Improved mobility in InAlN/AlGaN two-dimensional electron gas heterostructures with an atomically-smooth heterointerface

Daiki Hosomi¹, Yuta Miyachi¹, Takashi Egawa¹,², and Makoto Miyoshi¹,²

¹ Research Center for Nano Devices and Advanced Materials, Nagoya Institute of Technology
² Innovation Center for Multi-Business of Nitride Semiconductors, Nagoya Institute of Technology

Gokiso-cho, Showa-ku, Nagoya 466-8555, Japan
Phone: +81-52-735-5092, E-mail: d.hosomi.904@stn.nitech.ac.jp

Abstract
An InAlN/AlGaN two-dimensional electron gas (2DEG) heterostructure with an “regrown AIN initial layer” was grown on AlN/sapphire template by metalorganic chemical vapor deposition, and its structural and electrical properties were investigated. It was confirmed that the prepared sample had an atomically-smooth heterointerface and exhibited an improved 2DEG mobility of 242 cm²/Vs compared to the sample without the regrown AIN layer.

1. Introduction
In addition to conventional AlGaN/GaN two-dimensional electron gas (2DEG) heterostructures, modified 2DEG heterostructures, such as AlGaN/AlGaN or InAlN/AlGaN, have also been attracting much attention, owing to their extremely high breakdown voltages [1] or large 2DEG densities [2]. We have also reported the growth and characterization results about InAlN/AlGaN heterostructures [3] as well as heterostructure filed-effect transistors (HFETs) [4]. Consequently, it was found that there are a few issues to be solved for considering the practical use of InAlN/AlGaN HFETs [4]. As for the 2DEG mobility, one of the most important issues, we have confirmed that the interface roughness scattering significantly suppressed it [5]. In this study, therefore, we attempted to improve the 2DEG mobility in InAlN/AlGaN 2DEG heterostructures by achieving an atomically-smooth heterointerface.

2. Experiments
Samples were grown by a horizontal metalorganic chemical vapor deposition (MOCVD) system with conventional precursors. A 2-inch-diameter AlN template, which had a 1-μm epitaxial AlN film on a c-face sapphire, was used as an underlying substrate. Fig. 1 shows a schematic of the InAlN/AlGaN heterostructure employed in this study. The heterostructure consisted of, from bottom to top, a 2-μm-thick AlGaN channel layer, a 1-nm-thick AlN interlayer, and a 15-nm-thick InAlN barrier layer. During the MOCVD growth of the heterostructure, a “regrown AIN layer” was initially formed on the AlN template. This is the most distinctive point in this study to achieve an atomically-smooth AlGaN surface. The regrown AIN layer contains a few different-growth-rate AlN layers (see Fig.1). To analyze the AlGaN surface by atomic force microscopy (AFM), an additional sample without the top AlN and InAlN layers was also prepared. Then, electrical characteristics of the heterostructure were evaluated using the Hall effect and C-V measurements.

3. Results and discussion
Figs. 2(a) and 2(b) show AFM images of the AlGaN surfaces with and without the regrown AIN layer, respectively. Here, the latter sample is the same as that shown in our previous study [3]. As obvious in these images, the sample with the regrown AIN layer exhibited a smoother surface with clear atomic steps than that of the other sample. Also, the measured root mean square (RMS) roughness was significantly reduced from 1.2 nm to 0.26 nm. Then, an InAlN/AlGaN 2DEG heterostructure with the regrown AIN layer was prepared, and their electrical characteristics were evaluated. Table 1 summarizes the room-temperature 2DEG properties of InAlN/AlGaN heterostructures, which also shows their precise alloy compositions determined by X-ray diffraction measurements. The obtained results revealed that the sample with the regrown AIN layer exhibited a high 2DEG mobility of 242 cm²/Vs and a similar 2DEG density of 2.6 × 10¹³/cm² compared to our past samples [3]. Consequently, the present sample showed a low sheet resistance of 998 Ω/sq, which is much closer to that of the conventional AlGaN/GaN 2DEG heterostructures than those of our past samples.

Fig. 1. Schematic cross section of the InAlN/AlGaN heterostructure with a regrown AIN layer.

Fig. 2. AFM images of the AlGaN surface morphologies for samples (a) with and (b) without the regrown AIN layer.
Table I Room-temperature 2DEG density ($N_s$), mobility ($\mu$), and sheet resistance ($R_{sh}$) values of InAlN/AlGaN HFET structures measured by Hall effect measurements

<table>
<thead>
<tr>
<th>Sample structure</th>
<th>$N_s$ ($\text{cm}^{-2}$)</th>
<th>$\mu$ (cm$^2$/Vs)</th>
<th>$R_{sh}$ (Ω/sq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/o regrown</td>
<td>$\text{In}<em>{0.14}\text{Al}</em>{0.86}\text{N/Al}<em>{0.21}\text{Ga}</em>{0.79}\text{N}$</td>
<td>$3.0 \times 10^{13}$</td>
<td>165</td>
</tr>
<tr>
<td>AlN layer</td>
<td>$\text{In}<em>{0.12}\text{Al}</em>{0.88}\text{N/Al}<em>{0.21}\text{Ga}</em>{0.79}\text{N}$</td>
<td>$2.8 \times 10^{13}$</td>
<td>162</td>
</tr>
<tr>
<td>(Ref.[3])</td>
<td>$\text{In}<em>{0.12}\text{Al}</em>{0.88}\text{N/Al}<em>{0.31}\text{Ga}</em>{0.69}\text{N}$</td>
<td>$2.5 \times 10^{13}$</td>
<td>130</td>
</tr>
<tr>
<td>w/ regrown</td>
<td>$\text{In}<em>{0.17}\text{Al}</em>{0.83}\text{N/Al}<em>{0.15}\text{Ga}</em>{0.85}\text{N}$</td>
<td>$2.6 \times 10^{13}$</td>
<td>242</td>
</tr>
<tr>
<td>AlN layer</td>
<td>$\text{In}<em>{0.17}\text{Al}</em>{0.83}\text{N/Al}<em>{0.15}\text{Ga}</em>{0.85}\text{N}$ (77 K)</td>
<td>$2.6 \times 10^{13}$</td>
<td>375</td>
</tr>
</tbody>
</table>

Fig. 3. C-V depth profiling of 2DEG in the InAlN/AlGaN heterostructure with regrown AlN layer.

Fig. 3 shows the result of the C-V depth profiling. As the figure clearly shows, electrons were highly concentrated at a depth of approximately 15 nm that corresponds to the InAlN barrier thickness. Thus, it was confirmed that the electrons were two-dimensionally generated at the InAlN/AlGaN heterointerface. Fig. 4 shows the relationship between the measured 2DEG densities and mobilities. Also, Fig. 5 shows the relationship between Al content in AlGaN channel and the 2DEG mobilities. These figures obviously indicate that the 2DEG mobility of the InAlN/AlGaN 2DEG heterostructure was considerably improved with the introduction of the regrown AlN layer.

4. Conclusion

We attempted to improve the 2DEG mobility in InAlN/AlGaN 2DEG heterostructures by achieving an atomically-smooth heterointerface. It was confirmed that the introduction of a “regrown AlN layer” can improve the AlGaN surface roughness and thereby results in a high 2DEG mobility. An InAlN/AlGaN heterostructure with the regrown AlN layer showed an improved 2DEG mobility of 242 cm$^2$/Vs with a 2DEG density of $2.6 \times 10^{13}$/cm$^2$.

Acknowledgements

This work was partially supported by the Super Cluster Program of the Japan Science and Technology (JST) Agency and JSPS KAKENHI Grant Number JP16K06298.