Extreme reduction of on-resistance in vertical GaN $p$–$n$ diodes by low dislocation density and high carrier concentration GaN wafers fabricated using oxide vapor phase epitaxy method

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Low dislocation density and low-resistance GaN wafers are in high demand for improving the performance of vertical GaN power devices. Recently, GaN wafers with the dislocation density of $8.8 \times 10^4$ cm$^{-2}$ and the resistivity of $7.8 \times 10^{-4}$ $\Omega$ cm were fabricated using oxide vapor phase epitaxy (OVPE). In this study, GaN $p$–$n$ diodes on GaN wafers prepared by the OVPE method were evaluated for verifying their suitability as vertical GaN power devices. An extremely low-differential specific on-resistance of 0.08 mΩ cm$^2$ and a high breakdown voltage of 1.8 kV were obtained from forward and reverse $I$–$V$ measurements. © 2020 The Japan Society of Applied Physics

Next-generation optical and electronic devices using gallium nitride (GaN) are being actively developed$^{1−5}$ to achieve some of the sustainable development goals.$^{4,6} Among the developed devices, vertical GaN power devices, which are expected to be driven at high current densities while retaining a compact size, have attracted much attention.$^{7,8}$ One challenge toward improving the performance of vertical GaN power devices and expanding their usage is the establishment of a manufacturing technology for producing high-quality, large-diameter, and low-cost GaN wafers.$^{9−15}$ It is considered that lower screw dislocation densities and lower electrical resistance of the GaN wafers are necessary to suppress leakage currents and reduce the on-resistance ($R_{on}$)$^{16−20}$

We have developed an oxide vapor phase epitaxy (OVPE) method using oxide as a gallium source for manufacturing high-quality, large-diameter, and low-cost GaN wafers. In previous research, we reported the fabrication of a 2 inch GaN wafer via OVPE with low dislocation density, low-resistance, and high carrier concentration.$^{21}$ The dislocation density and resistivity were on the order of $10^{4}$ cm$^{-2}$ and $10^{-4}$ $\Omega$ cm, respectively, which are both extremely low compared to those of typical GaN wafers.$^{22}$ The carrier concentration was in the upper half of the $10^{19}$ cm$^{-3}$ order, which is very high compared to that of typical GaN wafers.$^{22}$ Furthermore, OVPE does not produce solid by-products in the chemical reaction system, and allows the prolonged growth of GaN crystals with simple apparatus. Therefore, it is expected that large GaN crystals can be grown easily, and the costs of their wafers can be reduced. Thus, GaN wafers produced by OVPE (OVPE-GaN wafers) are promising as a base material for high-performance and low-cost vertical GaN power devices; however, evaluations of the epitaxial growth using metal-organic vapor phase epitaxy (MOVPE) and demonstrations of vertical GaN power devices on OVPE-GaN wafers are yet to be realized. Herein, firstly, the crystal qualities of GaN layers grown using MOVPE (MOVPE-GaN layers) on OVPE-GaN wafers were investigated. Secondly, the characteristics of the $p$–$n$ diodes on the OVPE-GaN wafers were evaluated to verify whether OVPE-GaN wafers can be applied to vertical GaN power devices.

