

Evaluation of GaN Substrate for Vertical GaN Power Device Applications

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Pn diodes were fabricated on a GaN substrate prepared by the Na flux method. Edge and mix dislocations that developed from the GaN substrate were observed in the diodes. These threading dislocations did not induce leakage current even when the dislocation density was in the range of 10^5 – 10^6 cm⁻². These results indicate that a GaN substrate that does not include pure screw dislocations will be applicable to vertical power devices.

1. Introduction

Hybrid vehicles (HVs) and electric vehicles (EVs) are now widely recognized as green vehicles. The introduction of electric power to conventional gasoline engine vehicles is one of the solutions to environmental problems, such as CO₂ problems experienced worldwide, exhaust gas problems in urban areas and fuel consumption problems. These vehicles need power electronics to drive high-power motors. Figure 1 shows schematically the power electronics used in Toyota HVs. For driving the main motor, a high-power inverter module is used. In the recent Toyota HV system, the battery voltage is raised to a power source voltage of 650 V by a voltage booster (DC-DC converter) and then supplied to the motor through an inverter. The DC-DC converter and the inverter control a high electric power of over 50 kW. Si-insulated gate bipolar transistors (IGBTs) are used in high-power modules as switching devices. Moreover, the other power modules in Fig. 1 control medium- and low-power accessories, in which Si power metal-oxide-semiconductor field-effect transistors (MOSFETs) are used as power devices.

However, Si devices have the limitation of electric power loss due to their material limitations. Devices with higher performances, namely, higher operating temperature and lower on-resistance, are required for future vehicles. To realize the above requirements, new material devices are expected. As an alternative to Si, wide-band-gap

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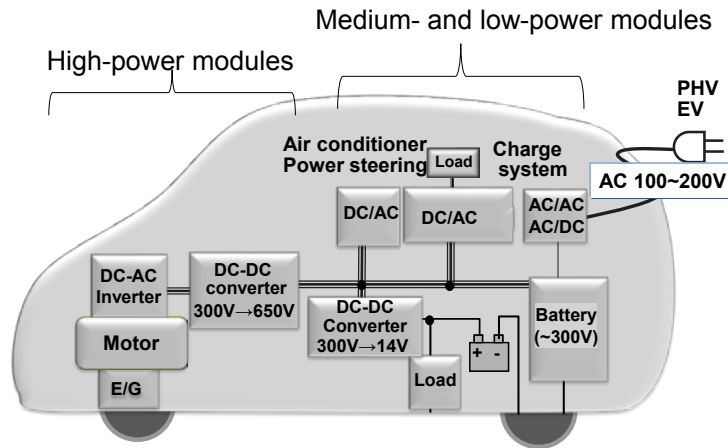


Fig. 1. Schematic diagram of power modules used in TOYOTA hybrid vehicle system.

semiconductor materials such as SiC and GaN have been focused on, because of their attractive material properties. GaN has the best potential for the post-Si-power devices among possible semiconductor materials.⁽¹⁾ As GaN power devices, a vertical structure device and a lateral structure device are being developed at present. A lateral GaN device on a Si substrate has recently been the main stream of the development of GaN power devices. For high-power applications, such as automotive motor control, the vertical structure is more suitable because of the possibility of obtaining a high current density. However, few studies on vertical GaN devices have been reported until recently owing to the lack of high-quality free-standing GaN substrates.⁽²⁻⁷⁾ To realize high-performance GaN power devices, high-quality GaN substrates are needed. GaN also has potential as sensor material as well as power devices and light-emitting diodes.⁽⁸⁾ High-quality GaN substrates will contribute to and accelerate the improvement of sensor performances. Recently, the quality of GaN substrate has been improving owing to liquid-phase growth technology.^(9,10) The Na flux method is one of the novel growth methods for realizing high-quality bulk GaN. In this paper, we report our evaluation results of GaN substrates made by the Na flux method for GaN power device applications.

