I. INTRODUCTION

Recent progress in high-power/high-frequency field-effect transistors (FETs) based on GaN and its related heterostructures has demonstrated that they are key devices for next-generation high-density communication systems. However, these devices still have surface/interface-related problems, including collapse in drain current, excess gate leakage, and formation high-density communication systems. However, these devices still have surface/interface-related problems, which may induce defects on the processed GaN and AlGaN surfaces. A surface passivation process consisting of a suitable surface treatment and the formation of the insulated gate (IG) and passivation structure can solve these problems. In this regard, understanding and controlling surface properties of GaN and GaN-based heterostructures are of utmost importance.

For a passivation process, it is important to investigate cleaning processes for GaN and AlGaN surfaces. However, there are a few reports on the processed surfaces such as chemically treated surfaces, plasma-treated surfaces, etc. King et al. and Hartlieb et al. have investigated wet and dry cleaning processes for GaN and AlN surfaces, and proposed the ammonia-based high-temperature chemical vapor process. Our group has investigated correlation between chemical and electronic properties of GaN and AlGaN surfaces after various types of surface treatments and reported that the surface treatment using N₂ plasma excited by electron-cyclotron-resonance (ECR) source was very effective in improving the electronic properties of GaN and AlGaN surfaces.

For the final stage of surface passivation and insulated gate structures, the use of dielectric films is indispensable. In this regard, there have been several studies on the properties of metal–insulator–semiconductor (MIS) structures using GaN and the surface passivation of GaN/AlGaN heterostructure field effect transistors (HFETs). A pioneering work on the GaN MISFET using a SiNx gate was reported by Binari et al. They deposited a SiNx film on GaN by radio-frequency (rf) plasma enhanced chemical vapor deposition. However, the devices displayed low transconductance (g_m) due to high-density interface states. Kawai and co-workers have demonstrated good dc performance of the GaN IG FET using an epitaxial AlN layer as a gate dielectric. However, it is very difficult to suppress the leakage current through AlN because of the difficulty of growing high-quality AlN films. Hashizume, Nakasaki and Hasegawa demonstrated for the first time that good interface properties can be realized in SiNx/GaN passivation structures prepared by the ECR-N₂ plasma treatment and ECR-assisted chemical vapor deposition (ECR CVD). Thereafter, SiNx-based surface passivation
structures have been applied to the GaN/AlGaN HFETs.\textsuperscript{1,15–19} Green \textit{et al.}\textsuperscript{15} and Lee \textit{et al.}\textsuperscript{16} reported the improvement of rf-power performance in the GaN/AlGaN HFETs. The reduction of current collapse was reported in the SiN\textsubscript{x} IG GaN/AlGaN HFET,\textsuperscript{17} or the SiN\textsubscript{x}-passivated GaN/AlGaN HFETs.\textsuperscript{1,18,19}

Other dielectrics such as SiO\textsubscript{2}, Ga\textsubscript{2}O\textsubscript{3}, MgO and the native oxide of AlGaN have also been applied to the surface passivation of GaN and AlGaN surfaces. Therrien \textit{et al.}\textsuperscript{20} reported the passivation process including separate plasma oxidation of GaN and the deposition of thick SiO\textsubscript{2} film using remote plasma. Hong \textit{et al.}\textsuperscript{21} demonstrated that the Ga\textsubscript{2}O\textsubscript{3}(Gd\textsubscript{2}O\textsubscript{3})/GaN system fabricated by molecular beam epitaxy (MBE) and electron beam evaporation showed low interface state densities. Gaffey \textit{et al.}\textsuperscript{22} reported good interface properties of the SiO\textsubscript{2}/GaN structures prepared by jet vapor deposition. Inoue and co-workers\textsuperscript{23} fabricated the IG AlGaN/GaN HFET using native oxide of AlGaN itself formed by thermal oxidation at 900 °C. Luo \textit{et al.}\textsuperscript{24} reported the passivation effects of the MBE-grown MgO films on the AlGaN/GaN HFETs.

In spite of these efforts, properties of insulator-semiconductor interfaces of GaN and AlGaN are not fully understood and successful surface passivation of GaN/AlGaN HFETs is not achieved.

