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MOVPE Growth Behavior of AlGaN/GaN Heterostructures with AlGaN Directly on RIE-GaN Showing a High Electron Mobility (>1300 cm^2/Vs)

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Abstract

This paper reports the MOVPE growth behavior of AlGaN layer on RIE-GaN surface without regrown GaN layers and the characterization of AlGaN/RIE-GaN structures fabricated. RIE-processed GaN surfaces were pre-annealed in NH_3 flow just before growth. A 30 nm-thick $Al_{0.3}Ga_{0.7}N$ layer was grown by MOVPE. It was found that, compared with as-grown GaN surfaces, both pre-annealing temperature (T_{NH3}) and growth temperature (T_g) should be lowered to get excellent electrical properties for the AlGaN/RIE-GaN structures. By optimizing T_{NH3} and T_g, an electron mobility as high as 1350 $cm^2V^{-1}s^{-1}$ was achieved for the fabricated GaAlN/RIE-GaN structures.

1. Introduction

Reactive ion etching (RIE) has become an indispensable technology in the III-nitride semiconductor device processes. The importance of RIE processes has further increased because of the recent developments in GaN-based transistors, such as high electron mobility transistors (HEMTs) with a recessed gate structure for normally-off operation. It is well-known that ion bombardment in the RIE process introduces structural damage on the etched surface. The RIE-induced surface damage of GaN was attributed mainly to the preferential loss of nitrogen atoms. Although the electrical/optical properties of RIE-damaged GaN surfaces have been extensively studied [1], there have been very few reports on the epitaxial growth of semiconductor films on RIE-treated surfaces [2]. Provided that RIE damage is effectively reduced and high quality interfaces are formed between RIE surfaces and epitaxial films, we can widely use such interfaces as electrically/optically active regions in a variety of nitride-based devices.

In this paper, we studied the MOVPE growth behavior of AlGaN directly on RIE-GaN surfaces and demonstrated that, by optimizing pre-annealing temperature (T_{NH3}) and growth temperature (T_g), an electron mobility as high as 1350 $cm^2V^{-1}s^{-1}$ was achieved for the fabricated AlGaN/RIE-GaN structures.

2. Experimental

As substrates, n^--GaN with a c^+-face grown on 6H-SiC or on α-Al_2O_3 were used. A ~200 nm-thick surface layer of the n^--GaN was etched off by RIE with a bias power 30 W. The substrates were pre-annealed in the NH_3 flow at a temperature T_{NH3}=850-950˚C for 15 min just before growth. This is because the annealing of GaN in NH_3 was reported to be able to reproduce atomically-clean and stoichiometric GaN surfaces [3]. Then, a ~30 nm-thick $Al_xGa_{1-x}N$ ($x\sim0.3$) layer was grown at T_g=950-1050 ˚C using TMA, TMG, and NH_3. Samples with an AlGaN layer grown on as-grown (without RIE) GaN or with an AlGaN and a GaN (0.35 μm thick) layers grown on RIE-GaN were also prepared for comparison. Sheet electron density n_s and Hall electron mobility μ at 70-300 K were measured by Hall-effect measurements using van der Pauw contact configuration.

3. Results and discussion

Figure 1 shows the X-ray diffraction (XRD) 2Θ/ω profiles for AlGaN/GaN samples prepared under different conditions. As can be seen in Fig. 1, a sample grown on RIE-GaN with a higher T_{NH3} shows an AlGaN (0002) peak with a lower intensity and a lower Al content. Such changes in intensity and position of AlGaN (0002) peak were scarcely observed for AlGaN/GaN samples prepared with as-grown (w/o RIE) GaN even for T_{NH3}= 950 ˚C, as shown in Fig. 1(d). Figure 2 shows the surface morphologies of the AlGaN/GaN structures prepared with a different T_{NH3}. As can be seen in this figure, the surface morphology of samples prepared with RIE-GaN was deteriorated with increasing T_{NH3}. In the case of GaN surfaces without RIE, on the other hand, such deterioration of surface morphology was not observed as shown in Fig. 2(d). It was also found that

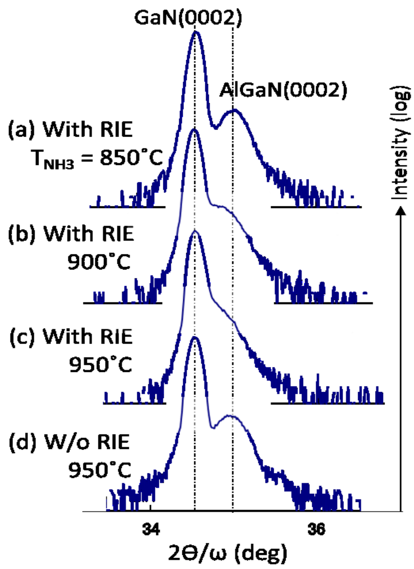

Fig. 1. XRD 2Θ/ω profiles for AlGaN/GaN structures prepared with and without RIE and with a different TNH3. T_g is 950˚C for all samples.

