Low On-Resistance High Breakdown Voltage GaN Diodes on Low Dislocation Density GaN Substrates

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Vertical gallium nitride (GaN) Schottky barrier diodes (SBDs) were fabricated on freestanding GaN substrates with low dislocation density. A high quality n-GaN drift layer with an electron mobility of 930 cm^2/Vs was obtained under the growth condition optimized by reducing the intensity of yellow luminescence using conventional photoluminescence measurements. The concentration of impurities in the n-GaN drift layer was less than the detection limit of secondary-ion-mass spectroscopy. The specific on-resistance ($R_{on}A$) and the breakdown voltage (V_B) of the SBDs were 0.71 $m\Omega cm^2$ and over 1100 V, respectively. The figure of merit ($V_B^2/R_{on}A$) was 1.7 GW/cm^2, which is highest among previously reported SBDs for both GaN and SiC. With a forward current of 6 A at a forward voltage of 1.46 V and a breakdown voltage of 600V, the SBD with an electrode area of 1.1 x 1.1 mm^2 demonstrated the possibility of application for power devices.

Keywords: GaN, Schottky barrier diode, SBD, photoluminescence

1. Introduction

Facing the need to realize an energy-saving society due to the depletion of fossil fuels, global warming, rising oil and natural gas prices, and the nuclear accident that followed the Great East Japan Earthquake, customer demands for high-efficiency electric power conversion systems has been increasing. Gallium nitride (GaN) was originally developed for use in light-emitting diodes (LEDs), laser diodes (LDs). Today, the application of this compond semiconductor to power devices is also expected. GaN is superior to silicon (Si) in material characteristics as shown in **Table 1**. In particular, the bandgap energy, breakdown field, and electron saturation velocity of GaN are respectively about 3 times, 10 times, and 2.5 times higher than those of Si. To improve the efficiency of electric power conversion systems, reducing the on-resistance*1 of semiconductor devices is essential. The on-resistance of semiconductor devices is inversely proportional to the cube of their breakdown field. It is theoretically possible to reduce the on-resistance of semiconductor devices to one-thousandth that of Si by using GaN that has a high breakdown field. Along with SiC, GaN is expected as a material for power devices having a high figure of merit.

The structure of most existing GaN power devices is lateral since they are made by epitaxially growing GaN on a foreign substrate such as sapphire or SiC. However, most conventional high-capacity power devices comprising Si or SiC are of vertical structure. The reason is that vertical devices simplify wiring and packaging and provide a higher area efficiency, and are therefore more advantageous for large-current, high-voltage applications than lateral devices. To fabricate vertical power devices comprising GaN, it is indispensable to (1) reduce the dislocation density of GaN substrate, thereby suppressing current leakage resulting from crystalline disturbance, and (2) develop an organometallic vapor phase epitaxial (OMVPE)*2 growth technique applicable to GaN substrates.

At our Semiconductor Technologies R&D Laboratory, we have conducted an evaluation study(1),(2) to verify the superiority of our power devices comprising low dislocation density GaN substrates. For the study, we used Schottky barrier diodes (SBDs), one of the basic power devices. This paper describes our evaluation results for which we developed a photoluminescence (PL)*3-based technique that enables measurement and evaluation of impurities exceeding the detection limit of conventional secondary ion mass spectroscopy (SIMS)*4. This new technique has helped us enhance the quality of n-GaN drift layers on GaN substrates and advanced epitaxial growth technology. As a result, we dramatically improved the electron mobility of n-GaN drift layers, which led to the fabrication of a GaN SBD of vertical structure with its specific on-resistance as low as 0.71 $m\Omega cm^2$ and reverse breakdown voltage as high as 1100 V. The GaN SBD had a figure of merit*5 ($V_B^2/R_{on}A$) of 1.7 GW/cm^2, the highest among those of GaN SBDs and SiC SBDs that had been reported in previously published papers. Following the above, we succeeded in experimentally fabricating a large current capacity SBD with an electrode area of 1.1 × 1.1 mm^2. With a voltage of 1.46 V at a forward current of 6 A and a reverse blocking voltage of 600 V, the experimentally fabricated SBD demonstrated the possibility of application of GaN substrates to vertically structured power devices.