In this article, we present a systematic investigation on effects of ECR-plasma processing and SiO\textsubscript{2}- and SiN\textsubscript{x}-based passivation on chemical and electrical properties of GaN and AlGaN surfaces. We used the ECR-plasma process for the surface treatments and the deposition of dielectrics, because it is a remote plasma process and it utilizes ions with low energies of 10 to several tens of eV. It is also shown that an Al\textsubscript{2}O\textsubscript{3}-based surface passivation structure drastically improves the electrical properties of GaN/AlGaN HFETs. Table I summarizes values of band gap, dielectric constant, and breakdown field for dielectrics previously applied or to be applicable to surface passivation of AlGaN. Those for Al\textsubscript{2}O\textsubscript{3}/Ga\textsubscript{x,Ga\textsubscript{1-x}}N are also listed. Among them, Al\textsubscript{2}O\textsubscript{3} is very attractive as an insulated gate for GaN/AlGaN HFETs because it has larger bandgap than that of Al\textsubscript{0.3}Ga\textsubscript{0.7}N, a high dielectric constant and a high breakdown electric field. Furthermore, Al\textsubscript{2}O\textsubscript{3} is one of the native oxides of AlGaN. Thus, we developed the formation process of a thin Al\textsubscript{2}O\textsubscript{3} layer on AlGaN by a combination of molecular beam deposition of Al and the subsequent ECR-O\textsubscript{2} plasma oxidation.

### II. EXPERIMENT

#### A. GaN and GaN/AlGaN sample structures

Figure 1 shows schematic illustrations of GaN and GaN/AlGaN sample structures. High-quality epitaxial GaN wafers grown on sapphire substrates by metal organic vapor phase epitaxy (MOVPE) were used in this study. A buffer GaN layer (LT-GaN) was grown at low temperatures (500–550 °C) followed by the growth of a Si-doped GaN layer using SiH\textsubscript{4} as a dopant source at 1000 °C. Typical values of electron concentration and mobility of the Si-doped layer at room temperature (RT) is 2 × 10\textsuperscript{17} cm\textsuperscript{-3} and 500 cm\textsuperscript{2}/V s, respectively.

The heterostructure samples grown by MOVPE consist of undoped GaN, undoped Al\textsubscript{2}Ga\textsubscript{1−x}N, Si-doped Al\textsubscript{2}Ga\textsubscript{1−x}N, and undoped Al\textsubscript{x}Ga\textsubscript{1−x}N, as shown in Fig. 1(b). The Al content, x, ranged from 0.25 to 0.30. The samples showed clear Shubnikov–de Haas oscillation in magnetoresistance characteristics at 2 K, and the electron concentrations determined from the Landau plots of the oscillation were in good agreement with the values obtained by the Hall measurement at the same temperature. These results clearly indicated the existence of two-dimensional electron gas (2DEG) at the GaN/AlGaN heterointerfaces. Typical values of the electron concentration and mobility of 2DEG at RT were 1.1 × 10\textsuperscript{13} cm\textsuperscript{-2} and 900 cm\textsuperscript{2}/V s, respectively.

#### B. Surface passivation and device fabrication processes

The surface passivation process started from a simple wet treatment in organic solvents at RT and in an NH\textsubscript{3}OH solution at 50 °C for 5–10 min. The NH\textsubscript{3}OH treatment is effective in reducing natural oxides on GaN and AlGaN surfaces.\textsuperscript{7,8}

For successful surface passivation of GaN and AlGaN surfaces, \textit{in situ} processing and characterization were performed in the ultra-high-vacuum (UHV) multichamber system. All the chambers are connected to each other through a UHV tunnel chamber whose base pressure is 2 × 10\textsuperscript{−10} Torr.
For a pretreatment of the deposition of dielectric films, GaN and GaN/AlGaN surfaces were exposed to N$_2$ plasma or H$_2$ plasma excited by an ECR source with microwave (2.75 GHz) power of 50 W. The processing temperature and time were 280 °C and 1–5 min, respectively. The deposition of SiO$_2$ and SiN$_x$ was performed at 280 °C by ECR CVD, using SiH$_4$ and N$_2$O as precursors for SiO$_2$ and SiH$_4$ and N$_2$ for SiN$_x$, respectively. The thickness of the deposited films ranged from 20 to 70 nm. We obtained refractive index values of 1.47 and 1.98 for the deposited SiO$_2$ and SiN$_x$ films, respectively.

