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Effect of the formation temperature of the AlN/Si interface on the vertical-direction breakdown voltages of AlGaN/GaN HEMTs on Si substrates

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ABSTRACT

In this study, the initial AlN layer and the vertical-direction breakdown voltage (VDBV) of AlGaN/GaN high-electron-mobility transistors (HEMTs) were characterized. Prior to the formation of the interface between the AlN layer and the Si substrate, only trimethylaluminum (TMA) was introduced without ammonia to control the crystal quality of initial AlN layer (TMA preflow). HEMT structures were simultaneously grown on identical AlN layers on Si substrates (AlN/Si templates) grown using different TMA preflow temperatures. The density of screw- or mixed-type dislocations in the initial AlN layer decreased as the TMA preflow temperature increased. Further, the VDBV of the HEMT structure increased as the TMA preflow temperature increased. It is supposed that the screw- or mixed-type dislocations are the possible source of the vertical leakage current in the HEMT structures. The improvement in the crystal quality of the initial AlN layer affects the increase in the VDBV of the AlGaN/GaN HEMTs on Si substrates.

INTRODUCTION

AlGaN/GaN high-electron-mobility transistors (HEMTs) on Si substrates are expected to realize low-cost, low-loss, and high-output-power devices [1]. One of the main issues with AlGaN/GaN HEMTs on Si substrates is the relatively low vertical-direction breakdown voltage (VDBV) compared to the theoretical value. The VDBV can be increased by increasing the epitaxial buffer layer because of the decrease in the electric field in the epitaxial buffer layer. However, AlGaN/GaN HEMTs on Si substrates with thicker epitaxial layers have some disadvantages such as a low yield with a longer growth time and the occurrence of cracking due to large warpage of the wafer. Thus, AlGaN/GaN HEMTs on Si substrates with both thinner epitaxial layers and higher breakdown voltages are required.

There are some reports on improvements in the VDBV by various techniques, e.g., the use of a strained superlattice (SLS) [2] and heavy carbon doping [3]. In addition, the initial AlN layer may contribute. The initial AlN layer acts to prevent the melt-back etching reaction between the Si substrate and Ga. It has been reported that the VDBV has been increased by the suppression of V-shaped pits, which were generated by melt-back etching [4]. In our previous report, we characterized the initial AlN layer, and the vertical leakage current and breakdown voltage of HEMTs were investigated [5]. As a result, the full width at half maximum (FWHM) of the X-ray diffraction (XRD) rocking curve of the AlN (0002) planes of the initial AlN layer was correlated with the VDBV of the HEMT structure [6]. This suggests that the VDBV is decreased by the dislocations generated in the initial AlN layer.

In this study, the initial AlN layer of AlGaN/GaN HEMTs was characterized using the TMA preflow as a parameter. The type and density of the dislocations in the initial AlN layer and the characterization of the VDBV of the HEMTs are discussed in this paper.

EXPERIMENT

All of the samples used in this study were grown on 8-inch *p*-type Si substrates using a metalorganic chemical vapor deposition (MOCVD) tool (UR26K, Taiyo Nippon Sanso Corp., 8 inch \times 6 wafers) [7]. Trimethylgallium (TMG) and trimethylaluminum (TMA) were used as the group-III sources, and high-purity ammonia (NH₃) was used as the group-V source. Hydrogen and nitrogen were used as carrier gases.

A scanning electron microscope (SEM; S-4700, Hitachi) was used to compare the surface conditions and layer structures of each sample. XRD (D8 DISCOVER, Bruker) was employed to determine the crystal quality of each sample. The etch-pit method was used for specific types of dislocations. An aqueous potassium hydroxide (KOH) solution with a concentration of 4 mol/L was used as the etchant at 100 °C for 3 min.

The device structure for VDBV measurements was prepared from the HEMT structures using the following procedure. First, a mesa-like structure was formed by reactive-ion etching. Then, an ohmic electrode (Ti/Al/Ni/Au = 15/80/12/40 nm) was deposited using electron-beam deposition followed by rapid thermal annealing (N₂ atmosphere, 850 °C, 30 s). The diameter of the electrode was 100 μ m. Vertical leakage currents were measured using a semiconductor parameter analyzer (B1505A, Agilent Technologies).

