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5.0 kV Breakdown-Voltage Vertical GaN p-n Junction Diodes

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Abstract

A high breakdown voltage of 5.0 kV has been achieved for the first time in vertical GaN p-n junction diodes by our newly developed guard-ring structures. Resistance device was inserted between the main diode portion and the guard-ring portion to generate a voltage drop to the guard-ring portion by leakage current under negatively biased conditions before the breakdown. The voltage drop partially released electric field at the outer edge of the diode where the electric field became highest and the breakdown usually occurred. By adopting this structure, a few hundred volts improvements in the breakdown voltages (V_B) were observed. With combining a measured low on-resistance (R_{on}) of 1.25 mΩcm^2, Baliga's figure of merit (V_B^2/R_{on}) was as high as 20 GW/cm^2.

1. Introduction

Since gallium nitride (GaN) has very excellent physical properties compared with Si, it has great expectations as the ultimate material for highly efficient power devices. Conventionally, GaN has been grown on Si, Sapphire and SiC substrates, but in recent years it has been possible to grow high quality freestanding GaN substrates which enable to grow high quality GaN epitaxial layers on the substrates. This homo-epitaxial growth has dramatically improved in GaN device performances by introducing vertical device structures. Previously, we realized a device with a high V_B of 4.7 kV by field plate structures and insertion of low donor-concentration n-GaN layers on top of the drift layer in GaN p-n diodes on high quality free-standing substrates [1]. A higher breakdown voltage, however, can be expected from a calculation by Poisson's equation to the layers and there is some room for structural improvements. For the further increment of V_B, we have developed guard-ring structure p-n junction diodes.

2. Device Structure and Fabrication Process

The schematic structure of the guard-ring structure p-n diodes is shown in Fig.1. The guard-ring portion was disposed around the main p-n diode portion, and a ring resistance device was inserted between the guard-ring portion and the main p-n diode portion. In ring-shaped diodes, when the reverse voltage is applied the electric field concentrates most at the mesa edge of the outermost ring portion. Therefore, the destruction of the diodes has occurred at the mesa edge of the outermost ring portion. This is because there is a relationship of $V_{b2} > V_{b1}$, where V_{b1} is V_B of the mesa edge of the outermost ring portion and V_{b2} is that of the mesa edge of the main p-n diode portion. By inserting a resistance devices between the ring portion and the main p-n diode portion (in this case, the ring portion is called the guard-ring portion), a voltage drop (V_{d1}) occurs between them when a reverse voltage is applied to the p-n diode and the voltage applied to the guard-ring portion decrease by the voltage drop. When the applied reverse voltage V to the p-n diodes is V_{b1}, a voltage of V_{b1} - V_{d1} is applied to the p-n junction of the guard-ring portion and breakdown does not occur at the mesa edge of the guard-ring portion. When V exceeds V_{b1}, if $V_{d1} < V_{b12}$ (= V_{b2} - V_{b1}), breakdown occurs at the mesa edge of the guard-ring portion at V = V_{b1} + V_{d1}, and if $V_{d1} > V_{b12}$, breakdown occurs at the mesa edge of the main p-n diode portion at V = V_{b2}. Therefore, by inserting a resistance device having a resistance value such that $V_{d1} \geq V_{b12}$, it is possible to achieve high V_B corresponding to the difference of V_{b1} and V_{b2}.

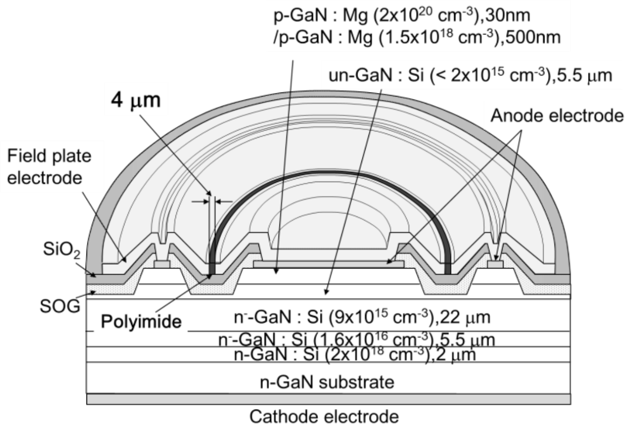

Fig. 1. Schematic cross sections of the guard ring structure GaN p–n diodes.

The layer structure shown in Fig. 1 was grown by metal-organic vapor phase epitaxy (MO-VPE) on a free-standing GaN substrate fabricated by the void-assisted separation method with threading dislocation densities less than 3 x 10^6 cm^{-2} [2-3]. Drift layers under the p-GaN layer consist of undoped GaN with a residual Si concentration of < 2 x 10^{15} cm^{-3}, n$^-$-GaN with a Si concentration of 9 x 10^{15} cm^{-3}, and n$^-$-GaN with a Si concentration of 1.6 x 10^{16} cm^{-3}. After the MO-VPE growth thermal annealing was performed at 850 ºC for 30 minutes under N_2 ambient in order to activate Mg acceptors by removing adherent hydrogen atoms.