The device isolation was performed by an ECR-assisted reactive ion beam etching using a gas system consisting of CH$_4$, H$_2$, Ar, and N$_2$. The addition of N$_2$ to the gas system is very effective in achieving smooth and stoichiometric GaN and AlGaN surfaces even after the etching. As an Ohmic contact, a Ti/Al/Ti/Au layered structure was deposited on the surfaces of GaN and GaN/AlGaN followed by the annealing at 600 °C for GaN and 800 °C for GaN/AlGaN for 2 min in N$_2$ ambient. A Ni/Au contact was used as a Schottky gate on GaN and AlGaN.

C. Characterization methods

The surface chemical properties of GaN and GaN/AlGaN samples were characterized by x-ray photoelectron spectroscopy (XPS). The XPS system is connected to the UHV multichamber system, thereby in situ XPS characterization of the processed GaN and GaN/AlGaN surfaces is available. The XPS measurement system (Perkin Elmer PHI 1600C) consists of a spherical capacitor analyzer and a monochromated Al $K \alpha$ x-ray source ($\hbar \nu = 1486.6$ eV). The binding energies of the spectra were carefully calibrated through separate measurements of Cu 2$p_{3/2}$, Ag 3$d_{5/2}$, and Au 4$f_{7/2}$ peak positions. Atomic force microscope (AFM) observation of GaN surfaces after various types of surface treatments was carried out using a Nanoscope II (Digital Instruments). Current–voltage ($I$–$V$) and capacitance–voltage ($C$–$V$) measurements were performed using HP 4156A semiconductor parameter analyzer and HP 4192A LF impedance analyzer, respectively.

III. RESULTS AND DISCUSSION

A. Effects of plasma processing on chemical and electronic properties of GaN and AlGaN surfaces

Figure 2 shows XPS Ga 3$d$ and Al 2$p$ spectra obtained from the air-exposed Al$_{0.25}$Ga$_{0.75}$N surface. Both the Ga 3$d$ and Al 2$p$ peaks showed asymmetric features with shoulders at higher binding energies. We assigned these higher peaks to Ga$_2$O$_3$ and Al$_2$O$_3$, respectively. For deconvolution of the observed spectra, we have separately determined the peak energies and linewidths of the spectra in the Al$_2$O$_3$ and Ga$_2$O$_3$ phases, using a crystalline sapphire substrate and a sample prepared by oxidizing the metallic Ga layer, respectively. Both spectra include large amounts of oxides. This feature was responsible for the disorder in chemical composition, leading to the deterioration of surface electronic properties of GaN and AlGaN.

In order to remove the disordered layer including natural oxides, the ECR-assisted plasma treatments were employed on AlGaN surfaces. Figure 3 shows the integrated XPS intensities of O 1$s$ and C 1$s$ normalized by the N 1$s$ intensity. After a wet treatment in NH$_4$OH solution, the O 1$s$ intensity was reduced remarkably, because the Ga$_2$O$_3$ component can easily be dissolved in alkali solutions. However, the C 1$s$ intensity remained almost unchanged. Both H$_2$- and N$_2$-plasma treatments at 280 °C for 1–5 min are effective in removing oxides and contamination from the AlGaN surface, as shown in Fig. 3.

However, the effects of the surface processing on electronic properties of GaN and AlGaN surfaces are very different between H$_2$-plasma and N$_2$-plasma treatments. The AFM images of the plasma-treated GaN surfaces are shown in Fig. 4. The ECR-N$_2$ plasma treated GaN exhibited a smooth surface with a root-mean-square (rms) roughness of 0.29 nm. The surface morphology showed the characteristic feature dominated by monolayer steps, and many of the steps were terminated by the large dark pits at the edges which could be
correlated to the surface termination of the edge-screw mixed dislocations. After the H₂-plasma treatment, however, the surface feature changed drastically. Large numbers of particles with diameters of about 20–30 nm were found on the treated GaN surface, as shown in the right-hand image in Fig. 4. From the XPS analysis, these particles were assigned to Ga droplets.

