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Interface Control of III-Oxide/Nitride Composite Structures

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1. Introduction

AlGaN/GaN heterostructures have a unique property on two-dimensional electron gas (2DEG) formation that intentional doping is unnecessary to form high-density 2DEG of over 1×10^{13} cm^{-2}. It is believed certain that AlGaN surface donor is an origin of electrons forming 2DEG. However, there are still many unknown fundamental issues in mechanism, and these are very important for further development of GaN heterostructure field-effect transistors (HFETs). Among various factors to affect nitride surface states, we have been focusing on effects of oxidation and intentional control of oxide structure at the surface.

In this paper, we report on systematic study of oxidation effects on AlGaN surface barrier height and *in-situ* molecular-beam epitaxy (MBE) growth of AlO_x/n-GaN composite structures in the same growth chamber without exposure of the nitride surface to the atmosphere.

2. Thermal Oxidation Effects on Surface Barrier Height of AlGaN/GaN Heterostructures [1,2]

We focused on the relation between oxidation and surface donor states and studied the oxidation condition dependences of surface barrier height by investigating the chemical bonding of surface structures using room-temperature Hall measurement and x-ray photoelectron spectroscopy (XPS). The $Al_{0.27}Ga_{0.73}N$/GaN heterostructures with three different AlGaN barrier thicknesses of 10, 17.5, and 23 nm were grown by metalorganic chemical vapor deposition on c-face sapphire substrates. The structures consisted of AlGaN barrier, 700-nm-thick unintentionally-doped GaN, 1-µm-thick Fe-doped GaN layers on the sapphire from top to bottom.

The Hall measurement was performed for two types of samples with alloyed Ti/Al/Ni/Au and as-deposited Al/Ni/Au electrodes. Both Hall and XPS data showed a constant surface barrier height regardless of the AlGaN thickness for the annealed samples above 800°C, indicating a pinned Fermi level by high-density donor states. On the other hand, the as-deposited (non-annealed) samples showed a linear increase in barrier height with the thickness, indicating an unpinned Fermi level owing to low-density distributed donor states. Another characteristic is that the barrier height was almost the same for the samples annealed at 800°C in both N_2 and O_2 gas atmosphere. Figures 1(a) and (b) show Al 2*p* and Ga 3*d* core-level XPS spectra, respectively, from the 17.5-nm-thick AlGaN layers that were as-grown and annealed in different conditions. From the XPS peaks, we characterized chemical bonding states at the AlGaN surface annealed in several different conditions. Both peaks can be separated into two different ones related to nitride and oxide. The Al-O peak intensity significantly increased after annealing at 800°C compared with the as-grown (non-annealed) and 400°C-annealed samples. Furthermore, it was almost the same level among the 800°C-annealed samples regardless of annealing atmosphere and time, indicating that AlGaN surface oxidation tends to progress quickly and saturate soon. Note that the Ga-O peak showed a much smaller increase after annealing than the Al-O one. The closely-similar behaviors between the surface barrier height and Al oxidation imply that oxidation is a key factor to decide surface donor distribution and consequently a position of Fermi level at the surface. These results also suggest the possibility of intentional control of surface donor distribution by forming specific oxide structure on the AlGaN surface.

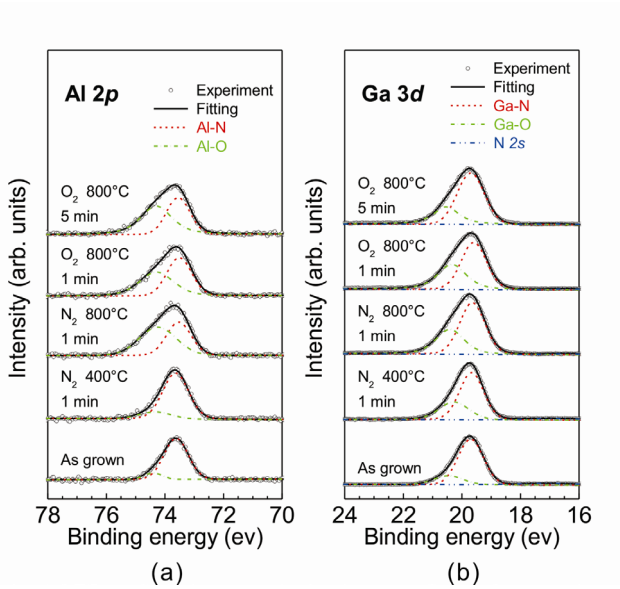

Fig. 1 (a) Al 2*p* and (b) Ga 3*d* XPS spectra from AlGaN barriers annealed in various conditions.

