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Characteristics of InAlN/GaN Heterostructures Fabricated by Regrowth Technique

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1. Introduction

InAlN is one of the attractive barrier materials for GaN-based high electron mobility transistors (HEMTs) for high-power applications because of the large two dimensional electron gas (2DEG) density induced by the difference in the spontaneous polarization between InAlN and GaN [1, 2]. In addition, InAlN can be grown lattice-matched to GaN, reducing the stress in the barrier layer. This is expected to improve the reliability of the devices [3]. In InAlN growth by vertical metalorganic vapor phase epitaxy (MOVPE), however, we recently found a critical issue: an unintentional Ga incorporation into the InAlN epilayer on GaN due to the residual Ga adhered to the walls of the flow channel of the MOVPE reactor [4]. Fortunately, it turned out that the Ga incorporation can be suppressed by cleaning the reactor prior to the growth of the InAlN layer. This cleaning process requires an interruption of the growth sequences, and thereby a regrowth of InAlN, to complete the InAlN/GaN heterostructures. Although the regrowth effectively suppresses the Ga incorporation, the generation of some carrier trap states is unavoidable at the regrowth interface. In this work, therefore, we investigate the influence of the regrowth on the electrical properties of the InAlN/GaN HEMTs. Two kinds of regrowth sequences were examined to obtain a clue to minimize the interface state formation.

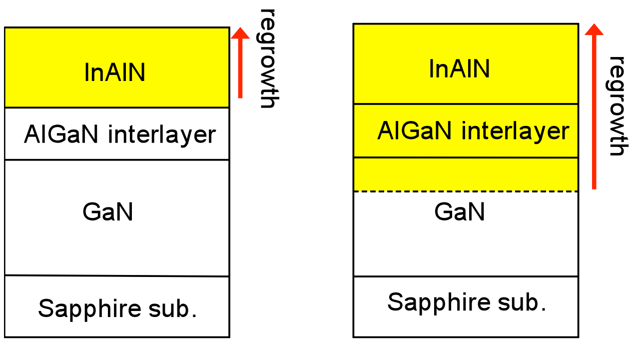
2. Experimental

The layer structures of InAlN/AlGaN/GaN were grown by vertical MOVPE. The AlGaN layer was inserted to improve the mobility and surface flatness of the heterostructures [5]. The precursors were trimethylgallium (TMGa), trimethylaluminum (TMAl), trimethylindium (TMIn), and ammonia (NH_3). The layer structures are shown in Figure 1, where the yellow color represents the regrowth layers. For the sample S1 [Fig. 1 (a)], we first grew 2-µm-thick GaN and 2-nm-thick $Al_{0.45}Ga_{0.55}N$ on a sapphire substrate and then cleaned the reactor to remove the residual Ga. After a surface treatment, we finally regrew 10-nm-thick $In_{0.17}Al_{0.83}N$ on the AlGaN/GaN structure. For sample S2 [Fig. 1 (b)], we only grew 2-µm-thick GaN on a sapphire substrate before the reactor cleaning and the sample surface treatment. Then, we regrew 20-nm-thick GaN, 2-nm-thick $Al_{0.45}Ga_{0.55}N$, and 10-nm-thick $In_{0.17}Al_{0.83}N$ on the GaN surface. In the latter case, we confirmed that the Ga incorporation into the InAlN is less than 1% when the thickness of the GaN growth after the cleaning is as small as 20 nm. We fabricated HEMTs using the S1 and S2 wafers. Ti/Al/Ni/Au metals were deposited by e-beam evaporation as the source and drain electrodes and annealed at 850°C for 30 seconds. The gate electrode was Ni/Au. The gate length (L_G) and the source-drain gap were 1 and 5 µm, respectively.

To clarify the influence of the regrowth on the electrical properties, we investigated the electrical properties of the regrown InAlN/AlGaN/GaN heterostructures by eddy current measurements. The characteristics of the fabricated HEMTs were also measured with a semiconductor parameter analyzer at room temperature (RT).

3. Results and Discussion

Table I summarizes the electrical properties of samples S1 and S2. The sheet resistance (R_{sh}) is approximately 300 Ω/sq. for both the samples. The electron mobility (μ) and the sheet carrier density (N_s) are about 1,000 cm^2/Vs and 2 × 10^{13} cm^{-2}, respectively. The large N_s is likely due to the large differences in the spontaneous polarization between InAlN and GaN. The values of μ are essentially identical for the two samples. This suggests that the interfaces are common, since the dominant factor determining the μ value here is interface roughness scattering. The fairly high values of μ can be ascribed to the insertion of the thin AlGaN layer between InAlN and GaN. The high µ values also confirm that the 2DEG is free from possible regrowth-induced effects, which is likely due to isolation from the regrowth interfaces by the 2-nm-thick AlGaN (S1) or the 20-nm-thick GaN (S2). It is inferred that the 2DEG properties are not deteriorated as long as the AlGaN/GaN



Figs. 1 Layer structures of InAlN/AlGaN/GaN heterostructures. The regrowth layers are indicated as yellow. (a) Only InAlN is regrown, (b) InAlN/AlGaN/thin GaN (20 nm) layers are regrown.