The surface state density ($D_{SS}$) distributions of the ECR-plasma treated GaN surfaces were compared in Fig. 5. The $D_{SS}$ values were determined by the C–V analysis (Terman method) using SiNₓ-covered GaN samples. Except for the plasma treatments, the samples were processed under the same condition exactly. As clearly seen in Fig. 5, a localized surface level was found at approximately $E_c - 0.5$ eV for the H₂-plasma treated surfaces, while continuous $D_{SS}$ distributions were observed in both the N₂-plasma treated surface and control sample without plasma treatment. Thus, the H₂-plasma treatment causes the formation of surface defects on the GaN surface.

In order to investigate the effects of plasma processing on the transport properties of 2DEG at GaN/AlGaN heterointerface, a gateless HFET structure shown in Fig. 6(a) was prepared. The current–voltage ($I_{DS} - V_{DS}$) characteristics of the fabricated gateless HFET are shown in Fig. 6(b). We fabricated more than 100 devices on one chip of the GaN/AlGaN structure before plasma treatments. After measuring the initial $I–V$ characteristics of the devices, the chip was divided into two samples: one for the H₂-plasma treatment and the other for the N₂-plasma treatment. After the plasma treatments, we compared the $I–V$ characteristics for the certain devices that had the same initial $I–V$ characteristics. All the devices showed a steep linear increase of current followed by current saturation. After the H₂-plasma treatment for 1 min, a large current reduction was observed. On the other hand, N₂-plasma treatment slightly increased currents. The Hall measurement results showed that the change in currents after the plasma treatments was not due to change in mobility but due to the change in the 2DEG density. Additionally, the H₂-plasma-treated devices exhibited serious hysteresis in dc $I–V$ curves as well as transient behavior in pulse-responses of the drain currents. These results indicate that the H₂-plasma treatment produced high-density surface defect states on the AlGaN surface, causing various kinds of instabilities in the 2DEG transport at GaN/AlGaN interface. No such effects were observed in the N₂-plasma treated devices.

Figure 7 shows the XPS core-level spectra taken from the AlGaN surfaces after the treatments in H₂ plasma and N₂
plasma for 1 min. We detected the photoemission from the AlGaN surfaces using an electron escape angle of 10°, implying that the obtained spectra reflected information from the topmost region (within 1.0–1.5 nm). In the N 1s core-level spectrum of the H2-plasma treated sample, a clear shoulder peak appeared at around 399 eV, corresponding to the N–Hx bond. In addition, the decrease in the peak intensity of the N 1s line was observed. The V/III ratio of the AlGaN surface after the H2-plasma treatment was found to be far below unity (0.79), clearly indicating the depletion of N atoms at the surface. The broadening of spectrum was also observed in Al 2p core level. Thus, the H2-plasma treatment for only 1 min produced disordered layer at the AlGaN surface with a highly nonstoichiometric chemical phase.

Figure 8 schematically shows a possible reaction process on GaN or AlGaN surfaces during the H2-plasma treatment. It is expected that highly active hydrogen plasma species such as hydrogen radicals react with the surface to form volatile NHx products, as manifested as a shoulder in the XPS N 1s spectrum (Fig. 7). This process led to the N depletion and left Ga and/or Al metallic clusters at the topmost GaN or AlGaN surfaces. Such a surface reaction process in H2 plasma caused the formation of surface disordered layer and could introduce surface defect states including N–vacancy-related defects. Neugebauer and Van de Walle,29 and Boguslawski et al.30 have calculated energy levels of native point defects in GaN using the first-principle supercell method. They concluded that the simple N–vacancy creates resonant levels in the conduction band and contributes to the conduction band edge, supplying free electrons in GaN. On the other hand, recent results of calculation using the Green’s function method by Yamaguchi and Junnarkar31 predicted that the VN defect can form an s-like discrete deep level within the gap. Thus, these suggest a possibility that N–vacancy-related clusters and/or defects may act as donor-type deep levels.

On the other hand, no such decrease of N atoms was observed after the N2-plasma treatment, although it was also effective in removing oxides from the surface. As compared with the air-exposed AlGaN surface, the peak shift of 0.4–0.5 eV toward higher binding energies was observed in the Al2p spectrum in the N2-plasma treated AlGaN surface, as shown in Fig. 7. A similar peak shift was also observed in XPS core levels at the N2-plasma treated GaN surface. These peak shifts indicate the reduction of the surface band bending.9 Thus, the ECR-N2 plasma treatment seems to partially recover or terminate surface defects, leading to the reduction of densities of surface states on GaN and AlGaN.

