Characterization of Two-Dimensional Hole Gas at GaN/AlGaN Heterointerface

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Abstract—Electrical properties of two-dimensional hole gas (2DHG) at GaN/AlGaN heterointerface have been investigated. Existence of 2DHG at the interface is confirmed by capacitance-voltage and Hall Effect measurement. We have discussed transport mechanism of 2DHG by comparison with hole generated by conventional Mg impurity, based on experimental evaluations by X-ray diffraction, transmission electron microscope, atomic force microscope, secondary ion mass spectroscopy, and temperature dependence Hall Effect measurements.

I. INTRODUCTION

Si-based integrated circuit technologies, which have been developing for the last six decades, are comprised of complementary operations of $n$-channel and $p$-channel transistors. The Si-based technologies are regarded to have reached its material limit in the near future. Recently, electronic devices in which wide-bandgap semiconductors, such as GaN and SiC, are used, have been studied extensively due to their superior material properties over Si. In GaN devices, low specific on-resistance and high breakdown voltage have been demonstrated beyond the Si material limit in $n$-channel type heterojunction field effect transistors (HFETs)[1,2].

It is possible to realize complementary circuits based on wide-bandgap GaN, if $p$-channel GaN transistors had been produced with adequate performances for real applications. However, on-resistances of $p$-channel GaN transistors are still much higher than that of $n$-channel ones[3]. That activation energies of Mg, which is used as doping impurity in $p$-type GaN are large (about 170 meV), is treated as the reason of high on-resistance[4].

Spontaneous and piezoelectric polarization properties are used in the $n$-channel HFETs, and both high carrier density of two-dimensional electron gas (2DEG), and high mobility have been obtained by them[5]. Recently, two-dimensional hole gas (2DHG) with high density due to spontaneous and piezoelectric polarization was also reported to be demonstrated in $p$-channel HFETs[6-8]. However, physical properties of 2DHG was not clear. In this paper, we will report some experimental results to characterize 2DHG at GaN/AlGaN heterointerface.

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square configurations for Hall Effect measurement were fabricated as follows. The both wafers were diced in 5 mm square. Ni/Au (20 nm/ 20 nm) electrodes were deposited on the tops of the both samples. Subsequently, the samples were annealed in air ambient to reduce contact resistance between the electrodes and 2DHG. Finally, Ti/Au (20 nm/ 100 nm) was deposited on the electrodes.

III. EXPERIMENT AND RESULTS

Several experiments were conducted in order to clarify layer structures, crystal quality and electrical properties of the both samples, including XRD, TEM, atomic force microscope (AFM), secondary ion mass spectroscopy (SIMS), capacitance-voltage (C-V), and temperature dependence Hall Effect measurements.

Figure 2. Measured (0004) 2θ-ω curve of sample-A (solid line) and a simulation result (dashed line).

Figure 3. Bright-field cross-sectional TEM image of the top of GaN/AlGaN/GaN layer structure in Sample-A.

Firstly, XRD measurements were performed here in order to characterize a layer structure and crystal quality of Sample-A. Figure 2 shows a measured 2θ-ω curve, where GaN(0004) and AlGaN(0004) peaks, and also several satellite peaks is observed. We have simulated diffraction curves with assuming GaN/AlGaN/GaN double heterostructure and the best fitting to the measured curve was obtained when a GaN cap layer thickness is 38 nm, an AlGaN barrier thickness is 48 nm, and an Al composition is 23%, as shown in Fig.2. We have also measured a rocking curve of the GaN(0004) diffraction and a full-width at half-maximum value of 290 arcsec was obtained.

Figure 3 shows a typical bright-field cross-sectional TEM image of the top region in Sample-A. A GaN/AlGaN/GaN double heterostructure is observed clearly in Fig. 3, demonstrating abrupt heterointerfaces are successfully obtained. From the TEM image, measure thicknesses of the top GaN layer and the AlGaN barrier are 40 nm and 49 nm, respectively, which is consistent with the extracted values from the XRD measurement (Fig. 2), which indicates that the layer structure is obtained with good uniformity. Figure 4 shows AFM images of Sample-A surface. Atomically flat morphology with step and terrace structures are observed without any cracks. Measured RMS roughness was 0.2 nm. Some pits located at the step edges were also observed, as shown in Fig. 4.

Next, electrical properties of the both samples were evaluated. We have measured C-V characteristics at 100 kHz by putting Hg probes on the sample surfaces. Figure 5 shows a carrier distribution profile calculated from a measured C-V curve. The peak of the carrier concentration is located at 40 nm depth which is correspond to the position of the upper GaN/AlGaN heterointerface confirmed by the TEM observation, and then the concentration decreases in the inner part of the sample.
On the other hand, 2DHG in Sample-A shows temperature independent carrier density. Figure 8 shows measured sheet resistance. Although the both samples have a comparable resistance at around room temperature, resistance of Sample-A at 80 K, was four orders of magnitude smaller than that of Sample-B. From the carrier concentration and resistance dependence on temperature, Hall mobility was obtained as shown in Fig. 9.