Table 1. Characteristics comparison between Si, SiC and GaN

	Si	4H SiC	GaN
Bandgap energy Eg (eV)	1.1	3.26	3.39
Electron saturation velocity v_{sat} (× 10^7 cm/s)	1.0	2.0	2.5
Breakdown field Ec (× 10^6 V/cm)	0.3	3.0	3.3
Figure of merit $\varepsilon\mu Ec^3$ (= $V_B^2/R_{on}A$ compared with Si)	1	565	957

2. Experimental Method

The construction of the experimentally fabricated vertical GaN SBD is shown in **Fig. 1**. The GaN substrate was fabricated by hydride vapor phase epitaxial (HVPE) method. The dislocation density of the substrate was less than 1×10^6 cm^{-2}. For the GaN drift layer, the OMVPE method was used to grow a 5 μm thick crystal layer while doping Si at a growth temperature of 1050°C. Trimethylgallium (TMG), which is an organic metal, and ammonia (NH_3) were used as the raw materials of the n-GaN drift layer and silane (SiH_4) was used for n-doping. The flow rate of SiH_4 was controlled so that the Si concentration in the n-GaN drift layer was constantly maintained at 8×10^{15} cm^{-3}. The PL-based impurity concentration measurement and evaluation were carried out at room temperature using an He-Cd laser emitting a beam of 325 nm wavelength at an excitation density of 5 W/cm^2. For the Schottky electrodes on the front surface of the n-GaN drift layer, electron-beam (EB) vapor-deposited Ni/Au electrodes were formed in a 100 μm diameter pattern using a photolithography-based lift-off technique. The electron mobility of the n-GaN drift layer was determined from the dependence of the on-resistance of SBD on the thickness of the n-GaN drift layer. A field plate (FP)*6 structure comprising an SiNx film was used as the edge termination structure of the Schottky electrodes to lessen the concentration of electric fields at the electrode edges and thus protect the electrodes from early breakdown(2). The ohmic electrodes on the back surface of the substrate were formed by electron beam evaporation of Ti/Al/Ti/Au.