Growth of the AlN/Si templates and AlGaN/GaN HEMT structures on the AlN/Si templates

AlN/Si templates were grown by the following steps. Prior to growth of the initial layer, Si substrates were thermally cleaned in situ by annealing for 5 min at 1000 °C in a hydrogen atmosphere. Then, the initial layer was formed by flowing TMA and a carrier gas. NH₃ was not supplied during the formation of the initial layer (TMA preflow). The TMA preflow temperature was varied to investigate its influence on the interface between the AlN layer and the Si substrate. The partial TMA pressure was 3.91×10^{-9} , and the reactor pressure was 13 kPa during the TMA preflow. Finally, the AlN layers were grown by flowing NH₃, TMA, and the carrier gas simultaneously. The growth conditions for the AlN layers were constant for all AlN/Si templates to investigate only the influence of the TMA preflow temperature on the interface between the AlN layer and the Si substrate. The growth conditions for the AlN layers were as follows. The growth temperature was 1000 °C, the V/III ratio was 250, the thickness was 150 nm, the reactor pressure was 13 kPa, and the partial TMA pressure was 1.02×10^{-7} . Three types of AlN/Si templates were prepared with different TMA preflow temperatures of 622 °C (Sample A), 811 °C (Sample B), and 1000 °C (Sample C).

The HEMT structures consisted of Al_{0.23}Ga_{0.77}N, GaN, SLS, and Al_{0.5}Ga_{0.5}N layers with thicknesses of 25 nm, 1000 nm, 1800 nm, and 250 nm, respectively, and were regrown from the upper parts of the AlGaN layers on the three types of AlN/Si templates. HEMT structures denoted as Samples A', B', and C' were regrown on the AlN/Si templates denoted as Samples A, B, and C, respectively. All HEMT structures were simultaneously regrown by using an MOCVD system (UR26K, Taiyo Nippon Sanso Corp.).

RESULTS AND DISCUSSION

Characterization of the AlN/Si templates

Figures 1a to 1c show SEM images of the surfaces of the AlN/Si templates. The surface pit density appears to be uniform. Figure 1d shows the relationship between the TMA preflow temperature and the FWHM of the rocking curve of the AlN (0002) face as well as the surface pit density characterized using the SEM images. The FWHM is 2471 arcsec for a TMA preflow temperature of 622 °C, and the FWHM decreases as the TMA preflow temperature increases. The FWHM reaches 2194 arcsec when the TMA preflow temperature is 1000 °C. The dislocation densities generated from the interfaces between the initial AlN layers and the Si substrates decrease as the TMA preflow temperature increases. However, the surface pit density reaches a minimum value of $1.44 \times 10^{10} \text{ cm}^{-2}$ for a TMA preflow temperature of 811 °C. Further, the surface pit densities are $2.52 \times 10^{10} \text{ cm}^{-2}$ and $3.84 \times 10^{10} \text{ cm}^{-2}$ for TMA preflow temperatures of 622 °C and 1000 °C, respectively. The size of the grain in the initial layer may be influenced by the TMA preflow temperature.

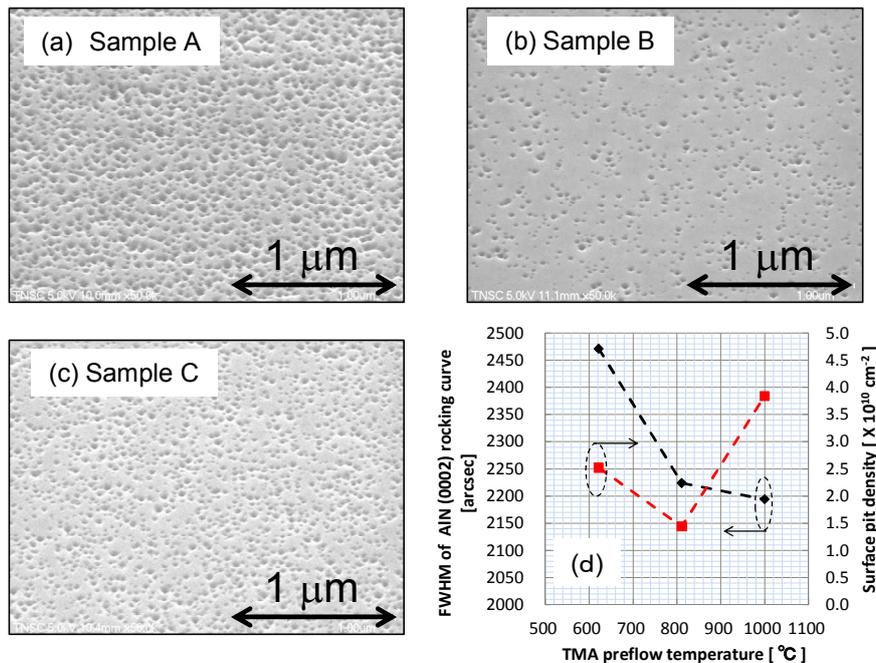


Figure 1. SEM images of the surfaces of AlN/Si templates for TMA preflow temperatures of (a) 611 °C, (b) 822 °C, and (c) 1000 °C. (d) FWHM of the AlN (0002) rocking curve and the surface pit density as a function of the TMA preflow temperature.

