Mechanism of Initial Failures in Breakdown Voltage of GaN-on-GaN Power Switching p-n Diodes

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Abstract

This paper describes the initial failure in the GaN-on-GaN p-n diodes. The diodes with pits showed fatal failures, that is, high leakage current at low forward bias voltage and very low reverse breakdown voltage. The pits made additional parallel circuits as Schottky barrier diodes. In this paper we will discuss the mechanism of pit formation and their reduction by optimizing the reactor.

INTRODUCTION

Vertical structured GaN power switching devices fabricated on GaN substrates are quite promising for highly efficient power-conversion systems because the devices can provide extremely low on-resistances (R_{on}) combined with high breakdown voltages (V_B) [1, 2]. Recently, we recorded the highest V_B of 4.7 kV with low specific differential R_{on} of 1.7 mΩ cm^2 from GaN p-n diodes fabricated on free-standing GaN substrates produced by the void-assisted separation (VAS) method [3]. How to minimize the killer defects that are fatal to device yield and reliability is an important issue. It has been reported that the structural defects such as nano-pipes, voids and pits make current short-circuits [4]. Some reports indicated that a pure-screw dislocation behaved as a current leakage path [5, 6].

In this work, we focused on an initial failure analysis of the GaN p-n diodes fabricated on GaN substrates. It was clarified that the epitaxy-originated defects were a fatal cause of the low breakdown voltage for the diodes. Prospects for reduction of the defects will also be discussed.

DIVEICE STRUCTURE & EXPERIMENTS

Figure 1 shows the schematic structure of the p-n diode. Epitaxial layers were grown on the VAS GaN substrates by Metal-Organic Vapor Phase Epitaxy (MOVPE). The detail was described in a previous report [7]. The threading dislocations with a density lower than 3 x 10^6 cm^{-2} were distributed almost uniformly throughout the substrate. It was confirmed that threading dislocations would not affect the V_B as mentioned in the previous study [7]. The drift layer under the p-GaN layer consists of an n$^-$-GaN layer with a Si concentration of 1.2 x 10^{16} cm^{-3} and a thickness of 13μm. It was expected to enable up to 2.0 kV of reverse breakdown voltage. First, the mesa structure was fabricated by inductively coupled plasma reactive ion etching (ICP-RIE), after which a circular Pd ohmic electrode was formed by a liftoff process on the p$^+$-GaN layer. Then a spin-on-glass (SOG) insulating film was deposited for passivation. The SOG film was annealed at 350 °C for 30min. Contact holes were formed by wet etching onto the Pd electrode. Diode dimensions were 60, 100, 200, 400, and 800 μm in diameter.

Current-voltage (I-V) characteristics were measured by using Keithley 4200-SCS. The breakdown voltages were evaluated using Keysight B1505A combined with an ultra-high-voltage unit at room temperature while measured chips were immersed in insulating oil. The pit density and location were confirmed by optical microscope to identify pits as the cause for initial failures.

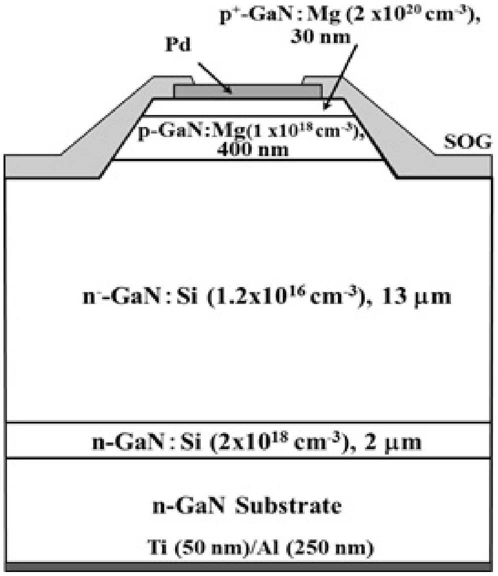


Figure 1. Structure of the GaN p-n diode. A breakdown voltage up to 2.0 kV was expected for this epitaxial layer structure.

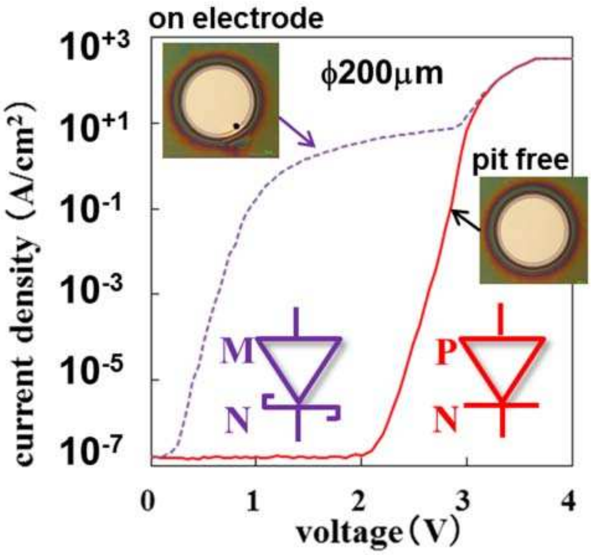


Figure 2. Forward I-V characteristics of the p-n diodes with and without pits. The insets show the microscope images of the diodes.