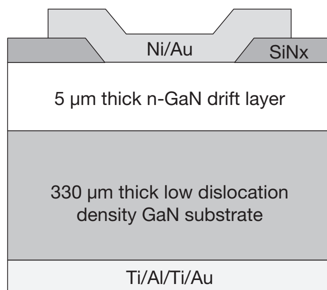

Fig. 1. Cross-sectional view of vertical GaN SBD of FP structure

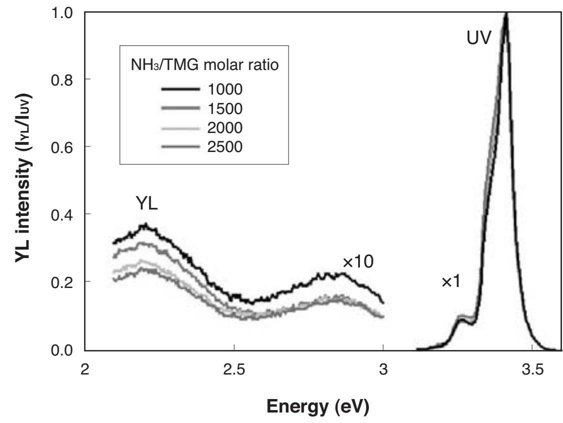

Fig. 2. Room-temperature spectra of n-GaN drift layer

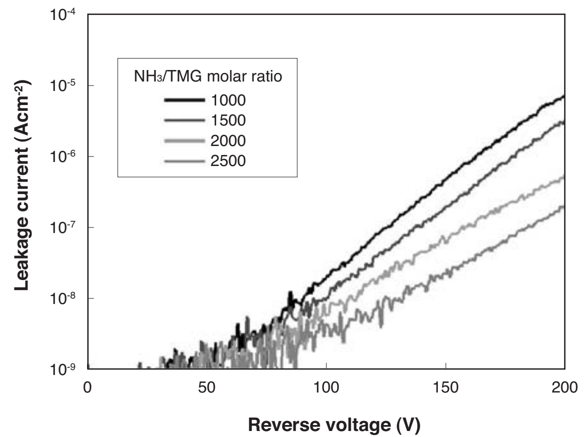

Fig. 3. Reverse leakage current vs. voltage characteristics of SBD

3. Experimental Results

The room-temperature spectra of n-GaN drift layers grown by the OMVPE method are shown in **Fig. 2**. The spectra show two peaks: near-band-edge ultraviolet (UV) at 3.4 eV and yellow luminescence (YL) at 2.2 eV. The latter peak is attributable to a defect. This figure shows that the YL intensity (I_{YL}/I_{UV}) normalized by UV peak intensity (I_{UV}) decreased as the NH_3/TMG molar ratio increased, proving that the crystal quality improved. **Figure 3** shows the reverse leakage current characteristics of the SBD with its n-GaN drift layer that were measured under the same NH_3/TMG molar ratio conditions as in **Fig. 2** using the 100 μm-diameter Schottky barrier electrodes without FP structure. The reverse leakage current decreased as NH_3/TMG molar ratio increased as shown in the figure. The relation between the leakage current at a reverse voltage of 200 V and YL intensity (I_{YL}/I_{UV}) under each NH_3/TMG molar ratio condition is plotted in **Fig. 4**. This figure suggests that reducing crystal defects in the n-GaN drift layer and minimizing the YL intensity would improve the crystal quality of the n-GaN drift layer and therefore suppress the leakage current.

Several papers have reported that yellow luminescence is caused by a deep acceptor level due to Ga site vacancy or deep acceptor level caused by carbon, an impurity(3)-(6). Another paper has reported that, under the growth condition with a high NH_3/TMG molar ratio, the number of Ga site vacancies in a GaN crystal tend to increase. However, our experimental results did not exhibit such tendency, confirming that yellow luminescence in the n-GaN drift layer is not attributed to Ga site vacancy. Another paper has reported that, under the growth condition with a high NH_3/TMG molar ratio, carbon impurities in a GaN crystal

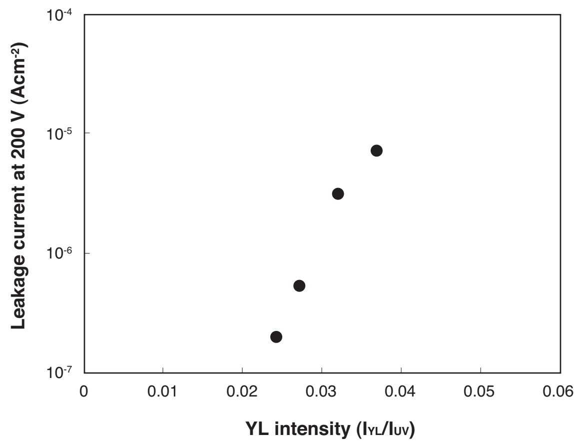

Fig. 4. Dependence of reverse current on YL intensity of n-GaN drift layer

decreased[7]. Since this result agreed with our experimental result shown in **Fig. 2**, we concluded that the yellow luminescence was caused by carbon impurities. SIMS was incapable of analyzing such changes in an epitaxial crystal. Use of the PL technique made it first possible to analyze and evaluate the impurities in more detail, and as a result, we succeeded in obtaining a high quality n-GaN drift layer containing a minimum quantity of impurities.

Figure 5 shows how the on-resistances of an SBD changed as its n-GaN drift layer thickness varied from 3 to 7 µm. The n-GaN drift layer was grown at an NH_3/TMG molar ratio of 2500, which was optimized by the newly introduced PL evaluation technique. The carrier density was continuously maintained at 8×10^{15} cm^{-3}. The electron mobility of the n-GaN drift layer was determined from the relation between on-resistance and drift layer thickness shown in **Fig. 5**. Electron mobility of the high quality n-GaN drift layer that was grown on a low dislocation density GaN substrate was 930 cm^2/Vs, which was as high as the theoretical value that was estimated in reference[9]. In **Fig. 5**, the dotted line intercepts the y-axis (zero n-GaN drift layer thickness line) at 0.28 mΩcm^2. This value is the resistance of the GaN

