PS-4-23

Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials, Nagoya, 2019, pp767-768

Effect of Post-metallization Annealing on Interface Properties of Al_2O_3/GaN Fabricated on *c*- and *m*-plane Free-standing GaN Substrates

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Abstract

Al_2O_3/GaN metal-insulator-semiconductor (MIS) interface properties were investigated using both capacitors and lateral accumulation-mode FETs fabricated on *c*- and *m*-plane free standing GaN substrates. Effect of post metallization annealing (PMA) were also investigated. It was confirmed that PMA was effective for decreasing the interface trap density and improving the channel mobility for both samples. The highest channel mobility was observed in the *m*-plane sample after PMA, which was 192 cm^2/Vs.

1. Introduction

Nonpolar GaN is promising for applications in power-switching devices because there is no polarization-induced charge at a heterojunction interface, and enhancement-mode high-electron-mobility transistors (HEMTs) can be fabricated.[1] For power application, a metal-insulator-semiconductor (MIS) gate will be preferable because of its lower gate leakage current and larger operating power than a metal-semiconductor (MS) structure. To optimize such MIS gate HEMTs or field-effect transistors (FETs), the plane orientation of the channel will be a key parameter, as reported for other semiconductor materials.[2] We reported that, by using a vicinal *m*-plane substrate, we can suppress the density of unintentionally incorporated impurities into epilayers grown by MOVPE to below the SIMS detection limit, and Schottky barrier diodes with nearly ideal characteristics can be fabricated on the substrate.[3] Also, we compared the properties of Al_2O_3/GaN interfaces formed on a *c*-plane and an *m*-plane by characterizing lateral accumulation-mode MISFETs, and the channel mobility was higher on the *m*-plane sample.[4] Recently, it has been reported by Hashizume *et al.* that post-metallization annealing (PMA) is effective for reducing the interface trap density of Al_2O_3/GaN interfaces.[5] The aim of this study is to compare effect of PMA on mobility of channels fabricated on *c*- and *m*-plane GaN substrates.

2. Experimental Method

We used a vicinal *m*-plane GaN substrate ($N_D-N_A=2\times10^{17}$ cm^{-3}) with an angle and a direction of 5° toward [000−1] (*c*−5) and a *c*-plane substrate ($N_D-N_A=2\times10^{18}$ cm^{-3}) with a miscut angle of 0.4° toward [−12−10]. We carried out MOVPE to grow 5 μm unintentionally doped GaN on each substrate. After Si ions were implanted to form the source and drain regions, we deposited 50-nm-thick Al_2O_3 as a gate insulator on the surface using atomic layer deposition equipment with trimethylalminium and H_2O as precursors. We formed ohmic contacts on the source and drain, then formed a Ni/Au gate and pad electrode. All metals were deposited with an EB evaporator. We also prepared MIS capacitors in which insulator and gate electrode were formed in the same manner as above on Si-doped n-GaN ($N_D-N_A=4\times10^{16}$ cm^{-3}) grown on each substrate. After measuring samples, PMA was performed at 400°C in a nitrogen gas flow for 1 h.

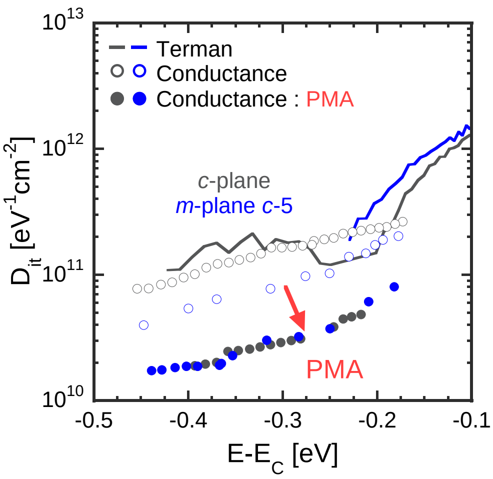

Fig. 1. D_{it} distributions in band gap estimated by high frequency and conductance methods. Gray and blue lines and dots correspond to the *c*- and *m*-plane, respectively. Solid dots are the results after PMA.

From the *C-V* characteristics (1 kHz to 1 MHz) of the Al_2O_3/n-GaN MIS capacitors, it was found that the frequency dispersion for all samples was very small, even without PMA, indicating that the interface state density (D_{it}) was low for all samples. Figure 1 shows the D_{it} distribution in the band gap estimated by the high-frequency (1 MHz) and conductance methods. In this energy range, D_{it} for samples without PMA was approximately 1×10^{11} eV^{-1} cm^{-2} and the *m*-plane sample showed slightly lower D_{it} than the *c*-plane sample. After PMA, D_{it} decreased to the order of 10^{10} eV^{-1} cm^{-2}. From these results, PMA was found to be effective for reducing the interface trap density of Al_2O_3/GaN MIS structures fabricated on both *c*- and *m*-plane samples.

