device design and applications. Previous reports of the impact ionization coefficients for electrons and holes in GaN p–n junctions grown on single-crystal bulk GaN substrates showed significant asymmetry between the coefficients for electrons and holes. In applications, this asymmetry can significantly impact the excess noise in avalanche photodiodes (APDs) and the performance of impact ionization avalanche transit time diodes (IMPATTs).

Multiplication noise arises from the statistical nature of the avalanche process. It is determined by the impact ionization coefficients of electrons and holes, and by the type of carriers injected into the avalanche region. Therefore, multiplication noise can be used as another method to evaluate the ratio of impact ionization coefficients of electrons and holes. By measuring the noise characteristics of GaN p–n diodes, additional understanding of the details of impact ionization can be obtained. In addition, noise measurements also serve as a valuable diagnostic tool for quality, reliability, and details of defects and carrier dynamics in electronic and optoelectronic devices. Previous studies on noise characteristics in GaN p–n junctions have been limited to devices grown on foreign substrates with large dislocation densities.

In this article, we report the first experimental low-frequency avalanche noise measurements of low dislocation density GaN p–n junction diodes grown on bulk GaN substrates. The excess noise characteristics of the GaN p–n diodes for pure hole injection using 390 nm UV light are also reported. In addition, the ratio of the impact ionization coefficients $(\alpha/\beta)$ is obtained from multiplication noise measurements and compared with results obtained from photocurrent-method extraction of the impact ionization coefficients.

2. Device Structure and Fabrication Process

Figure 1 shows a schematic cross-section of the device structures. Figure 1a shows the baseline GaN p–n diode. Grown on 2-in. bulk GaN substrates by metal-organic chemical vapor deposition, the structure (from top to bottom) consists of a 10 nm p$^{+}$ contact layer, a 100 nm p-GaN layer (Mg: $2 \times 10^{19}$ cm$^{-3}$), a 250 nm n-GaN drift layer (Si: 2$\times$10$^{16}$ cm$^{-3}$), and 2 $\mu$m n$^{+}$-GaN layer (Si: 4$\times$10$^{18}$ cm$^{-3}$). Figure 1b shows the GaN p–n diode structure with an InGaN layer used for hole injection in the excess noise characterization study. This GaN p–n diode has a similar...
structure as Figure 1a, except that an 80 nm undoped pseudomorphic In\textsubscript{0.07}Ga\textsubscript{0.93}N layer has been inserted on the cathode side, and the n-GaN drift layer thickness has been reduced to 150 nm. The In\textsubscript{0.07}Ga\textsubscript{0.93}N layer is designed to produce pure hole injection under 390 nm UV illumination because this wavelength is beyond the absorption edge of GaN. With pure hole injection, the ratio of the impact ionization coefficients can be directly estimated by measuring the multiplication noise. Because the InGaN layer is adjacent to the cathode contact layer and is well away from the metallurgical junction, it has no effect on the high-field performance of the device. For both structures, Ni/Au anode ohmic contacts to the p-GaN and Ti/Al/Au ohmic back cathode contacts were used. The top p-contact was ring shaped to allow UV illumination. Edge termination with N-ion implantation was used to suppress edge effects. The fabrication process details have been reported in the study by Cao et al.\textsuperscript{[5]}

### 3. Noise Characteristics for Baseline p–n Diode

The forward and reverse current–voltage characteristics of a typical baseline device (Figure 1a) at room temperature are shown in Figure 2. As shown in Figure 2a, the device turns on around 3.3 V (current density of 100 A cm\textsuperscript{-2}). An ideality factor, \( n \), of approximately 2 is measured from 2.1 to 2.6 V, indicating Shockley–Read–Hall (SRH) recombination-dominated current; \( n \) drops to 1.65 at a bias of 2.9 V, indicating the onset of diffusion-dominated current. As shown in Figure 2b, the devices break down around 99.7 V (current density of 100 A cm\textsuperscript{-2}) at room temperature. The inset in Figure 2b shows the temperature-dependent reverse bias characteristics for the device. As can be seen, the breakdown voltage increases from 99.7 to 102.6 V as the temperature increases from 25 to 175 \( ^\circ \)C. The breakdown voltage has a positive temperature coefficient (+1.98 \( \times \) 10\textsuperscript{-4} K \textsuperscript{-1}), which is a signature of avalanche breakdown.

The noise characteristics have been measured using a Keysight E4727A low-frequency noise analyzer, a Cascade probe station, and a Keysight B1500A semiconductor parameter analyzer to bias the devices. The noise floor of the setup, determined by the low-frequency noise analyzer, is around 10\textsuperscript{-28} A\textsuperscript{2} Hz\textsuperscript{-1}.