Table I Electrical properties of the samples S1 and S2

sample	S1	S2
R_{sh} (Ω/sq.)	314	295
N_s (cm^{-2})	1.81×10^{13}	2.06×10^{13}
μ (cm^2/Vs)	1,100	1,030

interface is fabricated in a consecutive manner.

Next, we evaluated the DC characteristics of the HEMTs. Figure 2 shows the drain current-voltage (I_d-V_{ds}) characteristics of the InAlN/AlGaN/GaN HEMTs at RT. Solid and dotted lines correspond to the I_d-V_{ds} curves of the HEMTs for the samples S1 and S2, respectively. Gate voltage was varied from 2 to -8 V in -1 V steps. Clear pinch-off characteristics are observed for both HEMTs. Both devices had almost the same transconductance (g_m ~ 230 mS/mm) and on-resistances (R_{on} ~ 2.4 Ωmm). The g_m values over 200 mS/mm are relatively large among GaN-based HEMTs with a long L_g of 1 µm. The I_d of about 1.5 A/mm is also relatively large for HEMTs fabricated on sapphire substrate. In the saturation region of the I_d-V_{ds} curves, kinks were observed only for sample S1. One of the possible reasons is that the electron emission and capture on traps more frequently occur during device operation for S1, reflecting the difference in the regrown interface.

We investigated the device performance under gate bias stress. The applied stress condition was that V_{gs} = V_{th} - 2 V for 30 seconds at V_{ds} = 20 V, where V_{gs} and V_{th} are the gate-source voltage and the threshold voltage, respectively. Figure 3 shows the transfer characteristics of the InAlN/AlGaN/GaN HEMTs for samples S1 and S2 before and after the gate stress. Although the reduction of I_d for S2 is only 3%, it is 20% for S1. Such a large reduction in I_d after gate bias stress is the so-called current collapse. This is caused by charging-up of a virtual gate formed by the electron capture at traps near the gate edge on the drain side, where the electric field is highly concentrated by the gate bias stress [6]. Since AlGaN surfaces, generally, are more easily oxidized than GaN surfaces, we were able to remove the residual oxides formed at the regrowth interface to a lesser extent in S1 by the surface treatment. This is one of the plausible scenarios for the prominent I_d reduction observed only in S1.

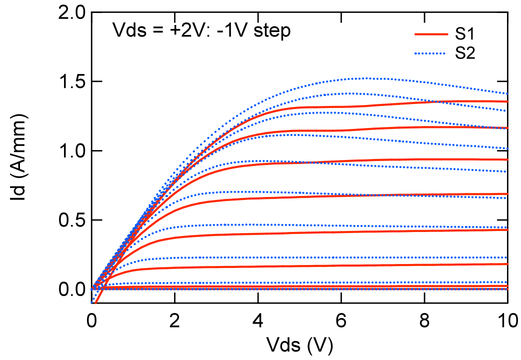


Fig. 2 I_d - V_{ds} characteristics of the InAlGaN/AlGaN/GaN HEMTs at RT. Solid and dotted lines correspond to the samples S1 and S2, respectively. Gate voltage is varied from 2 to -8 V with -1 V steps.

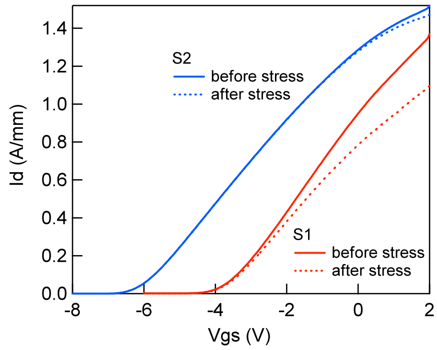


Fig. 3 Transfer characteristics of InAlN/AlGaN/GaN HEMTs for sample S1 and S2. Solid and dotted lines correspond to the characteristics before and after the gate stress.

The current reduction of as small as 3% in S2 without device passivation has seldom been achieved in conventional AlGaN/GaN HEMTs. Although finite Ga contamination into the InAlN layer is unavoidable with the S2-type device fabrication sequence, the contamination is negligibly small when the regrown GaN is very thin (20 nm). As a result, the InAlN barrier layer effectively suppresses the current collapse in the S2 device.

4. Conclusion

We fabricated InAlN/AlGaN/GaN heterostructures using a regrowth technique. When the growth was restarted on the AlGaN surface, the HEMT performance was degraded due to trap generation at the regrowth interface. When the initial growth was interrupted just before the completion of the GaN layer, followed by the regrowth of InAlN/AlGaN/thin GaN layers, such degradation did not occur. By careful optimization of the fabrication sequence, InAlN can actually act as a good barrier for GaN-based HEMTs.

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