SiO₂ film deposition and subsequent high-temperature annealing resulted in the generation of a two-dimensional electron gas (2DEG) at Al(Ga)N/GaN hetero-interfaces, of which the 2DEG was originally fully depleted. The obtained mobilities and sheet carrier concentrations were over 1100 cm²/Vs and 3.0 × 10¹⁵ cm⁻², respectively. Surface energy lowering, which is proof of the generated 2DEG, was observed by electron state analysis using hard X-ray photoelectron spectroscopy. This damage-less method that selectively generates a 2DEG can contribute not only to improving some characteristics in existing devices but also toward creating entirely novel devices.

Introduction: AlGaN/GaN high-electron-mobility transistors (HEMTs) are currently being applied to high-power RF devices [1, 2], as well as to high-power switching devices [3, 4]. This is due to the high electric breakdown field of GaN and a high electron mobility of two-dimensional electron gas (2DEG) at an AlGaN/GaN hetero-interface. Although it is impossible to selectively control the 2DEG density, the 2DEG density of these conventional AlGaN/GaN HEMTs can be controlled by adjusting the Al composition and thickness of the AlGaN barrier layer [1, 2, 5]. These adjustments are mostly performed during epitaxial growth. Moreover, the dry etching process can be employed to selectively decrease the 2DEG density by reducing the thickness of the AlGaN barrier layer [3, 4]; however, it causes the deterioration and dispersion of some device characteristics. Alternatively, SiN deposition and fluorine plasma exposure on an AlGaN barrier layer have been reported to selectively control the 2DEG density without adjusting the thickness and Al composition of the barrier layer [6–8]. However, these studies were achieved by using a hetero-epitaxial structure, of which the 2DEG was not fully depleted of the barrier layer [6–8]. However, these studies were achieved by using hard X-ray photoelectron spectroscopy. This damage-less method that selectively generates a 2DEG can contribute not only to improving some characteristics in existing devices but also toward creating entirely novel devices.

Device structure: Figure 1 shows a cross-sectional structure of the samples used to investigate the characteristics of the 2DEG. Al(Ga)N/GaN hetero-epitaxial layers were grown by metal–organic chemical vapour deposition on semi-insulated SiC substrates. Three kinds of barrier layers consisting of 1 nm-thick AlN, 5 nm-thick Al₀.₃₅Ga₀.₆₅N and 7 nm-thick Al₀.₁₅Ga₀.₈₅N were investigated. The 2DEG carrier densities were calculated and found to be less than 1.0 × 10¹⁵ cm⁻². The calculations were performed using the freely available software BandEng (a band diagram simulator developed by Michael Grundmann at the University of California at Santa Barbara) [9]. Fermi-level pinning locations in the calculations were interpolated and extrapolated as 0.95 eV of GaN and 1.7 eV of Al₀.₃₅Ga₀.₆₅N, which were experimentally inferred by Heikman et al. [10].

Ohmic contact regions were formed by Si-ion implantation and subsequent activation annealing at 1150°C for 5 min in N₂ atmosphere [5, 11]. Ohmic electrodes were deposited on the Si-ion implanted region. After the formation of the device isolation regions by ion implantation [12], 30 nm-thick SiO₂ films were deposited by plasma-enhanced chemical vapour deposition. Then post-deposition annealing in N₂ atmosphere was repeatedly performed at a temperature of 300–950°C. Finally, the SiO₂ films were removed using a buffered hydrogen fluoride (BHF) solution. Current density–voltage (I–V) characteristics and Hall effect measurements were performed after each process in the same samples. In addition, no dry etching and fluorine plasma exposure processes were performed during fabrication. Therefore, the degradation and dispersion of the device characteristics would not be considered in this method.

Results and discussion: I–V curves between two ohmic electrodes before and after SiO₂ deposition, after annealing at 800°C, and after SiO₂ removal in three samples with different barrier layers: (a) 1 nm-thick AlN barrier layer, (b) 5 nm-thick Al₀.₃₅Ga₀.₆₅N barrier layer, (c) 7 nm-thick Al₀.₁₅Ga₀.₈₅N barrier layer.