Figure 2a shows the measured dark current noise spectra of a typical 100 \( \mu \)m radius device under several forward biases from 1 Hz to 100 kHz. As can be seen from the spectra, 1/f noise dominates in forward bias and the noise increases with increased bias current. Figure 2b shows the noise’s dc current dependence for the diode at a frequency of 30 Hz. The observed trend shows that the noise current spectral density, \( S_I \), is proportional to \( I^{1.6} \) for currents spanning more than four orders of magnitude, from 26 nA to 390 \( \mu \)A. This dependence is in agreement with the 1/f noise theory in APDs, where the current dependence (slope in Figure 3b) lies between 1 and 2. The slope is related to minority carrier lifetime and contact recombination velocity. For a long-base diode at a modest current density, \( S_I \sim I \); for a diode dominated by series resistance, a proportionality \( S_I \sim I^2 \) is expected.\textsuperscript{[13,14]}

Figure 3a shows the measured current noise spectral density from 10 Hz to 1 MHz as a function of reverse bias current, corresponding to the reverse bias voltages (red points) shown.
on the current–voltage characteristic in Figure 4b. As can be seen, the noise spectra is very different from those in forward bias. The 1/f-to-white noise corner frequency (i.e., the frequency at which extrapolations of the white and 1/f noise components intersect) drops with increasing reverse bias. For reverse biases below the onset of avalanche breakdown (small reverse current), 1/f noise dominates and no excess multiplication noise can be observed. As the reverse bias is increased to the onset of avalanche, the noise is observed to increase, but (unlike in forward bias) the spectral shape also changes, transitioning to a white noise spectrum. When the reverse bias is well into the avalanche region, the noise spectrum is white and no 1/f noise can be observed. This is consistent with multiplication noise in avalanche breakdown.

Figure 4c shows the measured noise power spectral density as a function of the reverse current at 1.6 kHz (in the white noise regime above the corner frequency), along with a comparison of the shot and thermal noise contributions. As shown in Figure 4c, the measured noise level is more than two orders of magnitude larger than the thermal noise and shot noise, and increases rapidly with current, which is a signature of avalanche multiplication noise. The avalanche multiplication noise $S_{M}$ is defined as

$$S_{M} = 2qIM^2F$$

where $q$ is the electron charge, $I$ is the bias current, $M$ is the multiplication gain, and $F$ is the excess noise factor. To further characterize the excess noise factor, GaN p–n diodes with a thin pseudomorphic \(\text{In}_{0.07}\text{Ga}_{0.93}\text{N}\) layer (Figure 1b) were fabricated and measured in the dark and under 390 nm UV illumination.

4. Multiplication Noise Characterization Using p–n Diode with InGaN Layer

Figure 5a shows the reverse bias dark IV characteristics of a GaN p–n diode (100 μm radius) with InGaN cathode side hole
injection layer. The diode breaks down at 84.7 V (current density of 1 A cm$^{-2}$) at room temperature. This is lower than the baseline p–n diode due to the thinner n$^-$ drift layer (150 vs 250 nm). Figure 5b shows the measured dark noise spectra from 10 Hz to 1 MHz as a function of reverse bias current, corresponding to the reverse bias voltages (red points) shown in Figure 5a. The dark noise spectra show similar trends as the baseline diodes without InGaN: 1/f noise dominates when the reverse bias is well below the avalanche region, and no white spectrum can be observed, whereas when the reverse bias approaches the avalanche breakdown region, white avalanche noise dominates the higher frequency region.

Representative measured reverse bias current–voltage curves of a GaN p–n diode (100 μm radius) with an InGaN layer in the dark and under 390 nm UV illumination are shown in Figure 6a. A 390 nm UV light-emitting diode (LED; 2 mW cm$^{-2}$) was used to generate the holes in the buried In$_{0.07}$Ga$_{0.93}$N layer. Because this wavelength is beyond the absorption edge of GaN, it creates pure hole injection from the holes that are photogenerated in the InGaN. The “shoulder” in the IV curve under illumination is due to the polarization-induced barrier at the n$^-$-GaN/In$_{0.07}$Ga$_{0.93}$N interface. As the reverse bias increases, the barrier flattens out and the photocurrent increases. When the reverse bias increases further, the multiplication process starts and both the photocurrent and dark current increase sharply.$^{[5]}$ The inset of Figure 6a shows the multiplication gain $M$ for pure hole injection. It should be noted that the InGaN layer is well away from the metallurgical junction, and is therefore not subject to large electric fields.