B. Surface passivation of GaN and GaN/AlGaN surfaces by SiO2 and SiNx

Electrical properties of the passivated GaN surfaces were investigated using MIS structures. Figure 9 shows typical C–V curves obtained from the SiO2/n-GaN and the SiNx/n-GaN MIS structures where the dielectric films were deposited on the GaN surfaces after the ECR-N2 plasma treatment. Also shown are the calculated curves based on the accumulation, depletion and inversion behavior for the MIS structure.32 For calculation, an effective electron mass of...
0.2\,m_0\), an effective hole mass of \(0.8\,m_0\), a dielectric constant of 9.5 and an energy gap of 3.40 eV were used for GaN at room temperature.

Poor \(C-V\) behavior was observed in the SiO\(_2\)-passivated sample, in spite of the fact that a natural oxide layer was almost removed from the GaN surfaces by the N\(_2\)-plasma treatment. A large discrepancy between the measured and calculated curves, including gradual slope in capacitance change from the accumulation region to the depletion region, indicates the existence of high-density interface states. In contrast, the SiN\(_x\)/GaN structure showed better \(C-V\) characteristics. The measured \(C-V\) curve was very close to the calculated one, and clear deep depletion behavior was observed even at room temperature. Similar deep depletion features with no inversion characteristics were reported in SiO\(_2\)/GaN (Ref. 22) and SiO\(_2\)/SiC systems,\(^\text{33}\) because the generation rate of the minority carriers (holes in this case) is extremely low at room temperature in wide-gap semiconductor MIS systems. These results indicated that the SiN\(_x\)-gate control of surface potential was achieved over a remarkably wide within the bandgap of GaN.

Figure 10 shows distributions of interface state density \((D_{it})\) of the SiO\(_2\)/\(n\)-GaN and SiN\(_x\)/\(n\)-GaN structures, which were calculated by applying the Terman method to the measured \(C-V\) curves at room temperature.\(^\text{32}\) One of the essential conditions for the Terman method is that the change in interface charges corresponding to the state density can appear in the shift in the measured \(C-V\) curve. For wide-gap semiconductors, however, there are some cases where this condition does not apply. It is expected, for example, that the states near midgap have large time constants for carrier emission. In this case, the charging state is remained almost unchanged during the gate voltage sweep even if the interface states have high densities. Thus, we estimated the limitation of applying the Terman method to calculation of interface state density in terms of the carrier emission time from the interface state at RT. The results showed that one cannot evaluate densities of interface states at the energies below \(E_C-1.0\,eV\) from \(C-V\) measurements at RT, due to the extremely long carrier emission times from the corresponding states.

As shown in Fig. 10, the presence of high-density interface states seriously disturb a smooth gate control of the surface potential for the SiO\(_2\)/\(n\)-GaN structure. We detected an interfacial Ga-oxide peak in XPS Ga\(_{3d}\) spectra in the separate SiO\(_2\)/GaN sample having a very thin (2 nm) SiO\(_2\) layer, as shown in Fig. 11(a). In the initial stage of the SiO\(_2\) deposition, unexpected and uncontrollable oxidation reaction could take place at the GaN surface due to the supply of oxygen-related active ions and/or radicals. Formation of such an interfacial oxide is believed to be one of the reasons for the degradation of electrical properties of the SiO\(_2\)/GaN interface.

In comparison with the SiO\(_2\)/\(n\)-GaN interface, the SiN\(_x\)/GaN structures showed relatively low densities of interface states, as shown in Fig. 10. Since the control
SiNₓ/GaN sample without the N₂-plasma treatment showed higher Dₛ values ranging from 3×10¹¹ to 5×10¹¹ cm⁻² eV⁻¹, the N₂-plasma treatment is effective in improving interface properties. No interfacial oxide was detected at the SiNₓ/GaN interface, as shown in Fig. 11(b). Furthermore, the Raman spectra taken by the backscattering geometry at RT indicated no pronounced stress at the GaN surface covered with a SiNₓ film.

