Robust avalanche in GaN leading to record performance in avalanche photodiode

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***Abstract*—This abstract presents a study on the avalanche capability of GaN p-i-n diode leading to the achievement of 60A/W, 278V GaN avalanche photodiode. The GaN p-i-n diode fabricated on a free-standing GaN substrate was avalanche capable due to optimal edge termination. Both electrical and optical characterizations were conducted to validate the occurrence of avalanche in these devices. The device showed a positive temperature coefficient of breakdown voltage, which follows the nature of avalanche breakdown. The positive coefficient was measured to be 3.85 ×10^{-4} K^{-1} (0.1V/K) under a measurement temperature ranges from 300 K to 525 K. Moreover, the fabricated device showed excellent performance as an avalanche photo detector with record device metrics: (1) record high photoresponsivity of 60 A/W; (2) high optical gain of 10^{5}; and (3) low cark current. Robust avalanche is a key requirement in various device applications and necessary for their reliable operation.**

***Index Terms*-- Avalanche, GaN, Photodiode, Avalanche Photodiode, avalanche photodetector.**

I. Introduction

The avalanche breakdown capability in GaN devices was not demonstrated until 2013 [1] due to the lack of well-developed homogeneous epitaxial techniques. GaN epitaxial layers are typically grown on foreign substrates, such as sapphire, silicon carbide and silicon. Due to the large lattice mismatch between GaN and these foreign substrates, GaN epitaxial layers exhibit high dislocation densities in the order of 10^9 cm^{-2}, leading to failures in demonstrating avalanche capability in GaN.

Homogeneous GaN films grown on free-standing GaN substrates leads to low defect density in the epitaxial material grown on top, which when combined with appropriate electric field mitigation technique, such as ion implanted edge termination, bevel etch termination, field plate and ion-compensated moat etch termination have demonstrated avalanche in GaN diodes [1-8].

In this study, we designed a GaN n-i-p diode with a buried p-type GaN layer and obtained a robust avalanche breakdown behavior from it. Both electrical and optical characterizations were conducted to ensure avalanche. The fabricated device when operated as avalanche photodiode (APD), showed an outstanding performance with record high photoresponsivity of 60 A/W. To the best of our knowledge this is the first demonstration of GaN avalanche photodiode showing strong avalanche as supported by the positive temperature coefficient of their breakdown voltage.

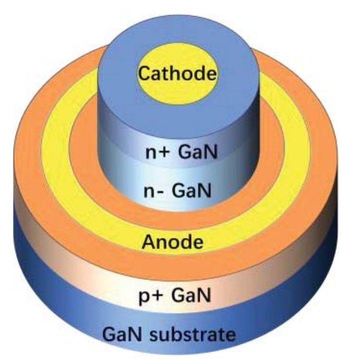

Figure 1. The schematic of the GaN avalanche photodiode (APD).

II. Device structure

The p-i-n diode used in this study is shown in Fig. 1. The epitaxial structure began with growing a 1-µm-thick p+GaN layer on top of the free standing GaN substrate. A 1-µm-thick n- GaN drift layer and a 200-nm-thick n+GaN layer were grown on top of the p+GaN by metal organic chemical vapor deposition (MOCVD). The measured dislocation density of the epitaxial layers was in the order of 10^6 cm^{-2}. The doping

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concentration of the n-GaN drift region was measured as 2×10^{16} cm^{-3} (measured by C-V). The device edge termination was implemented by double-energies Mg ion implantation (which was not shown in Fig.1).

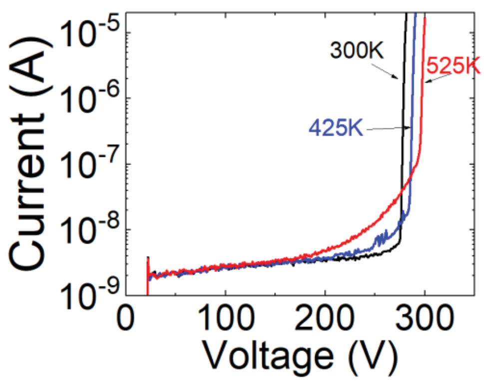

Figure 2. The measured reverse characteristics of the diode under different temperature from 300 K (room temperature) to 525 K (250 °C).

TABLE I: TEMPERATURE REPORTED TEMPERATURE COEFFICIENT OF AVALANCHE BREAKDOWN OF MAIN SEMICONDUCTORS

Mateiral	Temperature Coefficient (K^{-1})
Si [9]	$1.9–6.8\times10^{-4}$
GaAs [10]	$1.4–10\times10^{-4}$
4H-SiC [11]	1.5×10^{-4}
GaN (this study)	**3.85×10^{-4}**

III. DEVICE CHARACTERIZATION

The temperature-dependent reverse *I-V* characteristics is shown in Fig. 2. The breakdown voltage increased with the temperature with a positive temperature coefficient. The temperature-dependent breakdown voltage can be written as $BV(T)=BV_{300K}(1+\alpha\Delta T)$, where α is the temperature coefficient. By measuring the device under temperature ranges from 300 K to 525 K, the temperature coefficient is 3.85×10^{-4} K^{-1}. Table 1 compares the temperature coefficients of avalanche breakdown voltage of different materials, Si [9], GaAs [10], and 4H-SiC [11]. Although these materials have different crystal structure and bandgap, the temperature coefficients of avalanche breakdown voltage are quite close.

