Reliability Study of Vertical GaN PIN Rectifiers and The Origin of Premature Breakdown

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Abstract

1.2kV vertical homojunction vertical GaN PIN rectifiers were demonstrated. Nitrogen implantation was used for both electrical isolation and field termination. The fabricated devices showed BVs > 1.2 kV and the specific-on resistance < 1 mΩ·cm². BVs of 208 devices were measured, and statistical analysis was performed to reveal the origin of the premature breakdown. To evaluate the long-term reliability of the devices, mean time to failure (MTTF) of estimated based on step-stress accelerated lifetime stress (SSALT) measurements.

Keywords: Vertical GaN diode, device reliability, avalanche breakdown, GaN device reliability

INTRODUCTION

Gallium Nitride (GaN) is a wide-band-gap semiconductor that is widely used in optoelectronics and power electronics. For GaN devices to reach theoretical power switching limits with reliable operation, it is crucial to mitigate field crowding effects [1]. In the previous study , we demonstrated a process of 1.2kV PIN diode with floating guard ring (FGR) design defined by nitrogen ion implantation [2]. As a follow-up study, The breakdown (BV) versus device area was studied to reveal the mechanism of premature breakdowns of the devices. Furthermore, step-stress acceleration life test (SSALT) was performed for the device with ion-implanted FGR edge termination to evaluate long-term reliability.

DEVICE GROWTH AND FABRICATION

Vertical GaN p-i-n APD epitaxial structures were grown on a bulk or free-standing GaN substrate using an AIXTRON 6x2 close-coupled showerhead (CCS) metalorganic chemical vapor deposition (MOCVD) reactor. The epitaxial layers consists of 1000-nm *n*-type GaN:Si layer ($[n] \sim 7\times10^{18}$ cm^{-3}), a 8-µm undoped GaN drift layer ($[n] \sim 2\times10^{16}$ cm^{-3}), and a 450-nm *p*-type GaN:Mg layer ($[p] \sim 2\times10^{18}$ cm^{-3}). The device layer parameters such as thickness and doping, as well as FGR parameters are designed for 1.2 kV BV by TCAD Sentaurus™. Proper nitrogen ion-implantation energy and dose were used to achieve both effective device isolation and FGR formation [2].

The device process was started with p-contact metal deposition based on Ni/Ag/Ni/Au metal stack by an e-beam evaporator. the metal stack was annealed in CDA. CTLM shows that the device has an ohmic contact with 1.77E-4 cm^{-2} of p-contact resistivity. After the formation of *p*-contact, a thick metal contact layers of Ti/Au were deposited. After the contact metal deposition, the devices were passivated with SiO_2.

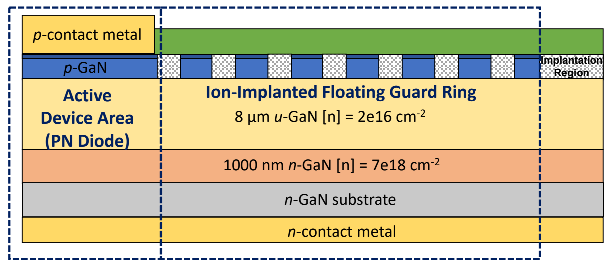
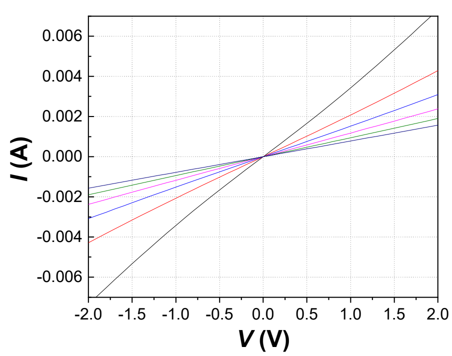


Figure 1. A schematic cross-section drawing of a vertical GaN *p-i-n* rectifier with nitrogen-implanted isolation and FGR design.



R_c (Ω)	R_s (Ω/Sq.)	L_T (µm)	ρ_c (Ω·cm²)
4.17E+01	2.47E+04	8.48E-01	1.77E-4

Figure 2. Circular transmission line measurement (CTLM) of the *p*-GaN with contact resistance (R_c), sheet resistance (R_s), transfer length (L_T), and contact resistivity (ρ_c).

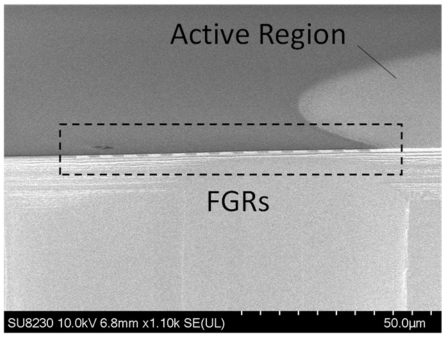


Figure 3. Scanning electron microscope cross section image of a vertical GaN PIN rectifier.