Photosensitive polyimide (HD8820 manufactured by Hitachi Chemical Co., Ltd.) was used for resistance devices inserted between the guard-ring portion and the main p-n diode portion. The width of the resistance device was set to 4 μm. After pattern formation by conventional lithography, the polyimide was baked at 350 ºC for 30 minutes under air to cure. The procedure of fabricating our conventional diode structures was mentioned in detail elsewhere [4]. The dimension of the circular Pd ohmic electrode was 60 μm. Current-voltage (I-V) characteristic were evaluated using Agilent B1505A combined with an ultra-high-voltage unit at room temperature while measured chips were immersed in insulating oil.

3. Result and Discussions

Figure 2 shows the forward I-V characteristics of guard-ring structure p-n diode and normal circular p-n diode. In the former diode, the on-resistance (R_{on}) was 1.25 mΩcm^2 at forward voltage 5 V. R_{on} was calculated with the area of the p-n diodes. The value was almost the same as R_{on} of the latter diode. Since a high resistance polyimide was inserted between the guard-ring portion and the main p-n diode portion, the guard-ring portion did not contribute to the forward current.

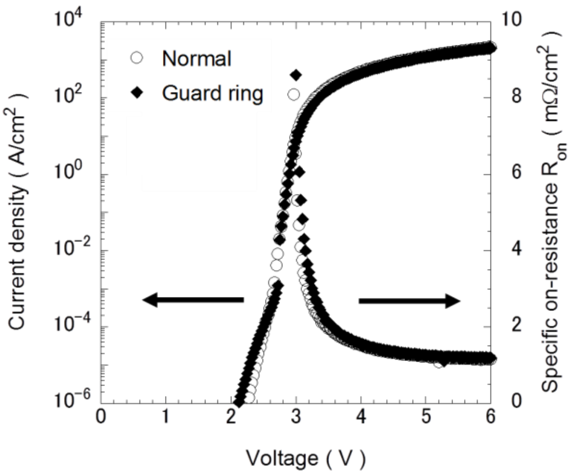

Fig. 2. Forward I-V characteristics.

Figure 3 shows the reverse I-V characteristics of guard-ring structure p-n diode and normal circular p-n diode. In the guard-ring structure p-n diode, the breakdown voltage (V_B) was 5.0 kV which is about 200 V higher than 4.8 kV of the normal circular p-n diode. This value is the highest among so-far reported V_B of the vertical structure GaN p-n diodes. The Baliga's figure of merit (V_B^2/R_{on}) [5] resulted in this study was 20 GW/cm^2.

Figure 4 shows the surface of the guard-ring structure diode after the V_B measurement. The diode was destroyed at the mesa edge of the main p-n diode portion. Therefore, it could be considered that the relation of $V_{d1} \geq V_{b12}$ was held at this width of the resistance device. A further improvement of V_B can be expected by optimizing the resistance device.

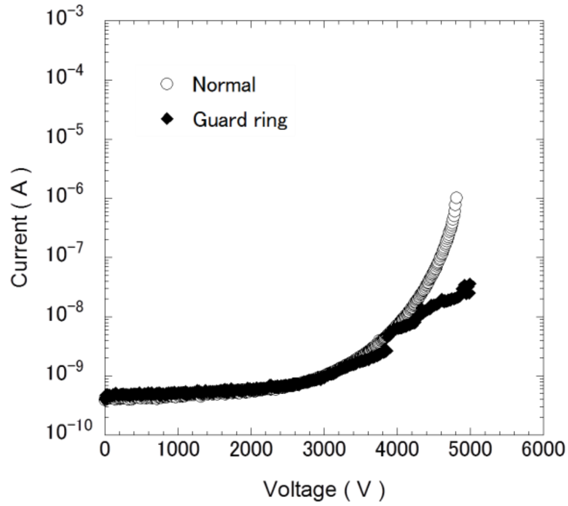

Fig. 3. Reverse I-V characteristics.

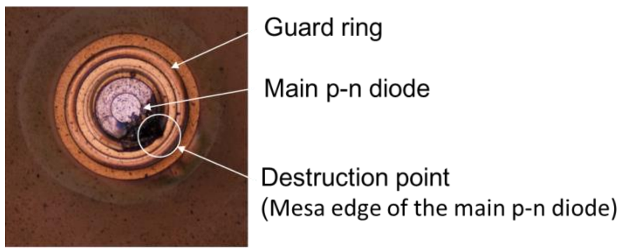

Fig. 4. Diodes surface after destruction.

4. Conclusions

In order to increase the V_B of the p-n diodes, we developed guard-ring structure p-n diodes in which resistance devices were inserted between the guard-ring portion and the main p-n diode portion. In the guard-ring structure p-n diode, the breakdown voltage was 5.0 kV which is about 200 V higher than 4.8 kV of the normal circular p-n diode. The Baliga's figure of merit resulted in this study was 20 GW/cm^2.

Acknowledgements

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