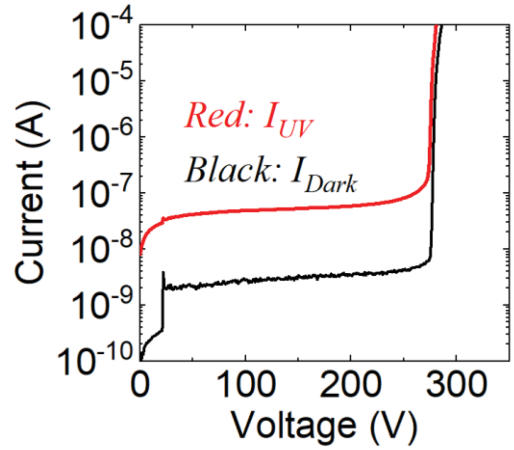

Figure 3. Reverse current measured in dark environment and under ultraviolet light illumination (λ=350 nm).

Figure 3 shows the reverse characterstics of the device. The cathode current was measured under UV light illumination and dark condition, respectivley. The dark current was in the order of nA, and no increase was observed until the voltage reached 278V, where avalanche breakdown occurred. The avalanche breakdown of the device was repeatable, after 10 measurements, the device was still functional. The red curve in Fig. 3 shows the cathode current meausred under UV light illumination. The wavelenght of the UV light was 350 nm. The gain of the device can be calculated by $Gain=(I_{UV}-I_{dark})/I_{inital,UV}$, where $I_{inital,UV}$ was the current measured under UV light illumination before the avalanche breakdown. The gain of the device is shown in Fig. 4, where a maximum gain of 10^5 was observed when the applied voltage was over 280 V.

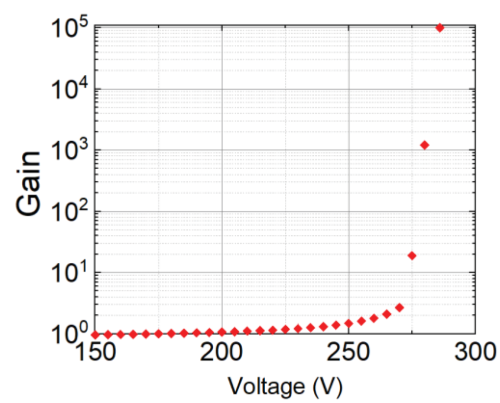

Figure 4. Gain of the fabricated device as a function of reverse bias. The maximum gain is 10^5.

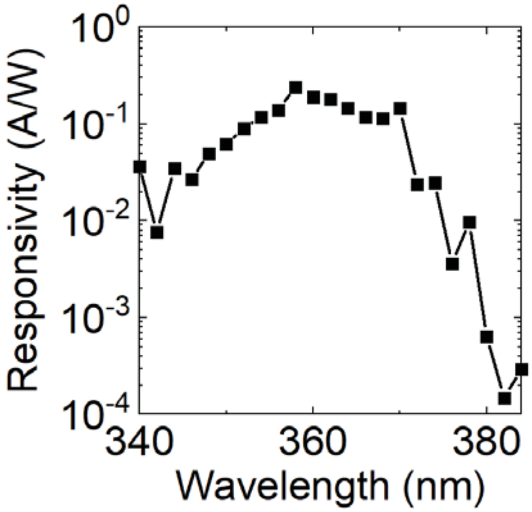

Figure 5. Responsivity of the photodiode. The peak response wavelength was from 350nm to 370nm.

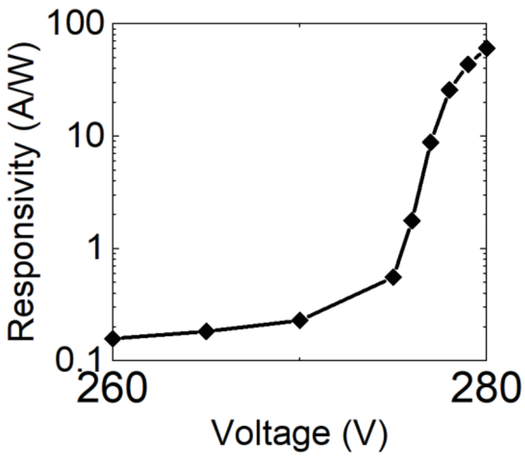

Figure 6. Responsivity as a function of reverse bias. A record high responsivity of 60 A/W was measured under a reverse bias of 280 V.

Fig. 5 shows the responsivity of the device as a function of light wavelengths. The device showed a peak responsivity in the wavelength range from 350nm to 370nm, which was determined by the bandgap energy of GaN. When a high voltage (>260 V) was applied on the cathode contact, an increase in the responsivity was observed. A record high responsivity of 60 A/W was measured under the reverse bias of 280 V. While several groups have reported APDs in GaN [12-17], no characterization on the robust avalanche breakdown capability has been reported in those studies making the current study a remarkably important contribution to the field.

IV. Conclusions

In summary, a combination of high quality GaN material grown on bulk GaN substrate and optimized field termination technique led to a robust avalanche capability in GaN p-i-n diode. The device showed a robust avalanche breakdown capability with a positive temperature coefficient of breakdown voltage. The device had a low dark current and high responsivity of 60A/W.

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