The present SiNₓ-based passivation was applied to the surface of GaN/AlGaN heterostructure. Figure 12 shows the C–V characteristics of the SiNₓ-gate structure formed on the GaN/AlGaN surface. The thickness of the SiNₓ film is 41 nm and the electrode diameter is 600 μm. The measured C–V curve clearly indicates a plateau region, reflecting the presence of 2DEG at the GaN/AlGaN interface. Thus, the capacitance value at the plateau region can easily be estimated from the total capacitance given by the AlGaN barrier layer, thereby leading to the expected modulation of the 2DEG density.

All these results indicated that the SiNₓ-based passivation structure achieved good electronic properties of the GaN and AlGaN insulator–semiconductor interfaces. However, a negative issue appeared in the leakage characteristics. Figure 13(a) showed I–V characteristics of the Al/SiNₓ/n–Al₀.₃Ga₀.₇N structure with the SiNₓ thickness of 20 nm. For comparison, the I–V curves of Ni/n–Al₀.₃Ga₀.₇N and Al/SiNₓ/n–Si structures were plotted in Fig. 13(a). As expected, the SiNₓ-insulated gate drastically reduced leakage currents in the reverse bias condition, as compared with the Schottky gate structure. For forward bias, however, a steep increase of leakage current was observed at around V₆ = 1.5 V for the SiNₓ/n–Al₀.₃Ga₀.₇N system, while the SiNₓ/n–Si structure keeps the low level of leakage current. We have replotted the I–V data at a large leakage region for the Al/SiNₓ/n–AlGaN structure in the form of log (J/E²) vs 1/E (here, J is the current density and E is electric field). The result is shown in Fig. 13(b). The linear relation of log (J/E²) vs 1/E indicates that the leakage is governed by the Fowler–Nordheim (FN) tunneling mechanism. From the fitting to this linear relation, we obtained the tunneling barrier height of 0.75 eV, corresponding to the conduction band offset, ΔEₛ, between SiNₓ and Al₀.₃Ga₀.₇N. In the fitting, we assumed the effective mass of electron in SiNₓ to be mₑ = 0.30 mₒ (mₒ: electron rest mass), often used in the SiO₂/Si system.

In order to investigate a band alignment between SiNₓ and Al₀.₃Ga₀.₇N, the XPS analysis was employed in the SiNₓ/Al₀.₃Ga₀.₇N structures. Figure 14(a) shows the N 1s spectrum obtained from a thick SiNₓ film (20 nm) on Al₀.₃Ga₀.₇N. From the onset of the energy loss peak, we estimated the bandgap of SiNₓ to be 4.9 eV. Miyazaki³⁴ reported the value of 4.75 eV for the SiNₓ/Si structure. Then, we estimated the valence band offset, ΔEᵥ, between SiNₓ and Al₀.₃Ga₀.₇N also from the XPS analysis.³⁵,³⁶ This was carried out by measuring the energy difference between the Si 2p and Al 2p core levels in the SiNₓ/Al₀.₃Ga₀.₇N structures having a thin SiNₓ film (2 nm). The band alignment obtained is schematically shown in Fig. 14(b). A relatively small value of ΔEᵥ = 0.7 eV was obtained, and this is well in

Fig. 12. C–V characteristics of the SiNₓ-gate structure formed on the GaN/AlGaN surface.

Fig. 13. (a) I–V characteristics of the Al/SiNₓ/n–Al₀.₃Ga₀.₇N structure with the SiNₓ thickness of 20 nm. For comparison, the I–V curves of Ni/n–Al₀.₃Ga₀.₇N and Al/SiNₓ/n–Si structures are plotted. (b) The plots of log(J/E²) vs 1/E for the SiNₓ/n–Al₀.₃Ga₀.₇N structure.
agreement with that estimated by the F-N fitting method [Fig. 13(b)]. Thus, a serious leakage problem can arise from the band alignment at the SiN$_x$/Al$_{0.3}$Ga$_{0.7}$N interface, thereby limiting the application of the SiN$_x$-based passivation structure to an insulated gate structure on GaN/AlGaN HFET system.