2. Experimental Procedure

Na flux GaN substrates were evaluated using pn diodes produced on the substrates. The typical structure of a GaN vertical device is shown in Fig. 2.⁽²⁾ Vertical GaN power devices can sustain high voltage owing to the expanding depletion layer from the pn junction to the drift layer. Therefore, the pn junction is the basic structure for the vertical devices to obtain a high breakdown voltage. We have examined the potential of the GaN substrate for high breakdown voltage using the pn diode structure. The GaN substrate

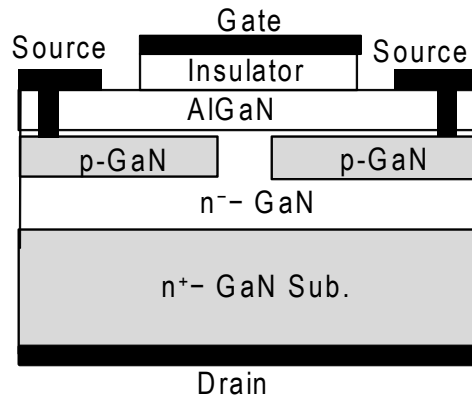


Fig. 2. Vertical GaN device structure.

contains threading dislocations, which develop in an epitaxial layer. Therefore, under a high reverse bias, high leakage current will be induced when the dislocations act as leakage pathways, which decrease the breakdown voltage. Therefore, first, we measured the leakage current of the pn diodes.

The fabricated pn diode structure is shown in Fig. 3. The fabrication process was as follows. A Si-doped n- GaN (Si: $2 \times 10^{16} \text{ cm}^{-3}$, $7 \mu\text{m}$) and a Mg-doped p⁺ GaN (Mg: $2 \times 10^{19} \text{ cm}^{-3}$, $1 \mu\text{m}$) were grown on a GaN substrate prepared by the Na flux method. Then, the mesa structure was fabricated by inductively coupled plasma (ICP) etching. The etching depth was about $1.2 \mu\text{m}$. After the etching, n-type and p-type ohmic electrodes were formed. We also observed irradiation from hot electrons, which indicated the leakage points. After these measurements, the electrodes were melted. Then, the pn diodes were etched to form etch pits originated from the dislocations. The etchant was a mixture of acids ($\text{H}_2\text{SO}_4:\text{H}_2\text{PO}_4 = 1:3$) and the etching temperature and time were 250°C and 120 min, respectively. The etch pit positions were compared with the irradiation points to determine which dislocations cause the leakage current.

3. Results and Discussion

Two typical types of leakage current are shown in Fig. 4. The diameter of the diode was $200 \mu\text{m}$. The maximum reverse bias voltage was 1 kV depending on the measuring instrument. Both diodes in Fig. 4 show a breakdown voltage of over 1 kV. The leakage currents of diode A and diode B at 1 kV were 10^{-4} and 10^{-6} A, the current densities of which were 0.32 and $3.2 \times 10^{-3} \text{ A/cm}^2$, respectively. These leakage currents are larger than the generally required leakage current of $1 \times 10^{-4} \text{ A/cm}^2$ for an on/off ratio of 10^6 . Next, we observed radiation from the diodes. The cathode electrode under the mesa was removed and the radiation was observed through the GaN substrate. The results are shown in Fig. 5, which shows images of the surface with etch pits. The strong radiation

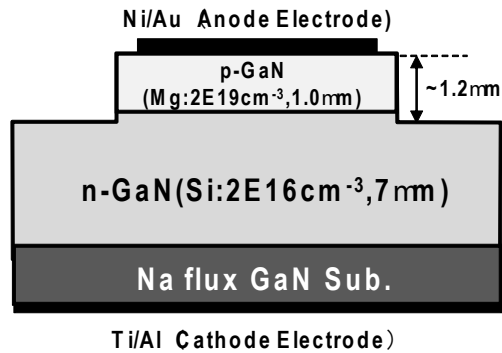


Fig. 3. Fabricated pn diode structure on GaN substrate.