Using the growth conditions detailed in Ref. 21 for fabricating OVPE-GaN wafers, multiple OVPE-GaN wafers were prepared as shown in Fig. 1. 2 inch freestanding GaN wafers prepared via hydride vapor phase epitaxy (HVPE), Ga$_2$O$_3$ gas (generated by reacting Ga metal with H$_2$O gas), NH$_3$ gas, and N$_2$ + H$_2$ gases were used as the seed wafers, the Ga source, the N source, and the carrier gases. The growth zone and source zone temperatures were 1200°C and 1130°C, respectively. OVPE-GaN crystals approximately 500 μm thick were fabricated with a growth rate of 60 μm h$^{-1}$. Thereafter, the seed wafers were removed from the rear surface (−c plane) and front surface (+c plane), and polishing was performed so as to obtain freestanding OVPE-GaN wafers. One of the fabricated OVPE-GaN wafers was extracted to evaluate its crystal quality. The dislocation density was $8.8 \times 10^4$ cm$^{-2}$, and the lattice curvature was convex with a radius of 11 m. The impurity concentrations of oxygen, hydrogen, carbon, and silicon were $4.3 \times 10^{20}$ atoms cm$^{-3}$, $1.2 \times 10^{17}$ atoms cm$^{-3}$, $2.6 \times 10^{15}$ atoms cm$^{-3}$ or less, and $9.5 \times 10^{18}$ atoms cm$^{-3}$, respectively. The carrier concentration, mobility, and resistivity were $8.9 \times 10^{19}$ cm$^{-3}$, $9.0 \times 10^2$ cm$^2$ V$^{-1}$ s$^{-1}$, and $7.8 \times 10^{-4}$ $\Omega$ pm, respectively. The crystal characteristics of the OVPE-GaN wafer included an extremely high oxygen concentration and low dislocation density. Accordingly, as the OVPE-GaN wafer was heavily doped with oxygen, there were concerns regarding the diffusion of oxygen into the MOVPE-GaN layer from the OVPE-GaN wafer, and the possibility of the occurrence of cracks and dislocations due to lattice mismatches between the MOVPE-GaN layer and OVPE-GaN wafer. Therefore, an undoped MOVPE-GaN layer (8 μm thick) was grown on the OVPE-GaN wafer and the crystal qualities were evaluated to investigate the validity of these concerns. The impurity concentration in the depth direction from the MOVPE-GaN layer to the OVPE-GaN wafer, the presence or absence of cracks in the MOVPE-GaN layer, the dislocation density of the MOVPE-GaN layer, and the lattice constants of the MOVPE-GaN layer and...
OVPE-GaN wafer were measured as the quality of the MOVPE-GaN layer. The impurity concentrations were evaluated by secondary ion mass spectrometry. The appearance of cracks was confirmed by visual inspection and scanning electron microscope (SEM). The dislocation density was estimated by counting the dark spot density in panchromatic cathode luminescence (CL) measurements. The lattice constants were measured by X-ray diffraction.

P-n diodes (structure shown in Fig. 2) were fabricated on the OVPE-GaN wafers and commercially available HVPE-GaN wafers to compare the electrical characteristics. The p-n diode was designed with a breakdown voltage ranging from 1.5 to 2 kV. The HVPE-GaN wafers presented a dislocation density of \( 1 \times 10^{10} \text{cm}^{-2} \) and carrier concentration of \( 1 \times 3 \times 10^{18} \text{cm}^{-3} \). The epitaxial structure of the p-n diode was grown by MOVPE: \( \text{p}^+\text{-GaN (Mg: } 2 \times 10^{19} \text{ cm}^{-3} \text{), 30 nm/p}^+\text{-GaN (Mg: } 1 \times 10^{18} \text{ cm}^{-3} \text{), 0.5 \mu m/n}^-\text{-GaN (Si: } 1 \times 10^{16} \text{ cm}^{-3} \text{), 13 \mu m/n}^-\text{-GaN (Si: } 2 \times 10^{18} \text{ cm}^{-3} \text{, 2 \mu m}) \). The mesa-structure of the p-n diodes was achieved by inductively coupled plasma dry etching. Subsequently, a spin-on-glass and a SiO2 film were deposited on the surface of the mesa-structure. The contact holes were formed by wet etching, and circular Pd anode electrodes were formed by a lift-off process on the \( \text{p}^+\text{-GaN surface. The anode electrode was 60 and 100 \mu m } \text{in diameter. Ti/Al field plate electrodes were then deposited on the SiO2 film and anode electrode. A Ti/Al cathode electrode was also formed on the rear surface of the GaN wafer. The detailed method for fabricating the p-n diode is described in Refs. 23–25. The reverse breakdown voltage, forward current density, and differential specific \( R_{on} \) were evaluated by reverse and forward \( I-V \) measurements.