**C. Novel Al$_2$O$_3$-based passivation structure**

As described in the Introduction, an Al$_2$O$_3$ film has a large band gap, a large dielectric constant and a high breakdown field. This indicates an advantage of Al$_2$O$_3$ as an insulated gate for the GaN/AlGaN HFETs. In order to form a thin Al$_2$O$_3$ film on AlGaN and to control the Al$_2$O$_3$/AlGaN interface properties, we have employed the molecular beam deposition of Al and the subsequent ECR-O$_2$ plasma oxidation process. A comparable rms roughness value of 0.33 nm to the as-grown sample was obtained from the passivated AlGaN surface. Figure 15 shows the XPS Al$_2$p and O 1$s$ spectra obtained from the GaN/AlGaN surface after the formation of the thin Al oxide layer. In the Al$_2$p spectra, no metallic Al peak was detected. The peak could be deconvoluted into two components corresponding to the Al–O bond and the Al–N bond. The Al–N peak intensity increased with an escape angle of photoelectrons. On the other hand, the Al–O peak intensity almost remained unchanged, similar to the behavior of the O 1$s$ peak. Furthermore, we confirmed no change in the spectra of Ga- and N-core levels before and after the formation process. These results indicated that a thin Al oxide layer was successfully formed on the top of GaN/AlGaN surface without disordering the chemical properties of the underneath AlGaN surface. From the comparison of integrated intensity ratios of O 1$s$ to Al$_2$p between the formed Al oxide and a crystalline sapphire substrate as a standard, the composition of the present Al oxide was found to be Al$_2$O$_3$. The thickness of the Al$_2$O$_3$ layer was estimated to be 3.5 nm from the angle-resolved analysis of the Al$_2$p core-level intensities.

Figures 16(a) and 16(b) show the XPS O 1$s$ spectrum of the Al$_2$O$_3$-passivated GaN/Al$_{0.3}$Ga$_{0.7}$N surface and the valence-band spectra of the surface before and after the passivation. The band gap, $E_G$, of the thin Al$_2$O$_3$ layer can be determined from the onset position of the energy loss peak in the O 1$s$ spectrum. As shown in Fig. 16(a), this analysis gave $E_G = 7.0$ eV. The valence band spectrum before the passivation showed a characteristic feature of “free” AlGaN surface consisting of Ga 4$s$, Al 3$p$, and N 2$p$ orbits. After the surface passivation, a drastic change in the spectrum appeared, reflecting the formation of the Al$_2$O$_3$ layer. The valence band offset, $\Delta E_V$, was estimated to be 0.8 eV from the energy difference between the leading edges of the valence-band spectra before and after the passivation, as shown in Fig. 16(b). From the values $E_G = 4.1$ eV for Al$_{0.3}$Ga$_{0.7}$N, $E_G = 7.0$ eV for Al$_2$O$_3$, and $\Delta E_V = 0.8$ eV, the conduction band offset, $\Delta E_C$, was estimated to be 2.1 eV. The obtained band alignment between Al$_2$O$_3$ and Al$_{0.3}$Ga$_{0.7}$N is shown in Fig. 16(c).
This band structure led to the reduction of leakage currents at forward bias as compared with the Ni-Schottky gate and the SiNx-insulated gate structures, as shown in Fig. 17, in spite of a very small thickness of the Al2O3 layer of 3.5 nm. A slope of gradual increase in leakage current for the Al2O3-insulated gate at forward bias is less than that of the SiNx-insulated gate, indicating a direct tunneling mechanism in leakage through the Al2O3 layer rather than the FN tunneling.

D. Application of the Al2O3-based passivation structure to insulated-gate GaN/AlGaN HFET

The present Al2O3-based passivation structure was applied to the fabrication of an insulated-gate type GaN/AlGaN HFET. The device structure is schematically shown in Fig. 18. After the device isolation and Ohmic electrode metallization, the surface of GaN/AlGaN HFET structure was passivated by the thin Al2O3 layer through a process described in the previous section. Subsequently, the submicron metal-gate patterns were defined and fabricated by a combination of electron-beam lithography and lift-off techniques.

Figure 19 shows typical drain I–V characteristics of the fabricated Al2O3 insulated-gate (IG) HFET and Schottky-gate (SG) HFET with a gate length of 0.4 μm. The Al2O3 IG HFET showed a good gate controllability up to VGS = +3 V and achieved high drain saturation current of about 0.8 A/mm, as shown in Fig. 19(a). These characteristics are better than SG HFET. The observed maximum gm value is 120 mS/mm.