Three-steps N ion implantations were implemented with energies of 45 keV, 140 keV, and 290 keV respectively to form a highly resistive insulation layer by compensating the Mg dopants in the *p*-GaN [1]. FGRs were formed during the process as well. After the ion implantation, a backside metallization for a n-contact with Ti/Al/Ni/Au metal stack.

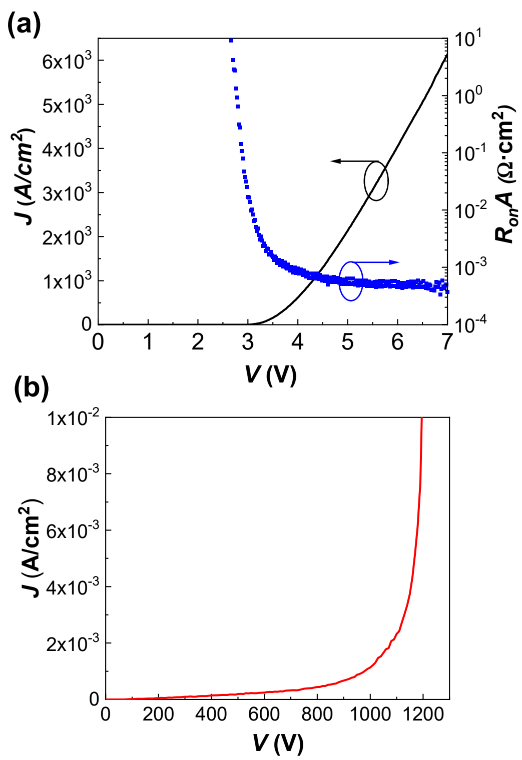


Figure 4. (a) Forward I-V curve in linear scale with specific-on resistance ($R_{on}A$), (b) Reverse I-V curve.

The pictures of completed vertical GaN *p-i-n* rectifier are shown (Figure 3).

TCAD simulation of the device was performed to design effective FGR numbers and dimensions for the BV at 1.2 kV in the previous work [2]. The width (4 μm) and the distance between FGRs (2 μm) were chosen so that it has uniform potential distribution along the FGRs region preventing premature surface BV.

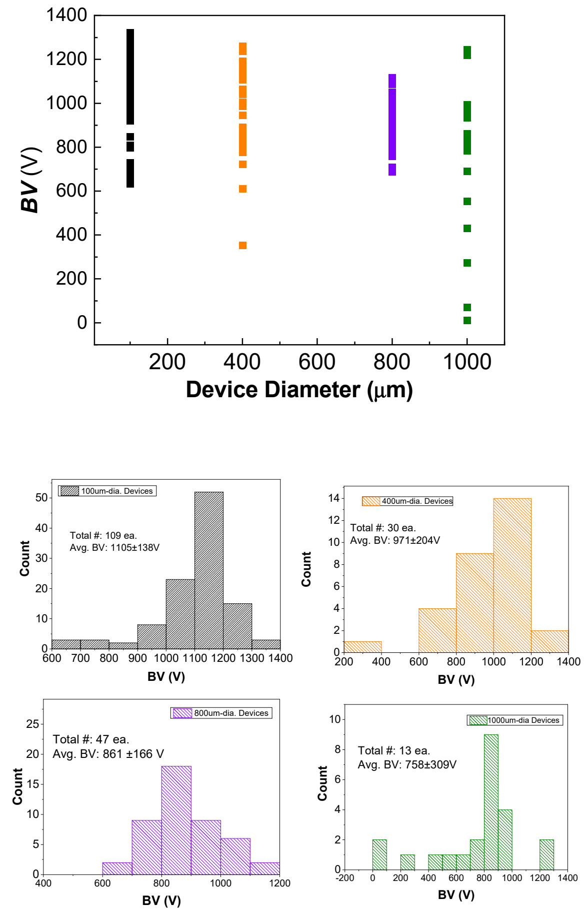


Figure 5. Record of 208 BV of the devices with different diameters: 100, 400, 800, and 1000 μm

DEVICE CHARACTERIZATIONS

Figure 4(a) shows forward bias characteristics of the devices. Keysight B1505 power device analyzer was used to measure both forward and reverse I-V characteristics. the turn-on voltages were from 3.4 V at 100 A/cm^2. The ideality factor was 1.95 at 2.5 V, and. The specific-on resistance (R_{on}) measured was 0.52 mΩ·cm^2 at 5 kA/cm^2. Figure 4(b) shows a reverse I-V curve with BV at -1.2 kV.