The transfer characteristics of lateral accumulation-mode MISFETs (L_{ch}=100 µm, width Z_{ch}=50 µm) were obtained under the condition of V_{DS}=0.1 V. Figure 2 shows the dependence of the field-effect mobility (μ_{FE}) on the bias between the gate and source (V_{GS}). The horizontal axis was normalized by the bias from threshold voltage (V_{TH}). For the samples without PMA, the *m*-plane showed a higher peak value of μ_{FE} (178 cm^2/Vs) than the *c*-plane (149 cm^2/Vs). After PMA, these peak values increased for both the *m*-plane (192 cm^2/Vs) and the *c*-plane (159 cm^2/Vs).

Figure 3 shows the dependence of the effective mobility (μ_{EFF}) on the surface carrier concentration (N_S). For all samples, the μ_{EFF} increased with increasing the N_S once, then decreased in high-N_S region. The increase in low-N_S region was considered to be a screening of Coulomb scattering centers with surface free carriers. From the subthreshold slope (SS) of the transfer characteristic, D_{it} for the *c*-plane sample was considered to decrease after PMA similarly to the capacitors. Thus, the mobility in the low-N_S region increased because of the decrease in density of Coulomb scattering centers. In contrast, SS was larger for the *m*-plane sample after PMA, indicating that interface traps or other scattering centers were introduced by PMA, and the mobility in the low-N_S region slightly decreased. However, the channel mobility in the higher-N_S (>5×10^{12} cm^{-2}) region ($V_{GS}-V_{TH}$>3 V in Fig. 2) was increased by PMA. Since the scattering of carrier in this high-N_S region is dominated by the phonon or surface roughness, it was indicated that PMA has effect to suppress these scattering. Although the *c*-plane sample showed higher channel mobility in the low-N_S region, the channel mobility for the *m*-plane sample was higher in the high-N_S region and was increased by PMA. As a result, the peak mobility for the *m*-plane sample after PMA was larger than that for the *c*-plane sample.

3. Conclusions

We investigated the channel mobility in lateral accumulation-mode MISFETs fabricated on *c*- and *m*-plane GaN and the effect of post-metallization annealing. From the result for an Al_2O_3/n-GaN MIS capacitor, it was confirmed that PMA was effective for reducing the interface trap density not only for the *c*-plane but also for the *m*-plane sample. Moreover, the peak channel mobility in lateral accumulation-mode MISFETs was increased by PMA. The mechanisms for this are considered to be different for the *c*- and *m*-plane samples. The former was the increased mobility at a low-N_S region caused by the decreased density of interface traps, whereas the latter was due to the increased mobility in high-N_S region. The highest peak mobility was obtained on the *m*-plane after PMA, and forming the channel on a plane parallel to the *m*-plane is considered to be appreciable for GaN power transistors.

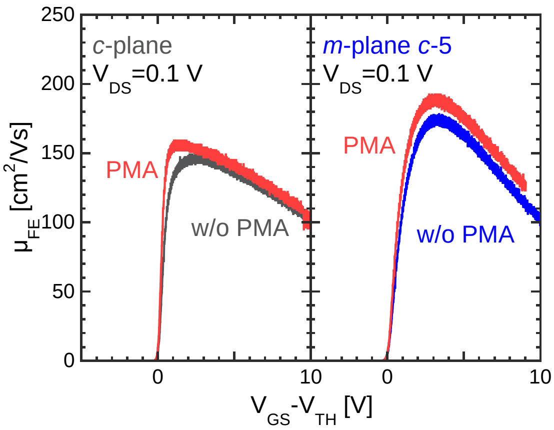

Fig. 2. Dependence of field-effect mobility (μ_{FE}) on bias voltage between gate and source calculated from transconductance. The horizontal axis was normalized by the threshold voltage (V_{TH}) estimated from the transfer characteristics. The results for the *c*-plane and *m*-plane are shown on the left and right, respectively. Red lines correspond to the results after PMA.

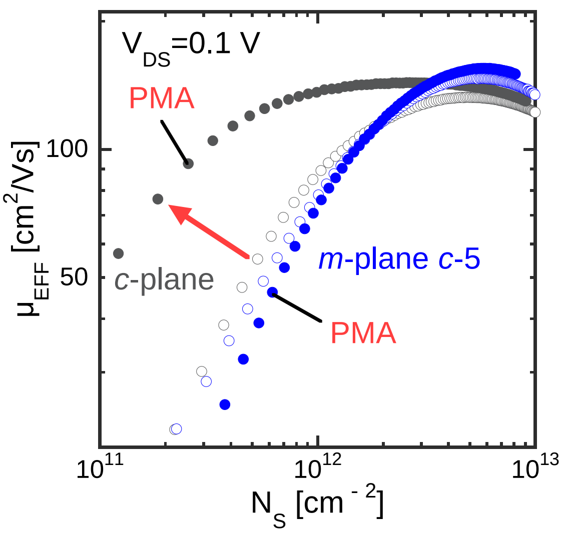

Fig. 3. Dependence of effective channel mobility (μ_{EFF}) on surface carrier concentration (N_S) measured from drainconductance. The V_{GS} dependence of N_S was estimated from the capacitance-voltage characteristics between the gate and channel. Gray and blue dots correspond to the *c*- and *m*-planes, respectively. Solid dots are the results after PMA.

Acknowledgement

This work was partly supported by the Cross-Ministerial Strategic Innovation Promotion Program.

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