

Systematic study of thermal stability of AlGaN/GaN two-dimensional electron gas structure with SiN surface passivation

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Abstract: An annealing study of the AlGaN/GaN 2DEG structure for HEMTs with or without SiN surface passivation films was conducted with the AlGaN layer thickness dependence taken into consideration. Without SiN, the sheet resistance of the samples with thin AlGaN layers increased significantly upon annealing at 620 and 800°C. In contrast, samples with SiN were thermally stable after annealing at up to 800°C even when the AlGaN layer was as thin as 152 Å. TEM observations revealed that neither surface roughness nor interfacial diffusion at the SiN/AlGaN interface occurred due to annealing. The SiN layer is very effective for passivating an AlGaN surface and improving the thermal stability of a thin-AlGaN 2DEG channel.

Keywords: AlGaN/GaN heterostructure, SiN surface passivation, sheet resistance, thermal stability, AlGaN thickness dependence

Classification: Electron devices

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1 Introduction

AlGa_{0.3}N_{0.7}/Ga_{0.5}N high-electron-mobility transistors (HEMT) have been intensively studied as high-temperature high-power high-frequency electron devices because GaN has a higher breakdown field and larger saturation velocity than GaAs and also exhibits excellent transport properties under a high electric field ($> 100 \text{ kV/cm}$) [1]. One of the main applications of AlGa_{0.3}N_{0.7}/Ga_{0.5}N HEMTs is in the power amplifiers of base stations for wireless communication. This application requires 100-W-class output power in the L-band, and submicrometer-gate AlGa_{0.3}N_{0.7}/Ga_{0.5}N HEMTs whose typical device parameters are AlGa_{0.3}N thickness of $\sim 300 \text{ \AA}$, Al content of $\sim 25\%$, sheet carrier density (n_s) of $\sim 1 \times 10^{13} \text{ cm}^{-2}$ have been demonstrated [2]. On the other hand, by scaling down device dimensions, i.e., reducing gate length (L_g) to around $0.1 \text{ }\mu\text{m}$, RF performance of over a 100-GHz cutoff frequency (f_T) and maximum oscillation frequency (f_{max}) have been achieved [3]. A HEMT structure with a shorter L_g ($< 0.1 \text{ }\mu\text{m}$), shallower channel (AlGa_{0.3}N thickness of 200 \AA), and larger mobility (μ) $\cdot n_s$ product is required for further improvement of RF performance for millimeter-wave applications. In the actual field effect transistor (FET) process, a high-temperature anneal ($\sim 800^\circ\text{C}$) is required in order to form Ti/Al ohmic contacts [4]. Hence, the thermal stabilities of the thin AlGa_{0.3}N layer and two-dimensional electron gas (2DEG) structure are also important.

We conducted an annealing study of AlGa_{0.3}N_{0.7}/Ga_{0.5}N heterostructure wafers for HEMTs and found that the sheet resistance (R_{sheet}) increases when annealing is performed below the growth temperature ($\sim 1000^\circ\text{C}$) and that the increase depends on the AlGa_{0.3}N crystal quality and thickness, especially at thicknesses less than 200 \AA [5, 6]. The origin of the R_{sheet} increase upon annealing would be in the vicinity of the AlGa_{0.3}N surface and caused by surface contamination with O and C atoms [6] and N outdiffusion [7]. To suppress the increase of R_{sheet} , we used SiN surface passivation films on the AlGa_{0.3}N layers. Because SiN forms a low-interfacial-state-density interface to GaN and AlGa_{0.3}N [8], SiN films are used as the surface passivation layer of AlGa_{0.3}N_{0.7}/Ga_{0.5}N HEMTs to reduce current collapse and as an insulator in the metal-insulator-semiconductor structure [9]. However, the effect of the SiN passivation on

the thermal stability of the AlGa_N/Ga_N 2DEG channel has not been well investigated.

This paper reports a systematic study of the thermal stability of the AlGa_N/Ga_N 2DEG structure with or without Si_N passivation layers in conjunction with actually measured AlGa_N layer thickness.