3. In-situ RF-MBE Growth of AlO_x/n-GaN Composite Structures

Based on the work investigating oxidation effects, we have been developing an *in-situ* MBE growth technique to grow III-oxide thin films directly onto nitride semiconductors in an ultra-high-vacuum chamber to improve the device characteristics of GaN HFETs and to make novel device structures. Using this technique, we don't need to worry about surface oxidation that affects the formation of surface (interface) states and we should be able to form ideal and controlled oxide/nitride interfaces

Figure 2 shows a schematic illustration of the MBE machine for this study, which equips nitrogen and oxygen RF-plasma cells in the same growth chamber. This configuration enables us to grow nitride/oxide composite structures without exposure of the sample surface to the atmosphere. First, we grew nitride structures on c-plane sapphire substrates. After nitridation of the substrate surface, AlN buffer (300 nm), unintentionally doped GaN (500 nm), and Si-doped GaN (1000 nm) layers were grown on the substrate in sequence. The substrate temperatures (T_s) for the AlN and GaN layers were 900 and 750°C, respectively. The Si-doping concentration was 2.5×10^{17} cm^{-3}. After growth of the nitride structure and cooling of the substrate, the sample was transferred to a buffer chamber connected to the growth chamber and kept in an ultra-high-vacuum atmosphere. After that, the substrate was transferred to the growth chamber again, and an AlO_x thin film was grown on the n-GaN in the following sequence. First, a 3-nm-thick Al was deposited on the n-GaN at T_s=200°C by using the same K-cell for the AlN growth. Then, the Al was oxidized by O-plasma irradiation for 5 min. Two samples were fabricated: one sample was taken out from the chamber just after the oxidation (sample A), and the other was heated up to T_s=800°C and annealed for 10 min (sample B). The structural properties of both samples were characterized by atomic force microscopy (AFM) and XPS.

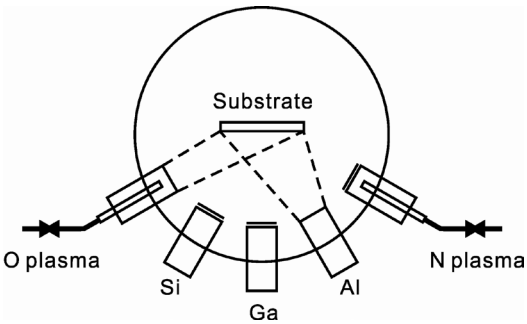

Fig. 2 Schematic illustration of RF-MBE machine for the growth of oxide/nitride composite structures.

Coverage of the AlO_x film on the n-GaN was much improved by the annealing at 800°C as shown in Figs. 3(a) and (b). The Al 2*p* XPS spectrum of sample A had two peaks related to Al-O bonding and metal Al. This was because part of the deposited Al remained as metal due to insufficient oxidation at a substrate temperature of 200°C. On the other hand, there was no metal Al peak from sample B, indicating that the remaining metal Al transformed into AlO_x during the annealing at T_s=800°C. The Ga 3*d* spectrum from sample A showed a small Ga-O peak due to oxidation of the n-GaN surface, whereas the spectrum of sample B showed no such peak. This result is consistent with the AFM observation. These structural properties indicate that a high-quality AlO_x thin film and AlO_x/GaN interface with good surface coverage were formed by the process of sample B, that is, by the three-step process of (1) Al deposition at low temperature, (2) oxidation by O plasma irradiation at the low temperature, and (3) annealing at high temperature.

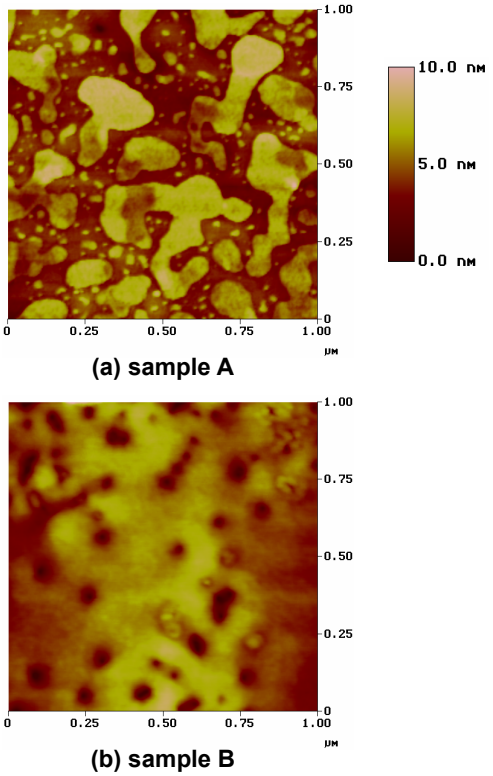

Fig. 3 Surface AFM images of (a) sample A (w/o anneal) and (b) sample B (w/ anneal).

3. Conclusion

We have been developing in-situ MBE technique to grow composite oxide/nitride structures with an intentionally controlled interface, because distribution of donor states at a nitride surface strongly depends on its oxidation.

Acknowledgements

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References

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