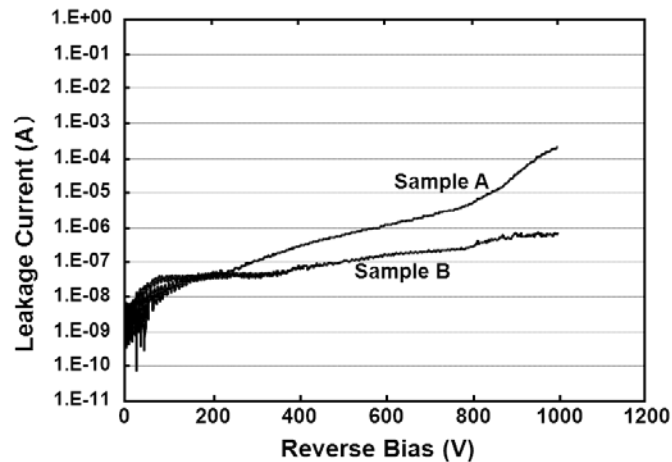
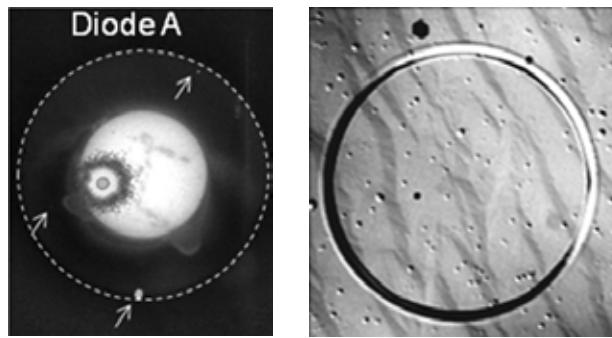


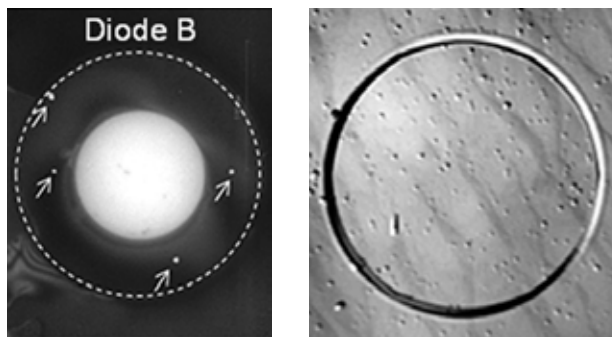
Fig. 4. Leakage currents of pn diodes on GaN substrate.

from sample A in Fig. 5(a) is caused by the defect accidentally produced by a probe, which is not substantial. We can observe 3 and 4 radiation points from diode A and diode B, respectively. A correlation between radiation points and etch pits was examined in detail by merging the two images, which showed that there was no correlation between them. This finding indicates that the dislocations, which are the origins of the etch pits, are not the origins of the leakage point.

Next, we examined the origin of the etch pits by cross-sectional transmission electron microscope (TEM) of the etch pits. The etch pits were classified into three groups (Nos. 1, 2, and 3) by size, as shown in Fig. 6. There are also several other pits larger than those



(a)



(b)

Fig. 5. Photographs of pn diodes. The left panels show radiation points and the right panels show etch pits on the diodes. (a) Diode A and (b) Diode B.

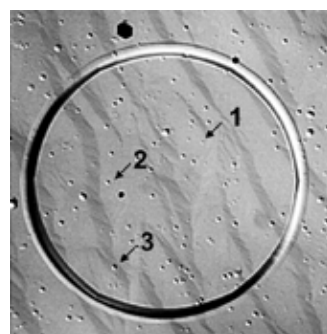


Fig. 6. Photograph of etch pits on pn diode No. 2. The etch pits are classified into three groups (Nos. 1, 2, and 3) by size.

in the groups. These large pits were not caused by dislocations. These were growth pits and defects due to inclusions formed during the growth. Cross-sectional TEM images of the etch pits (Nos. 1, 2, and 3) were obtained. Figure 7 shows TEM images obtained from different directions, the contrast of which was the basis for the assignment of the type of dislocation. For a No. 1 pit, there was no contrast in the (0002) observation but there was contrast of a dislocation in the (11-20) observation. This indicates that the dislocation below the No. 1 etch pit is an edge dislocation. For Nos. 2 and 3 etch pits, the contrasts of dislocations were observed on both images. This indicates that the Nos. 2 and 3 dislocations are a mixture of edge and screw dislocations. Note that no pure screw dislocations were observed in the etch pits.

The origin of the leakage point shown in Fig. 5 was unclear as the dislocations were not the candidate origins. We observed a similar radiation from the other pn diode samples. Small inclusions near the pn interface were observed by TEM at the radiation points. Therefore, we estimate that one candidate cause of the leakage points is inclusions near the pn interface formed during the growth.

From the experimental data of the pn diode, the following are concluded.

- 1) Leakage currents of the pn diodes are not caused by the threading dislocations included in the epitaxial layers.
- 2) The observed threading dislocations are the edge- and mix-type dislocations. No pure screw dislocations were observed.
- 3) The dislocation density of the sample was 10^5 – 10^6 cm^{-3} . However, these dislocations do not induce the leakage current as long as no pure screw dislocations are included.