2 Samples and experimental methods

Figure 1 shows the cross-sectional epitaxial structure, which was grown on a two-inch (0001)-plane sapphire substrate by metal-organic chemical vapor deposition. The structure comprises a semi-insulating Ga_N layer (3 μm), an undoped-Al_{0.25}Ga_{0.75}N spacer layer, an n-Al_{0.25}Ga_{0.75}N carrier-supply layer (Si doping concentration of $1 \times 10^{19} \text{ cm}^{-3}$), and an undoped Al_{0.25}Ga_{0.75}N cap layer. The thickness of each AlGa_N layer was assigned with a fixed ratio for all samples (undoped AlGa_N spacer:n-AlGa_N carrier supply layer:undoped AlGa_N cap = 17:55:28). Three different-total-AlGa_N-thickness wafers were grown. The total AlGa_N layer thickness was actually determined by grazing incidence X-ray reflectivity measurements because determining AlGa_N thickness from the epitaxial growth rate is less reliable. The measured thicknesses were 207, 161, and 152 Å. Eddy current measurements were repeatedly conducted to characterize the R_{sheet} nondestructively at the same point before and after annealing. The R_{sheet} values of each wafer ranged from 543 to 612 Ω/sq in the as-grown state.

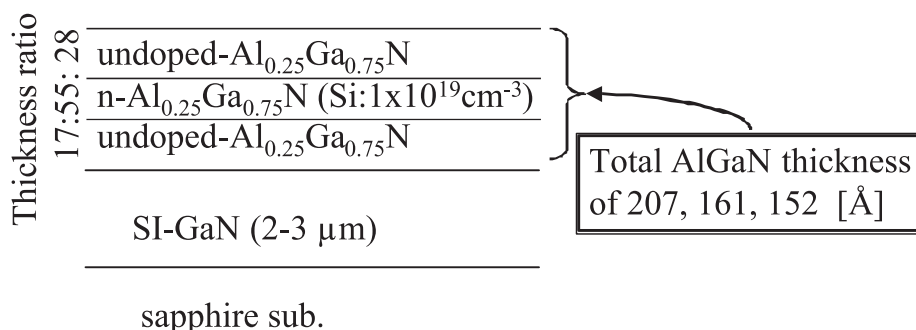


Fig. 1. Schematic cross section of the AlGa_N/Ga_N 2DEG epitaxial structure. Three samples with different AlGa_N thicknesses were grown. The thickness of each AlGa_N layer was assigned with a fixed ratio for all samples.

Firstly, the two-inch Ga_N wafers were loaded into a plasma-assisted chemical vapor deposition (p-CVD) chamber. Half of each wafer was covered with a glass plate to prevent Si_N deposition. The Si_N films were deposited on the other half using silane and ammonia gases. This method eliminates wafer-to-wafer variations. Then, the whole wafer was subjected to isochronal rapid thermal annealing (RTA) at 620 and 800°C for 30 s in 99.9999% N₂ flow. After the annealing, the Si_N/AlGa_N interface was observed by cross-sectional transmission electron microscopy (TEM).

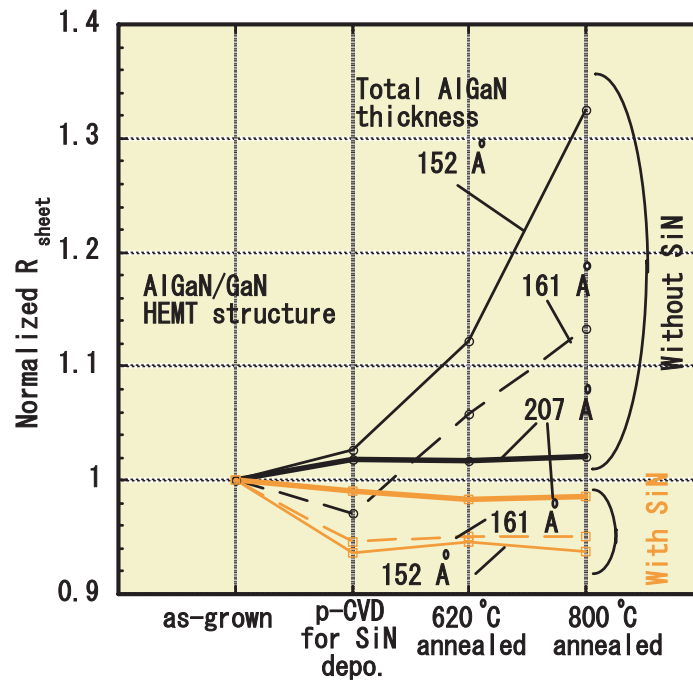


Fig. 2. Variation of R_{sheet} upon annealing for the samples with or without the SiN surface passivation films.