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**Fig. 1** Schematic cross-sectional structure of samples to be investigated

**Fig. 2** I–V curves between two ohmic electrodes before and after SiO₂ deposition, after annealing at 800°C, and after SiO₂ removal in three samples with different barrier layers: (a) 1 nm-thick AlN barrier layer, (b) 5 nm-thick Al₀.₃₅Ga₀.₆₅N barrier layer, (c) 7 nm-thick Al₀.₁₅Ga₀.₈₅N barrier layer.
Three samples with different barrier layers after annealing at 800°C.

Barrier layer | AlN | Al0.15Ga0.85N | Al0.20Ga0.80N
---|---|---|---
Nc (cm^-3) | 3.1 × 10^{12} | 4.2 × 10^{12} | 3.7 × 10^{12}
μhall (cm^2/Vs) | 143 | 1140 | 1270

Fig. 3 Annealing temperature dependences of Rsh estimated from TLM in three samples with different barrier layers.

Fig. 4 Al 1s core level spectra before and after SiO2 deposition, after annealing at 800°C, and after SiO2 removal in the sample with 7 nm-thick Al0.15Ga0.85N barrier layer.

Hall effect measurements were performed with Van der Pauw geometry in the samples annealed at 800°C. The sheet carrier concentrations (Nc) and Hall mobilities (μhall) of all the samples are shown in Table 1. For the two samples with the AlGaN barrier layers, the obtained Nc and μhall were over 3.0 × 10^{12} cm^-2 and 1100 cm^2/Vs, respectively. These are of the same order of magnitude as conventional AlGaN/GaN HEMTs. The results proved the generation of the 2DEGs at the heterointerfaces caused by SiO2 deposition and subsequent high-temperature annealing. The sample with the 1-nm-thick AlN barrier layer had the lowest μhall compared to those obtained for the samples with the AlGaN barrier layers although comparable Nc was obtained. Therefore, the 2DEG with the lowest mobility was generated at the AlN/GaN heterointerface. This low mobility was caused by considerable surface scattering due to the thin barrier layer (1 nm). In addition, the drastic current decrease after the SiO2 removal was attributed to the complete disappearance of the 2DEG.

Electron state analysis using hard X-ray photoelectron spectroscopy (HAXPES) was performed to clarify the phenomenon of 2DEG generation. The HAXPES experiments were conducted at SPring-8 BL16XU with an incident X-ray energy of 7948.2 eV, pass energy of 200 eV, and photoelectron take-off angle of 88°. Figure 4 shows the Al 1s core level spectra of the four samples before and after the SiO2 deposition, after annealing at 800°C, and after SiO2 removal. In these samples, the thicknesses of SiO2 films (~10 nm) were sufficiently thin to detect photoelectrons from the AlGaN/SiO2 interface. After SiO2 deposition, the peak shifted toward a deeper energy state from the initial state. This energy shift indicates a reduction of surface potential that causes an increase in the 2DEG. The reduction in energy could have been led by an increase in positive charges and/or enhancement of the polarization effect due to SiO2 deposition. Moreover, after annealing at 800°C, the spectrum did not change despite the decrease of Rsh, as shown in Figure 2. This result suggests the existence of a donor that is highly concentrated just above the surface Fermi energy and behaves as a positive charge at the AlGaN surface. The spectrum after SiO2 removal completely overlapped with that of the one in the initial state. The electron states at the AlGaN surface were entirely restored and the 2DEG disappeared, as shown in the previous paragraph.

Conclusion: The method used to generate 2DEG at normally depleted AlGaN/GaN hetero-interfaces without varying thickness and Al composition of the AlGaN barrier layer were acknowledged. In this method, SiO2 deposition and subsequent high-temperature annealing were performed. The variations in Nc over 10 orders of magnitude and the obtained Nc and mobility were over 3.0 × 10^{12} cm^-2 and 1100 cm^2/Vs, respectively. Electron state analysis using HAXPES revealed that the surface energy was lowered by SiO2 deposition. This reduction of energy is attributed to 2DEG generation. It was also confirmed that the generated 2DEG completely disappeared after SiO2 removal. Therefore, damage-less, and selective generation of 2DEG can be realized using this method without using any dry etching and fluoride plasma exposure processes.

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