We investigated current collapse characteristics under a quiescent gate voltage stress. The result is shown in Fig. 20. During the measurement, the drain voltage, VDS, was kept at 15 V. First, we set the initial gate voltage as VGS0 = 0 V for 10 s. After that, VGS was switched to +1 V instantaneously and then decreased to −8 V with a sweeping rate of 0.2 V/s. This measurement mode is indicated by “normal mode” in Fig. 20. In the “stress mode,” on the other hand, we applied VGS = −8 V (far below the threshold voltage) for 10 s as the initial stress of the gate voltage. Then, the VGS sweeping was carried out from +1 V to −8 V. As shown in Fig. 20(a), a significant collapse was observed more than 10% in the drain currents for the SG HFET. On the other
hand, no current collapse was observed for the IG HFET. This indicates a remarkable advantage of the present Al₂O₃-based passivation structure.

The current collapse effects have often been observed in GaN/AlGaN SG HFETs under quiescent gate stress or pulse-mode gate stress. The collapse is also induced by drain stress. As described in Sec. III A, the H₂-plasma treatment produces N–vacancy-related defects on GaN and AlGaN surfaces. We have also found that the ECR-N₂ plasma treatment is very effective in suppressing the formation of such N–vacancy-related surface defects. Based on these findings, Hasegawa and co-workers have recently proposed a unified surface model that the electronic states consisting of N–vacancy related surface levels and U-shaped surface state continuum are responsible for the electron trapping on GaN/AlGaN heterostructure surfaces. In case of SG HFETs, electrons can be injected into the surface states assisted by large leakage currents under the deep gate stress. The present Al₂O₃-based passivation process including ECR-N₂ plasma treatment can suppress the formation of N–vacancy related near-surface levels as well as surface states. In addition, the Al₂O₃ IG structure remarkably reduces the gate leakage currents. Thus, our Al₂O₃-based insulated gate and surface passivation structure is very effective in suppressing the current collapse effects, thereby leading to the reliability improvement of AlGaN/GaN HFETs.

IV. CONCLUSION

We have investigated the effects of plasma processing, formation of Si-based dielectrics and formation of a thin Al₂O₃ film on the chemical and electronic properties of GaN and AlGaN surfaces. The ECR-H₂-plasma treatment was found to produce nitrogen–vacancy-related defect levels at GaN and AlGaN surfaces, while the treatment in ECR-N₂ plasma improved the electronic properties of surfaces. The deposition of SiO₂ film on GaN and AlGaN surfaces induced high-density interface states, due to unexpected and uncontrollable oxidation reactions on the surfaces during the deposition process. In comparison, the SiNₓ/GaN passivation structure prepared by ECR CVD with the N₂-plasma pretreatment showed good interface properties with the minimum D_it value of 1 × 10¹¹ cm⁻² eV⁻¹. No pronounced stress remained at the SiNₓ/GaN interface. Excess leakage currents based on the Fowler–Nordheim tunneling were observed in the SiNₓ/Al₀.₃Ga₀.₇N structure, due to a relatively small conduction band offset, ΔE_C, of 0.7 eV between SiNₓ and Al₀.₃Ga₀.₇N. A novel Al₂O₃-based passivation structure was successfully formed on the AlGaN surface by molecular beam deposition of Al and the subsequent ECR-O₂-plasma oxidation. In situ XPS analysis showed a band gap of 7.0 eV for the formed Al₂O₃ layer with a thickness of 3.5 nm and a sufficiently large ΔE_C of 2.1 eV between Al₂O₃ and Al₀.₃Ga₀.₇N. The GaN/AlGaN insulated-gate HFETs having the Al₂O₃-based passivation structure showed a good gate control of drain currents up to VGS = +3 V and achieved drain saturation current of 0.8 A/mm. The observed maximum g_m value is 120 mS/mm. No current collapse was observed in the Al₂O₃ IG HFETs. These results indicate a remarkable advantage of the present Al₂O₃-based passivation structure for GaN/AlGaN HFETs, leading to the reliability improvement of AlGaN/GaN HFETs.
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