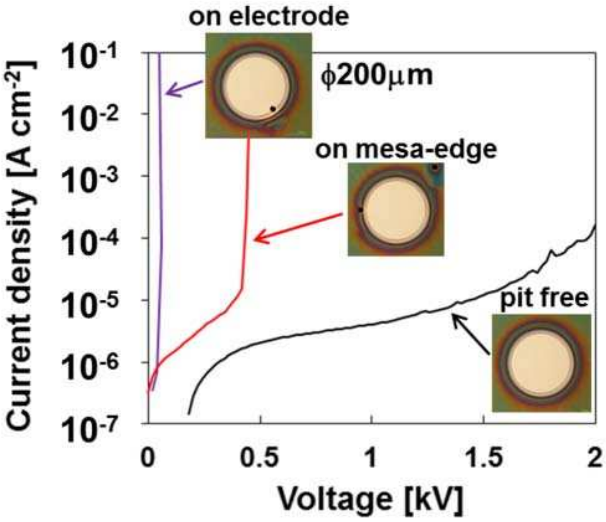


Figure 3. Reverse I-V characteristics of the p-n diodes with and without pits. The insets show the microscope images of the p-n diodes. The size of the pits sizes was approximately 15-20 μm.

RESULTS & DISCUSSIONS

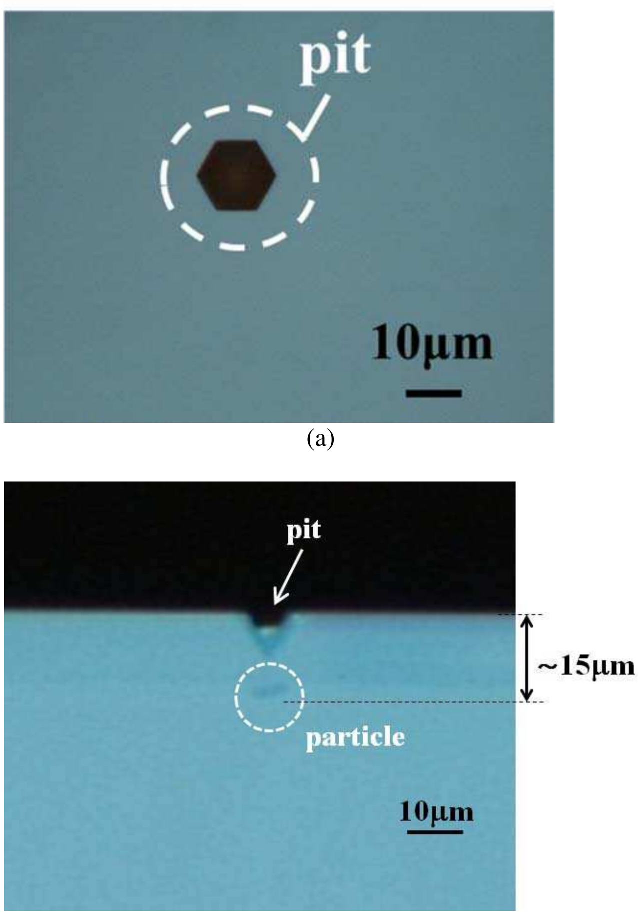
Figure 2 shows forward I-V characteristics of the p-n diodes with and without the pit on the 200μm-diameter electrodes. The diodes without the pit showed ideal forward rectifying properties with the ideality factor n = 2. It showed low specific differential R_{on} of 0.50 mΩ cm^2, which was calculated from the data of 60μm diodes. On the other hand, the diodes with the pit showed high leakage current even at low forward bias voltage. These results indicate that the pits made additional parallel circuits as Schottky barrier diodes.

The current density of p-n diodes in the resistive region was 100 times of that of a parallel Schottky barrier diode. It was shown in the microscope images of the diodes with and without the pit on the electrodes in the insets of Figure 2. The pit size was approximately 15 to 20 μm. Thus, the ratio of the pit area to the diode area was approximately 1/100. It correlated well with the I-V characteristics.

We measured many of the 200 μm diodes on this epi-wafer, and found that only a few diodes had leakage at low forward bias voltage. The relationship between the pit density and device yield will be discussed in a later section.