Figure 3 shows the relationship between the detection of the MOVPE-GaN layer to the OVPE-GaN wafer and the impurity concentrations.26 The detection elements were oxygen, hydrogen, carbon, and silicon, with lower detection limits of \( 6.0 \times 10^{15} \text{ atoms cm}^{-3} \), \( 2.0 \times 10^{16} \text{ atoms cm}^{-3} \), \( 2.0 \times 10^{15} \text{ atoms cm}^{-3} \), and \( 7.0 \times 10^{14} \text{ atoms cm}^{-3} \), respectively. The average concentration of oxygen, hydrogen, and silicon in the MOVPE-GaN layer at depths of 1.0–7.0 \mu m were below the detection limit, and the concentration of carbon was \( 8.1 \times 10^{15} \text{ atoms cm}^{-3} \). In contrast, the oxygen concentration in the OVPE-GaN wafer was \( 5.0 \times 10^{15} \text{ atoms cm}^{-3} \) at a depth of 8.2 \mu m. The hydrogen, carbon, and silicon concentrations were \( 2.5 \times 10^{11} \text{ atoms cm}^{-3} \), \( 2.0 \times 10^{15} \text{ atoms cm}^{-3} \), or less, and \( 1.5 \times 10^{16} \text{ atoms cm}^{-3} \) at a depth of 8.7 \mu m, respectively. Therefore, it was confirmed that oxygen and other high-concentration impurities did not diffuse from the OVPE-GaN wafer into the MOVPE-GaN layer.

A photograph of the OVPE-GaN wafer with a MOVPE-GaN layer is shown in Fig. 4(a); there are no observable cracks within the wafer. Similarly, as an example of the surface SEM image shown in Fig. 4(b), no cracks were found within the wafer even when viewed microscopically. Figure 5 shows the panchromatic CL images of the MOVPE-GaN layer on the OVPE-GaN wafer. The dislocation density was calculated by counting the number of dark spots in a 165 \mu m \times 220 \mu m area. The measurement points were \( x (\text{mm}), y (\text{mm}) = (−14, 14), (−14, −14), (0, 0), (14, 14), \text{and} (14, −14) \text{for a center point of the wafer of } (x, y) \).
The dislocation densities of the MOVPE-GaN layer were $5.2 \times 10^4$ cm$^{-2}$, $7.2 \times 10^4$ cm$^{-2}$, $4.7 \times 10^4$ cm$^{-2}$, $5.0 \times 10^4$ cm$^{-2}$, and $5.5 \times 10^4$ cm$^{-2}$, respectively. This result indicates that the dislocation densities did not increase at the interface between the OVPE-GaN wafer and MOVPE-GaN layer.

The lattice constants of the MOVPE-GaN layer and OVPE-GaN wafer were evaluated to investigate the stress between the MOVPE-GaN layer and OVPE-GaN wafer. They were evaluated at five points of the OVPE-GaN wafer and MOVPE-GaN layer on the OVPE-GaN wafer. The measurement positions were the same as for the CL evaluation. For the OVPE-GaN wafer, the average $a$-axis lattice constant was $3.1893$ Å and the $c$-axis lattice constant was $5.1863$ Å. In contrast, for the MOVPE-GaN layer, the average $a$-axis lattice constant was $3.1892$ Å and $c$-axis lattice constant was $5.1843$ Å. The average lattice mismatch in the $c$-axis lattice constants was $0.039\%$ between the OVPE-GaN wafer and MOVPE-GaN layer, but the mismatch in the $a$-axis lattice constant was only $0.003\%$. Therefore, as the MOVPE-GaN layer was hardly distorted along the $a$-axis with respect to the $c$-axis, it was considered that cracks and dislocations did not occur at the interface between the OVPE-GaN wafer and MOVPE-GaN layer. The above results show that the MOVPE-GaN layer on the OVPE-GaN wafer can maintain the low number of dislocations in the OVPE-GaN wafer without causing cracks.