We also confirmed by another method that the dislocations do not induce the leakage current. We observed leakage current in a Schottky barrier diode (SBD). The SBDs are directly fabricated on the n⁻-type Na flux GaN substrate, which has no epitaxial layer. The dislocation density was on the same order of magnitude as that used for pn

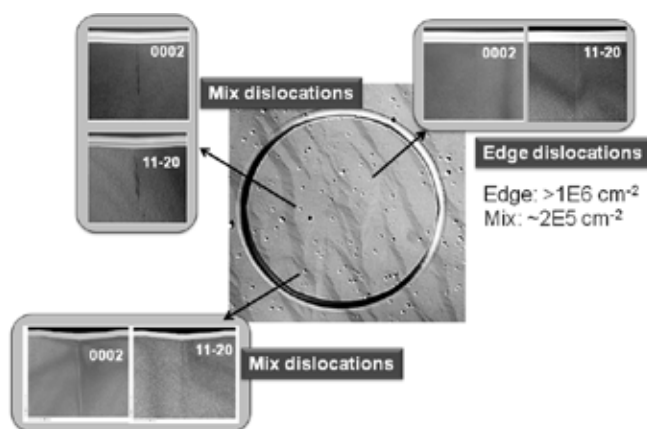


Fig. 7. TEM images of etch pits observed from (0002) and (11-20) directions.

diodes. The forward bias I - V characteristics are shown in Fig. 8. From this feature, we could obtain a Schottky barrier height of 0.91 eV and an n -value of 1.03. The carrier concentration was $1 \times 10^{16} \text{ cm}^{-3}$, which was calculated by CV measurement. Reverse bias characteristics are shown in Fig. 9. A theoretical reverse current was calculated using the formula shown in refs. 11 and 12. The formula was based on the thermionic field emission (TFE) model. The reverse current corresponds well to the theoretical curve. This result also supports the previous result. The electric characteristics of the dislocations have been reported.^(13,14) According to refs. 13 and 14, the edge- and mix-

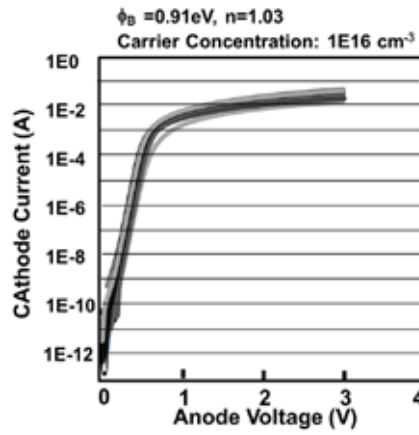


Fig. 8. Forward bias I - V characteristics of Schottky diodes.

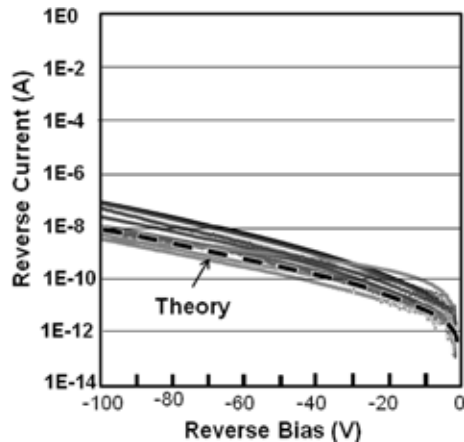


Fig. 9. Reverse bias characteristics of Schottky diodes. The dotted line shows theoretical reverse current.

type dislocations are not conductive, which expand the depletion region around them. On the other hand, pure screw dislocations are conductive; therefore, they are a leakage current source. These results are also in agreement with our experimental results.

4. Conclusions

We have evaluated the GaN substrate prepared by the novel Na flux method. Leakage currents of the pn diodes formed on the GaN substrates were measured. It was found that the edge- and mix-type threading dislocations did not induce leakage current in the pn diodes up to 1 kV. These results indicate that GaN substrates that do not have pure screw dislocations can be applied to high-power devices even when the substrates include dislocations at a density of 10^5 – 10^6 cm⁻³. However, it is not confirmed whether such a high dislocation density affects the reliability of power devices. The quality of GaN substrates has to be determined as the next step from the viewpoint of device reliability.

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