Figure 5. shows the records of BVs with device diameters within a quarter 2-inch area. A total 208 devices were measured, of which 87 devices achieved BV > 1.1 kV. We have shown previously that the vertical PIN rectifiers grown on a HVPE substrate have consistent BVs throughout the wafer regardless of the device diameter. However, for the device grown on a bulk GaN substrate showed device-size-dependent BV characteristics. The average BVs of the devices

are 1105±138, 907±204, 661±186, and 758±309 V for 100, 400, 800, and 1000 µm diameter respectively (Figure. 5). This relationship between BV and device size agreed with the earlier study by K. Nomoto et al [3]. They reported the BVs of devices with field plate edge terminations decreased with increasing device diameter while those of devices without FP are independent to the device sizes demonstrating the effectiveness of the edge termination. hey also claim the BV is dependent on the number of dislocations within the devices. That is, larger-size devices have more dislocations, therefore, the lower BVs. Another study reported the larger devices have lower BVs which ascribe to multiple statistically independent units and failure of one unit leads to device failure[4]. To understand detailed mechanisms of the premature BV and its relation to the bulk-oriented defects, further statistical analysis will be used based on the device BV measurement data.

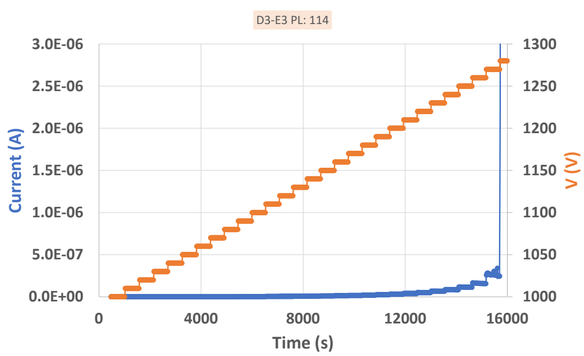


Figure 6. Current versus time plot under step voltage bias for step-stress accelerated life test (SSALT)

Step-stress accelerated life test (SSALT) was performed to test long-term reliability of the fabricated devices. Figure 6. shows an example of step-stress voltage bias and measured current response of a device in time scale. 1000V start voltage, 10 V of step voltage and 540 s of hold time were used for the measurement. The BV of devices under constant voltage stress and the lifetime can be fitted with Weibull distribution [4],

$$\mathrm{F}(\mathrm{t}; V_i) = 1 - \exp(-t(\frac{V_i}{V_o})^p)^\beta),$$

where V_o, p and β are fitting parameters and V_i is constant voltage. Since applied voltage is changing in SSALT, Weibull distribution was converted to a piecewise Weibull distribution with different constant stress voltage sections in time [5]. Then, the function was fitted to empirical breakdown voltage and V_o, p and β were extracted. Mean time to failure (MTTF) was estimated based on the parameters obtained from the Weibull distribution fitting and the equation,

$$\mathrm{MTTF} = \left(\frac{V_o}{V}\right)^p \Gamma\left(1 + \frac{1}{\beta}\right),$$

where Γ is gamma function.

24 devices were tested for SSALT, and MTTF of 10 years at reverse bias of 1168 V was estimated for 200-um-dia. devices shown in Figure. 7.

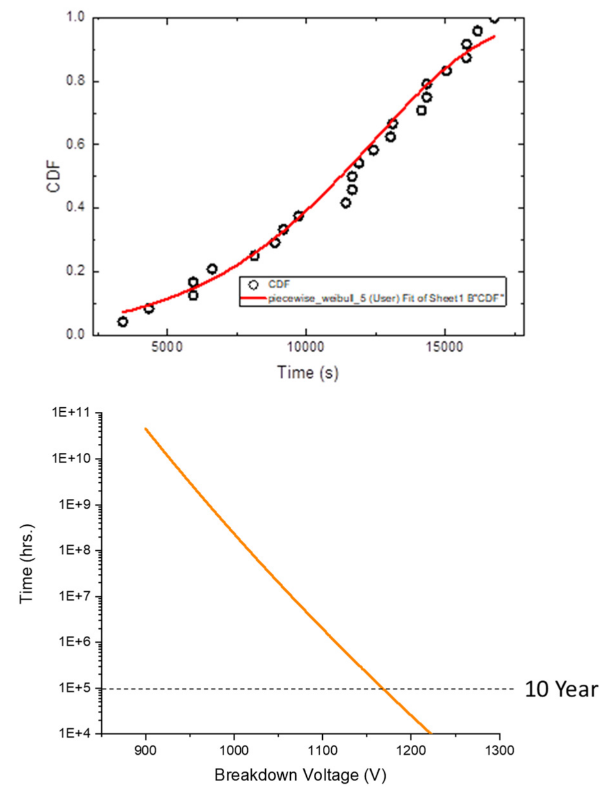


Figure 7. (Top) The cumulative distribution of 24 200-um-dia devices which is fitted with Weibul distribution ($R^2 = 0.98$). (Bottom) MTTF plot estimated from the distribution.

ACKNWLEDGEMENT

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ACRONYMS

MOCVD: Metal Organic Chemical Vapor Epitaxy
BV: Breakdown Voltage
FGR: Floating Guard Ring
CDA: Compressed Dry Air
CTLM: Circular Transmission Line Measurement
HVPE: Hydride Vapor Phase Epitaxy
SSALT: Step-Stress Accelerated Life Test
MTTF: Mean Time to Failure