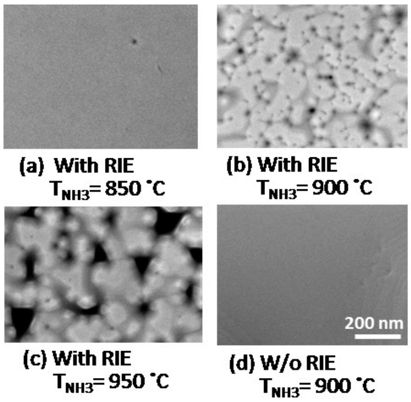

Fig. 2. Surface morphologies (SEM images) of AlGaN/GaN structures prepared with and without RIE and with a different TNH$_3$. T_g is 950˚C for all samples.

a higher T_g also brought about both AlGaN (0002) peak changes and surface morphology degradation, similar to the higher T_{NH3}. From the results shown in Figs. 1 and 2, it is interpreted that some mixing reactions between the growing AlGaN and the underlying RIE-GaN occur during growth. This indicates that the RIE-GaN surface is thermally unstable compared with GaN without RIE treatment. Such instability of the RIE surface may show that the deficiency of nitrogen atoms on the RIE-GaN surface can not be sufficiently recovered by the pre-annealing in NH_3 flow. However, excellent electrical properties were obtained for AlGaN/RIE-GaN structures by choosing relatively low T_{NH3} and T_g, as shown below.

Electrical properties of the AlGaN/GaN structures were characterized with Hall-effect measurement. The n_s obtained for fabricated AlGaN/RIE-GaN structures were in the range of (5-20) x 10^{12} cm^{-2}. On the other hand, sheet resistance R_s obtained varied from 2x10^2 to 1x10^4 Ω/□, resulting in an electron mobility μ between 1350 and 100 cm^2/Vs. The highest value, 1350 cm^2/Vs, was obtained with n_s =1.7x10^{13} cm^{-2} and R_s=270 Ω/□ [4]. The highest mobility is better than that for an AlGaN/RIE-GaN structure reported by Chan et al.[2]. Table 1 shows the Hall data for AlGaN/GaN structures with and without regrown GaN (T_{NH3}=850˚C, T_g=950˚C). The highest mobility 1350 cm^2/Vs for the AlGaN/RIE-GaN structure (sample B) is superior to the sample A having a 0.35 μm-thick regrown GaN layer. The relatively low mobility 1200 cm^2/Vs for sample A seems to be due to the relatively low growth temperature 950˚C for the regrown GaN layer. As reported by Chen et al. [5], a GaN layer grown at a lower temperature contains a higher carbon contamination level, resulting in a lower mobility. In the case of sample B, 2DEG can be formed in a high-temperature (>1000˚C)-grown underlying GaN containing a lower C contamination level. This is an advantage for the preparation of AlGaN/GaN structures by the direct AlGaN grown on GaN. As described above, the preparation of AlGaN/GaN structures with an AlGaN grown directly on RIE-GaN resulted in the widely scattered electrical properties. In the case of the samples prepared with a regrown GaN layer, on the other hand, the electrical data were scarcely

Table 1. Hall data for AlGaN/GaN structures with and without regrown GaN (T_{NH3}=850˚C, T_g=950˚C).

Sample	Regrown GaN (Thickness; μm)	R_s (Ω/□)	n_s (cm^{-2})	μ (cm^2/Vs)
A	With (0.35)	5.7x10^2	9.2x10^{12}	1200
B	W/o	2.7x10^2	1.7x10^{13}	1350

scattered, that is, all the three samples prepared had a mobility higher than 1000 cm^2/Vs. The widely scattered electrical properties for AlGaN/RIE-GaN samples indicate that the surface conditions of RIE-GaN just before AlGaN growth are different for each growth run. Therefore, in order to prepare reproducibly AlGaN/RIE-GaN structures with excellent electrical properties, higher attention should be paid in the preparation of RIE-GaN surfaces.

3. Conclusions

An AlGaN layer was grown on RIE-treated GaN surfaces without regrown GaN layers and electrical properties of AlGaN/GaN structures prepared were characterized. Pre-annealing temperature T_{NH3} of RIE-GaN in NH_3 and growth temperature T_g of AlGaN layer were studied as main growth parameters. It was found that higher T_{NH3} and T_g resulted in some mixing reactions between growing AlGaN and underlying RIE-GaN, indicating the lower thermal stability for RIE-GaN surfaces. By choosing relatively low T_{NH3} (~850 ˚C) and T_g (~950 ˚C), an electron mobility as high as 1350 cm^{2}V^{-1}s^{-1} was obtained for the fabricated AlGaN/RIE-GaN structures. The widely scattered electrical properties for AlGaN/RIE-GaN samples suggests that higher controllability and reproducibility are needed in the preparation of RIE-GaN surfaces

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