The evaluation results for the p–n diodes fabricated on the OVPE-GaN wafer and HVPE-GaN wafer are now presented. Figure 6 shows the reverse $I$–$V$ characteristics of the p–n diodes with $60\,\mu\text{m}$ diameter anode fabricated on the OVPE-GaN and HVPE-GaN wafers. It was confirmed that a low current density of $10^{-4}$ A cm$^{-2}$ or less was maintained up to a reverse voltage of $1.8\,\text{kV}$, and that a high reverse breakdown voltage could be obtained on the OVPE-GaN wafer; the measured diode was broken before reaching the compliance current of $10\,\mu\text{A}$. On the other hand, the diode on the HVPE-GaN wafer showed slightly lower breakdown voltage. However, the cause of the difference in the reverse $I$–$V$ characteristics has not yet been clarified, and the research is ongoing. The breakdown characteristics would be influenced not only by dislocations but also by the mesa-structure and surface morphologies, etc. Figure 7 also shows the current density and specific $R_{on}$ as a function of the forward voltage (with $100\,\mu\text{m}$ diameter anode electrode).
current obeyed the generation-recombination mechanism till the forward voltage of about 2.7 V, where the ideality factor $n$ was closed to 2. Here, the ideality factor $n$ was extracted, based on $J = J_s \exp(eV_t/\kappa T)$ ($J$: current density, $J_s$: reverse saturation current density, $e$: electric charge, $V_t$: forward voltage, $k$: Boltzmann constant, $T$: absolute temperature (300 K), and $n$: ideality factor). Then, the diffusion current appeared ($n \approx 1$) over the voltage, which confirmed the fabrication of ideal p–n junctions. The current density for the p–n diode on the OVPE-GaN wafer was higher than that on the HVPE-GaN wafer in the region over approximately 3 V, and the difference in current density between both wafers increased with increasing forward voltage. The specific $R_{on}$ of the OVPE-GaN wafer was lower than that of the HVPE-GaN wafer. Surprisingly, $R_{on}$ of the p–n diode on the OVPE-GaN wafer suddenly decreased starting from approximately 4.5 V. At 5.5 V, the $R_{on}$ of the HVPE-GaN wafer was 0.68 mΩ cm$^2$, whereas that of the OVPE-GaN wafer was 0.08 mΩ cm$^2$, which is an extremely low value. No major differences in contact properties of Pd$^{+}$+GaN/P$^{+}$+GaN were found between epitaxial layers simultaneously grown on the OVPE-GaN and the HVPE-GaN wafers; hence, the largely lowered $R_{on}$ was considered to come from the enhanced conductivity modulation. In contrast, $R_{on}$ increased at 5.8 V or more for the OVPE-GaN and HVPE-GaN wafers, presumably due to the influence of heat. The drastic conductivity modulation enhancement of the p–n diode on the OVPE-GaN wafer compared to that on the HVPE-GaN wafer was thought to be caused by high efficient photon recycling$^{9,30}$ due to the low dislocation density and high carrier concentration of the OVPE-GaN wafer. The dislocation density of the OVPE-GaN wafer was as low as approximately 1/30 of that of the HVPE-GaN wafer. Therefore, the p–n diode on the OVPE-GaN wafer had fewer non-radiative recombination centers between the valence band and conduction band than that on the HVPE-GaN wafer, consequently, photon emission was more efficient on the OVPE-GaN wafer. In other words, highly efficient photon emission in the n-GaN layer promoted electron emissions from ionized Mg acceptors to the conduction band in the p-GaN layer, and increased the number of neutralized Mg acceptors.$^{31,32}$ Moreover, neutralized Mg acceptors were likely to capture valence electrons, thereby increasing the number of holes. As the number of holes in the p-GaN layer increased, more conduction electrons were injected from the GaN substrate side to maintain electrical neutrality. As the number of conduction electrons in the OVPE-GaN wafer was approximately 45 times higher than that in the HVPE-GaN wafer, it was estimated that the injection amount of conduction electrons increased significantly for the OVPE-GaN wafer. Therefore, we surmised that the p–n diode on the OVPE-GaN wafer exhibited an extremely low $R_{on}$.

In this study, OVPE-GaN wafers with a low dislocation density, low resistivity, and high carrier concentration were shown to be promising materials for improving the characteristics of vertical GaN p–n diodes. The OVPE-GaN wafers had a very high oxygen concentration in the order of $10^{20}$ atoms cm$^{-3}$. However, the MOVPE-GaN layer on the OVPE-GaN wafer was of very high-quality, and could be fabricated without the occurrence of oxygen diffusion from the OVPE-GaN wafer and without dislocations and cracks at the interface. In addition, the specific $R_{on}$ of the p–n diode on the OVPE-GaN wafer was 1/8 of that for the diode on the HVPE-GaN wafer, and it was assumed that the effects of a low dislocation density and high carrier concentration were significant. Thus, GaN p–n diodes are the basic structure of vertical GaN power devices, and we believe that OVPE-GaN wafers are a key material for improving the performance of other vertical devices as well.

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