Figure 5. Calculated carrier concentration profile of Sample-A from C-V measurement.

Figure 6. SIMS depth profiles of Sample-A.

Mg impurity distribution in Sample-A was clarified through SIMS measurements. Figure 6 shows distributions of Al and Mg atoms, and relative intensities of CsN and CsGa signals in Sample-A, from the surface to 100-nm-depth. We observed that Mg exists in the whole GaN region, even though the 20-nm-thick GaN layer on the AlGaN layer was grown without Mg doping. The Mg concentration of the undoped GaN region was about $4 \times 10^{18}$ cm$^{-3}$ which is an order of magnitude lower than that in Mg-doped GaN. This existence of Mg in undoped GaN, should be due to thermal back diffusion effect of Mg atoms during MOCVD growth[10].

Hall Effect measurement was conducted here to clarify carrier density, mobility and resistance dependence on temperature, which are shown in Figs.7-9. Figure 7 shows measured sheet carrier densities. The carrier density of the Mg-doped p-GaN (Sample-B) depends on the temperature significantly due to high activation energies of Mg acceptor[4].

Figure 7. Sheet carrier density dependence on temperature of Sample-A (a) and Sample-B (b).

Figure 8. Sheet resistance dependence on temperature of Sample-A (a) and Sample-B (b). Sample-A showed much more independent on temperature.

Figure 9. Mobility dependence on temperature of Sample-A (a) and Sample-B (b).

IV. DISCUSSION

In this chapter, we discuss transport mechanism of 2DHG based on the experimental results above.

A. Hole generation by polarization

2DHG with a sheet carrier density of $1 \times 10^{13}$ cm$^{-2}$ at room temperature was confirmed by Hall Effect measurement.
Therefore, the sheet carrier density is independent on temperature at a wide range. Compared with Sample-A, Sample-B showed a totally different carrier density dependence on temperature.

### B. Limiting factor of 2DHG mobility

In previous investigations of 2DEG transport in AlGaN/GaN heterostructures [12-18], it is reported that several scattering mechanisms exist, such as interface-roughness scattering, AlGaN alloy scattering, dislocation scattering, and phonon scatterings, some of which are believed to also exist in 2DHG.

The measured Hall mobility in Sample-A decreases as a value of temperature as shown in Fig. 9. Interface-roughness scattering, alloy scattering, and dislocation scattering are treated independent upon temperature in 2D carrier[12,15-18]. A threading dislocation density of Sample-A can be estimated as $1 \times 10^9 \text{cm}^{-2}$ with assuming that the pits observed in the AFM images (Fig. 4) corresponds to locations of threading dislocations. In addition, the measured FWHM of GaN(0004) was 290 arcsec, which is comparable with that of conventional GaN wafers for n-channel HFETs. Although it is difficult to evaluate heterointerface roughness quantitatively, the cross-sectional TEM image shows clear contrast at the GaN/AlGaN interface (Fig. 3), and the surface morphology was atomically smooth (Fig.4). These results indicate that abrupt GaN/AlGaN heterointerface is obtained in sample-A.

The mobility dependence on temperature shows that Sample-A and Sample-B have same trends in high temperature region more than 200 K, as shown in Fig. 9. Therefore, same scattering mechanisms may restrict the 2DHG mobility in GaN/AlGaN heterointerface with Mg-doped GaN, which means that phonon scattering may be the main reason to limit mobility in high temperature. For exactly characterizing the scattering mechanisms quantitatively rather than qualitatively, further studies about crystal structure and electromagnetic property at atom level of GaN/AlGaN heterostructure are needed.

### C. Sheet resistance of 2DHG

Sheet resistance of Sample-A shows less dependence on temperature in compared with that of Sample-B. Temperature independence of the 2DHG resistance in a wide range, is a useful property for using GaN-based device in micro electric circuit.

### V. Conclusion

In this paper, we have reported the temperature dependence electrical property of 2DHG due to negative polarization at the GaN/AlGaN heterointerface. The layer structure was grown on sapphire substrate by MOCVD. The TEM and AFM observations revealed that abrupt GaN/AlGaN heterointerface was obtained successfully. We have confirmed 2DHG formation at the GaN/AlGaN interface independent on temperature by the C-V and Hall effect measurements. The measured temperature characteristic of 2DHG mobility indicated that 2DHG transport is restricted by phonon scattering similar with conventional hole generated by Mg impurity doping at high temperature.

### References