Figure 6b shows the measured noise spectra of the diode with the InGaN hole injection layer in the dark and under 390 nm UV illumination at different reverse biases. Below breakdown, the device acts as a conventional photodiode: 1/f noise dominates in the dark and under 390 nm UV illumination. As the reverse bias increases to the breakdown region, under 390 nm UV illumination, the photomultiplication gain introduces increased noise and the 1/f-to-white noise corner frequency (defined as the frequency at which extrapolations of the white and 1/f noise components intersect) decreases compared with the dark condition.

The measured current noise spectral power density $S_I$ can be described as a combination of 1/f noise and multiplication noise.$^{[12,13]}$
where $S_{1,M}$ is the noise spectral power density of the multiplication noise in Equation (1), and $S_{1,1/f}$ is the $1/f$ noise spectral power density in Equation (3). $I$ is the bias current of the device, $f$ is the frequency, and $A$ is the magnitude of the noise and depends on the device geometry and the quality of the device material. The coefficients $x$ and $y$ characterize the $1/f$ noise dependence on bias current and frequency, respectively. $x$ is typically between 1 and 2, whereas $y$ is typically around 1 for $1/f$ noise.[13,14] The measured noise spectra under 390 nm UV illumination at different reverse biases are bias- and frequency-independent.

As can be seen, for pure hole injection, the excess noise factor is less than the multiplication gain ($F < M$). This is promising for low-noise performance in GaN-based avalanche devices such as APDs and IMPATTs. The excess noise factor is directly related to the impact ionization rates of electrons and holes. With mixed injection (i.e., both holes and electrons being injected), the noise spectral density due to avalanche multiplication can be expressed as

$$S_{1,M} = 2q \{ 2[I_p(0)M^2(0) + I_n(W)M^2(W)] + I[2 \int_0^W \alpha M^2(x)dx - M^2(W)] \}$$

(4)

where $q$ is the electron charge, $W$ is the depletion width of the diode, and $M$ is the multiplication gain. $I_p(0)$ and $I_n(W)$ are the hole and electron currents, entering the two ends of the depletion region layer. In this coordinate system, $x = W$ at the top of the drift layer in Figure 1b and $x = 0$ at the bottom. $I$ is the total injected current and determined by

$$I = I_p(x) + I_n(x)$$

(5)

As can be seen from Equations (4) and (5), it is difficult to separate electron and hole currents for this mixed injection case. In contrast, with pure hole injection, the injected current can be approximated as $I \approx I_p(0)$, and the noise spectrum can be simplified as

$$S_{1,M} = 2qM^4 \left[ 1 - (1 - k) \left( \frac{M - 1}{M} \right)^2 \right]$$

(6)

and the excess noise factor $F$ is given as

$$F = M \left[ 1 - (1 - k) \left( \frac{M - 1}{M} \right)^2 \right] \approx kM + \left( 2 - \frac{1}{M} \right)(1 - k)$$

(7)

where $k = \alpha/\beta$, $\alpha$, and $\beta$ are the electron and hole impact ionization coefficients, respectively. According to Equation (7), $F < M$ for hole injection indicates that $\beta > \alpha$ in GaN. Figure 7b shows the ionization coefficient ratio $\alpha/\beta$ as a function of inverse electric field calculated using Equation (7). The $\alpha/\beta$ ratio is found to vary from 0.07 to 0.38 over electric field range from 2.8 to 3.7 MV/cm (as calculated by solving Poisson’s equation numerically[18]). The low excess noise in the GaN p-n diodes is attributed to the low $\alpha/\beta$ ratios. The ionization ratios $\alpha/\beta$ obtained from noise measurements are in excellent agreement with Chynoweth fits from the photocurrent technique obtained previously[19]

$$\alpha(E) = 4.48 \times 10^6 \exp(-3.39 \times 10^7/E)$$

(8)

$$\beta(E) = 7.13 \times 10^6 \exp(-1.46 \times 10^7/E)$$

(9)

Thus, the noise measurements reported here independently validate the electron/hole impact ionization asymmetry observed previously[5].

![Figure 7](https://www.advancedsciencenews.com)
5. Conclusion

The GaN p–n junction diodes grown on bulk GaN substrates are fabricated and the low frequency avalanche noise characteristics have been investigated. The measured noise spectra provide valuable insight into impact ionization processes and show clear signatures of avalanche noise. The excess noise factor under the hole injection conditions is experimentally characterized using GaN p–n diodes with a thin InGaN hole injection layer. The impact ionization ratio $\alpha/\beta$ is confirmed to match that obtained from the photomultiplication method. A low excess noise, corresponding to $k = 0.07–0.38$, was measured. The low excess noise factor is promising for realizing low noise APDs and IMPATT diodes. The avalanche noise measurement serves as an experimental validation for the promise of GaN-based avalanche devices.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

1/f noise, avalanche, excess noise factors, GaN, impact ionization ratio, multiplication noise