3 Results and discussion

Figure 2 shows the R_{sheet} normalized by the as-grown value after the SiN deposition and 620 and 800°C annealing for three different-AlGaIn-thickness samples with or without the SiN surface passivation films. For the samples without SiN, after the p-CVD process, a small variation within $\pm 2\%$ was seen. As mentioned in the previous section, the wafers were in the p-CVD ambient, but essentially the AlGaIn surfaces were not exposed to the plasma. This small variation may be attributable to the unintentional exposure of the AlGaIn surface to the silane and ammonia gases like in a gas-phase surface treatment. The R_{sheet} of the 207-Å-thick sample was stable even after the 800°C annealing. Meanwhile, the 161-Å-thick sample showed R_{sheet} increases of 6.1 and 13.7% after the 620 and 800°C annealing, respectively. The 152-Å-thick sample showed an R_{sheet} increase of 33% after the 800°C annealing. These results are consistent with our previous finding, that an AlGaIn/GaN HEMT structure with a less-than-200-Å-thick AlGaIn layer is thermally unstable [6]. In contrast to the unpassivated samples, the samples with SiN were very stable on annealing. After the SiN deposition, the R_{sheet} of the 207-Å-thick sample decreased only 1%, and that of the 161- and 152-Å-thick samples decreased about 6%. These small R_{sheet} decreases were normally observed in our experimental conditions. After removing the SiN with a chemical solution, the R_{sheet} returned to the as-grown value. This indicates that process-induced damages were not responsible. A possible explanation is downward band bending due to the SiN deposition. The R_{sheet} values of all the passivated samples were stable within 1% fluctuation up to 800°C annealing. Therefore, the SiN surface passivation is effective way to

prevent R_{sheet} increasing upon annealing even when the AlGaIn layer is as thin as 152 Å.

Figure 3 shows the cross-sectional TEM image of the sample after 620°C annealing at 900 000x magnification. The SiN/AlGaIn interface can be clearly seen and was atomically flat. Neither surface roughness nor interfacial diffusion was observed. The SiN layer was still amorphous after the annealing. The improved thermal stability for a thin-AlGaIn 2DEG channel was thusly also confirmed from the structural point of view.

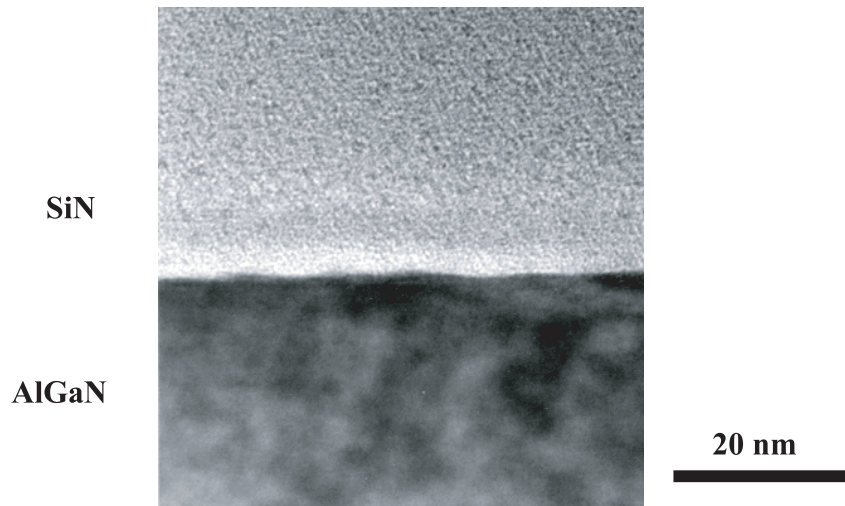


Fig. 3. Cross-sectional TEM image of the sample after 620°C annealing.

4 Conclusion

An annealing study of the AlGaIn/GaN 2DEG structure for HEMTs with or without SiN surface passivation films was conducted with the AlGaIn layer thickness dependence taken into consideration. Without the SiN layers, the R_{sheet} of samples with 161 and 152 Å-thick AlGaIn layers increased significantly when annealing was performed at 620 and 800°C. In contrast, samples with the SiN were thermally stable after annealing at up to 800°C, even when the AlGaIn layer was as thin as 152 Å. TEM observations revealed that the SiN/AlGaIn interface was atomically flat, and neither surface roughness nor interfacial diffusion was observed. Based on these results, we can conclude that the SiN layer is very effective for passivating an AlGaIn surface and forming a thermally-stable thin-AlGaIn 2DEG channel.

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