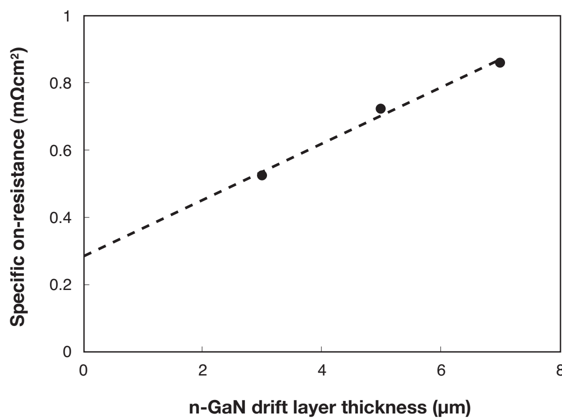

Fig. 5. Dependence of specific on-resistance on n-GaN drift layer thickness

substrate, and was very close to 0.33 mΩcm^2, which was estimated from the resistivity of the substrate (resistivity of the substrate: 0.01 Ωcm; GaN substrate thickness: 330 µm). This verified that the estimation was highly reliable.

Figure 6 shows the forward and reverse current-voltage (I-V) characteristics of an SBD device with a 5 µm thick n-GaN drift layer of FP structure. The SBD device had a specific on-resistance of 0.71 mΩcm^2 at a forward current density of 500 A/cm^2 and a breakdown voltage of more than 1100 V. The correlation between the reverse breakdown voltage (V_B) and specific on-resistance ($R_{on}A$) is shown in **Fig. 7**[10]-[12]. This figure verifies that the specific on-resistance versus reverse breakdown voltage characteristics of the newly fabricated SBD exceeded the upper limit of the material characteristics of SiC. The figure of merit ($V_B^2/R_{on}A$), an index for comparing the characteristics of

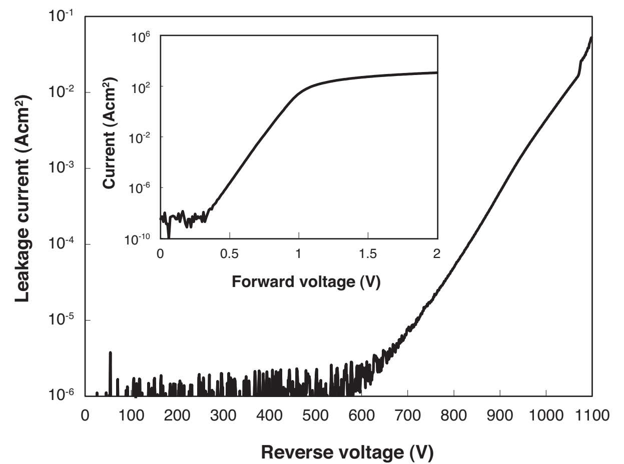

Fig. 6. Forward and reverse I-V characteristics of SBD of FP structure

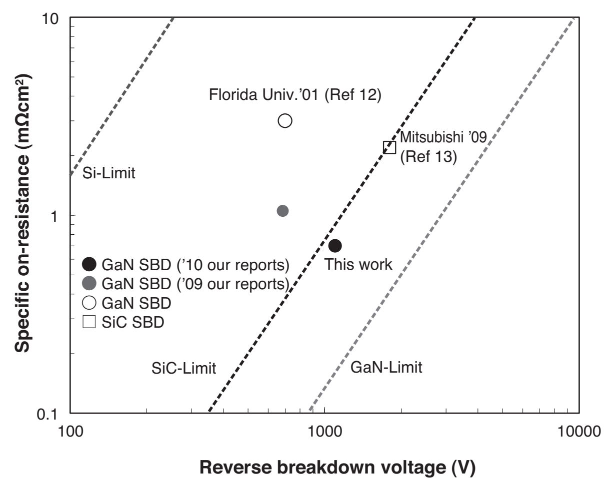

Fig. 7. Relation between specific on-resistance and reverse breakdown voltage for GaN and SiC vertical SBD devices in previous papers and this evaluation study

a newly fabricated device with devices fabricated from other materials, was 1.7 GW/cm^2, which was the highest among those of previously reported vertical GaN and SiC SBDs. This extremely low on-resistance and high figure of merit were realized by growing a high quality n-GaN drift layer on a low dislocation density GaN substrate. The PL technique made it possible to fabricate such a high quality device by reducing the YL intensity and thereby improving the n-GaN drift layer growing conditions. The study results confirmed the superiority of our GaN semiconductor power devices.