Figure 3 shows reverse I-V characteristics of the p-n diodes with and without the pit on the 200 μm electrodes. The diodes without the pit showed high V_B of up to 2.0 kV as expected for the epitaxial layer structure. The leakage current was 10^{-4} A/cm^2 at reverse bias voltage of 2.0 kV. The on/off ratio was higher 10^6, which reached a level high enough to be useful for switching applications. Its Baliga's figure of merit [8] (V_B^2 / R_{on}) was 8.0 GW /cm^2. The diodes with pits showed very low V_B of approximately 50 V. If the Pd electrode directly contacts the n-GaN substrate with 1 x 10^{18} cm^{-3} carrier density, the Schottky junction should have V_B of several tens of volts, consistent with the observation. These results indicate that the pits are the primary killer defects that are fatal to the device yield.

Figure 4 shows the cross section of the pit observed by an optical microscope. It showed that the pit was a V-shaped groove and there was a particle at the bottom, which indicated that GaN-epi growth was stopped at the pit. We estimated that the pits were formed above the particles on the substrate. We believed that the particles either originally existed on the substrate and/or got there during the MOVPE growth. The V-shaped groove also indicates that the facet growth occurred. It was attempted to evaluate the Si, O, and C concentration near the pits by time-of-fight secondary ion mass spectrometry (TOF-SIMS), because of the high spatial resolution. The TOF-SIMS results indicate that the particles included higher Si, O, and C comparing with that of the n$^-$-GaN drift layer. Thus the origin of the particle seems to be the some deposition in the reactor or the some contamination on the GaN substrate. In addition, the particle seems to be formed by gas phase reaction from the Si source during GaN-epi growth.



(a)

(b)

Figure 4. Optical micrographs of the p-n diode with a pit. (a) The top view. (b) The cross section. The particle exists on the interface between the substrate and the 15um-thick epitaxial layers.

The relationship between the device yield and the killer defect density is given by

$$Yield = \exp\left(-D\,A\,S\right), \tag{1}$$

where D is the killer defect density in cm^{-2}, A is device size in cm^{2}, and S is the percentage of defect sensitive area. We assumed that the device size is the same as the electrode size of p-n diodes, and S equals to 1. Figure 5 shows the yield of p-n diodes calculated by equation 1. The experimental data were obtained from the yield of the p-n diodes with different electrode size, such as 100, 200, 400, 800 µm in diameter. The killer defect density was assumed to be 20 cm^{-2}. The calculated defect density had a good consistency with that of the pit density obtained from an optical microscope analysis.

We then optimized the cleaning of the reactor, the pre-cleaning of the GaN substrate, and the growth condition to cope with the pits as the device killer defects. As a result, we achieved almost pit-less GaN-on-GaN epi wafers. Recently, the pit density was less than 2 cm^{-2}, which was shown in Figure 5 with the estimated device yield.

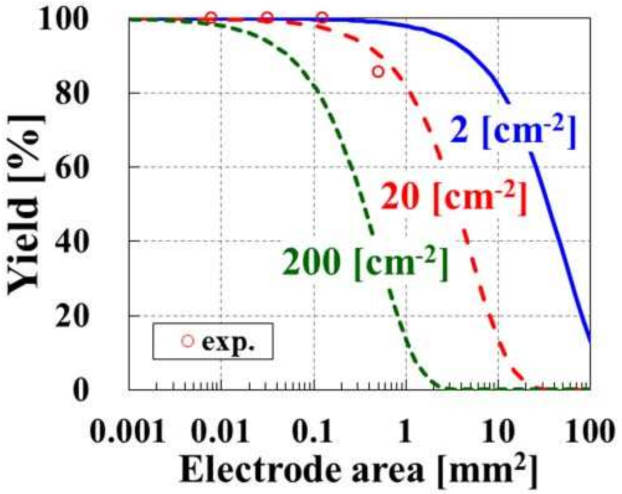


Figure 5. The yield of p-n diodes calculated by equation 1. The experimental data were obtained from the yield of p-n diodes with different electrode size, such as 100, 200, 400, 800 µm diameter. The killer defect density was assumed to be 20 cm^{-2}. This density had a good consistency with that of pit density obtained by an optical microscope analysis.

CONCLUSIONS

In this paper, we reported the investigation of the mechanism of the initial failure in the GaN-on-GaN p-n diodes. The diodes with pits showed fatal failures, that is, with high leakage current at low forward bias voltage and very low reverse breakdown voltage. The pits made additional parallel circuits as a Schottky barrier diodes. The pit density was reduced to less than 2 cm^{-2} by optimizing the reactor. This reduced pit density realizes a high-yield fabrication for large size vertical structured GaN-on-GaN power devices.

ACKNOWLEDGEMENTS

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ACRONYMS

R_{on}: specific differential on-resistance
V_B: breakdown voltages
VAS: Void-Assisted Separation
MOVPE: Metal-Organic Vapor Phase Epitaxy
ICP-RIE: Induced Coupled Plasma Reactive Ion Etching
SOG: The spin-on-glass
TOF-SIMS: Time-of-Flight Secondary Ion Mass Spectrometry