Figure 8 shows the I-V characteristics of a newly fabricated large area SBD with a chip size of 1.3 × 1.3 mm^2 and an electrode size of 1.1 × 1.1 mm^2. In practice, the chip was mounted on a CuW stem and bonded with Au wires. This SBD exhibited a forward current of 6 A at a forward voltage of 1.46 V and a specific on-resistance of 0.84 mΩcm^2 at a forward current density of 500 A/cm^2. The blocking voltage at a reverse leakage current of 10 μA (current density: 8×10^{-4} A/cm^2) was 600 V. This result confirmed that growing a high quality n-GaN drift layer on a low dislocation density GaN substrate prevents the degradation of reverse breakdown voltage and thereby enables fabrication of actually usable several-ampere capacity power devices having a blocking voltage of 600 V.

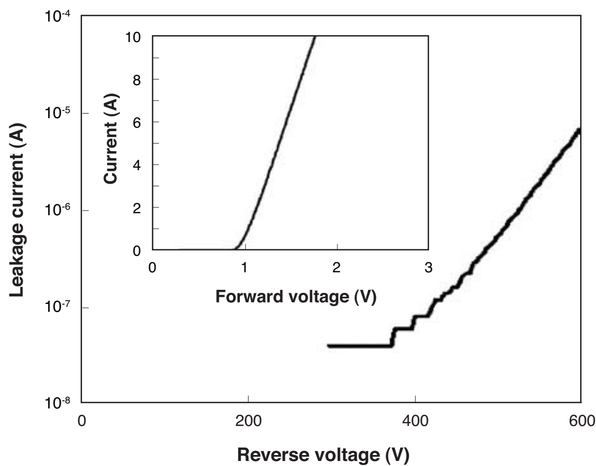

Fig. 8. Forward and reverse I-V characteristics of 1.1 × 1.1 mm^2 SBD

4. Conclusion

Because of its superior material characteristics, GaN is expected to be a key semiconductor material for next-generation power devices. GaN is also the material for which our technological expertise can be fully utilized. In this evaluation study, we newly introduced the PL technique to optimize the growth condition that minimizes carbon impurities, and could form a high quality n-GaN drift layer on a low dislocation density GaN substrate. The drift layer had excellent electron mobility as high as 930 cm^2/Vs. A vertical GaN SBD comprising this high quality n-GaN drift layer exhibited such high electrical characteristics as a breakdown voltage of more than 1100 V, an specific on-resistance of 0.71 mΩcm^2, and a figure of merit ($V_B^2/R_{on}A$) of 1.7 GW/cm^2. These characteristics exceeded the upper limit of the material characteristics of SiC, and the figure of merit was the highest among those of previously reported GaN and SiC SBDs. We have also succeeded in fabricating a prototype of large area SBD (with an electrode size of 1.1 × 1.1 mm^2). With a forward voltage of 1.46 V at a forward current of 6 A and a blocking voltage of 600 V, this prototype of SBD has a capacity of several amperes and can be put to practical use. These study results confirm the superiority of GaN semiconductor power devices and the applicability of our low dislocation density GaN substrates for power devices.

Technical Terms

*1 On-resistance: The resistance of a live switching element. Reducing on-resistance leads to lower loss and higher efficiency.

*2 OMVPE: An abbreviation for organometallic vapor phase epitaxy, a technique for growing vapor phases using organometallic vapor.

*3 PL technique: PL stands for photoluminescence. The PL technique is a high-sensitivity optical method of checking semiconductor materials for impurities and clarifying the cause of luminescence.

*4 SIMS: SIMS stands for secondary ion mass spectroscopy, a method for measuring impurity concentration. The carbon impurity detection limit of SIMS is nearly 10^{16} cm^{-3}.

*5 Figure of merit (Baliga index): An index for indicating the superiority of materials. The Baliga index is calculated from $V_B^2/R_{on}A$ (= $\mu\varepsilon Ec^3$)

*6 FP structure: FP stands for field plate. An FP structure comprises an insulation layer that covers the edge of a Schottky electrode as shown in Figure 1 to transversely distribute the electric field and thus lessen its concentration.

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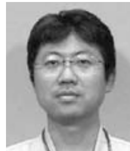

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