To identify the type of dislocations, KOH etching was performed. Figures 2a–2c show SEM images of the surfaces of the AlN/Si templates after KOH etching. Hexagonally shaped etch pits are observed for TMA preflow temperatures of 622 °C, 811 °C, and 1000 °C with densities of $1.50 \times 10^8 \text{ cm}^{-2}$, $1.03 \times 10^8 \text{ cm}^{-2}$, and $0.83 \times 10^8 \text{ cm}^{-2}$, respectively. The etch-pit density decreases as the TMA preflow temperature increases, similar to the FWHM of the rocking curve of the AlN (0002) face. The hexagonally shaped etch pits in GaN have been identified as screw- or mixed-type dislocations in a previous report [8]. Thus, these etch pits are

formed by screw- or mixed-type dislocations in the initial AlN layer. The sizes of the screw- or mixed-type etch-pits are significantly different for the three samples. Figure 2d shows the relationship between the average length of the diagonal dimension of the screw- or mixed-type dislocation pits and the TMA preflow temperature. The average length ranges from 1.14 μm to 0.59 μm for TMA preflow temperatures of 622 $^{\circ}\text{C}$ to 1000 $^{\circ}\text{C}$, respectively. This result indicates that the screw- or mixed-type dislocations might be localized at the hexagonally shaped etch pits. They might be bundled as the TMA preflow temperature decreases, then the pits becomes enlarged.

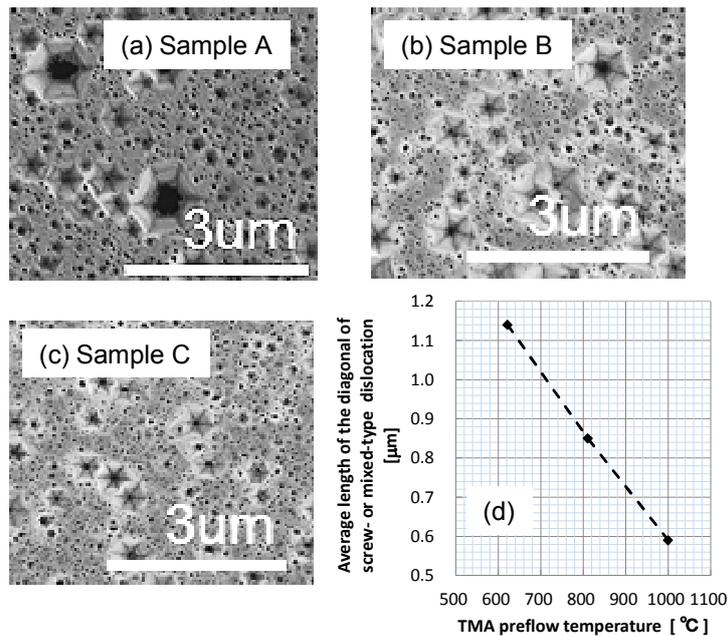


Figure 2. SEM images of the surfaces of the AlN/Si templates after KOH etching for TMA preflow temperatures of (a) 611 $^{\circ}\text{C}$, (b) 822 $^{\circ}\text{C}$, and (c) 1000 $^{\circ}\text{C}$. (d) The average diameter of screw- or mixed-type dislocations as a function of the TMA preflow temperature.

Characterization of the AlGaIn/GaN HEMT structures on AlN/Si templates

The HEMT structures were regrown on the AlN/Si templates, which were grown as previously discussed. The crystal quality of the GaN layer of HEMT structure for various TMA preflow temperatures was compared. The FWHMs of the rocking curves of the GaN (002) and GaN (102) planes are 850 arcsec and 1823 arcsec, respectively, for a TMA preflow temperature of 622 $^{\circ}\text{C}$; decrease as the TMA preflow temperature increases; and reach 765 arcsec and 1448 arcsec, respectively, at a TMA preflow temperature of 1000 $^{\circ}\text{C}$. The crystal quality of the GaN layer obviously improves as the TMA preflow temperature increases.

Figure 3a shows a schematic of the AlGaIn/GaN HEMT structure and the circuit for measuring the vertical leakage current. Figure 3b shows the measurements of the vertical leakage current in the AlGaIn/GaN HEMT structures grown on AlN/Si templates. A rapid increase in the vertical leakage current for Sample A' (TMA preflow temperature of 622 $^{\circ}\text{C}$) occurs at ~ 50 V. Similar increases do not occur until ~ 250 V for Sample B' (TMA preflow temperature of 811 $^{\circ}\text{C}$) and Sample C' (TMA preflow temperature of 1000 $^{\circ}\text{C}$). The vertical leakage current for sample

A' is the largest of the three samples. Figure 3c shows the dependence of the VDBV on the TMA preflow temperature. The VDBV is defined as the voltage at which the vertical leakage current density is equal to 1.0×10^{-6} A/mm². The VDBV increases as the TMA preflow temperature increases and is equal to 52 V, 358 V, and 385 V for TMA preflow temperatures of 622 °C, 811 °C, and 1000 °C, respectively. It is possible that the major leakage current paths are screw- or mixed-type dislocations.

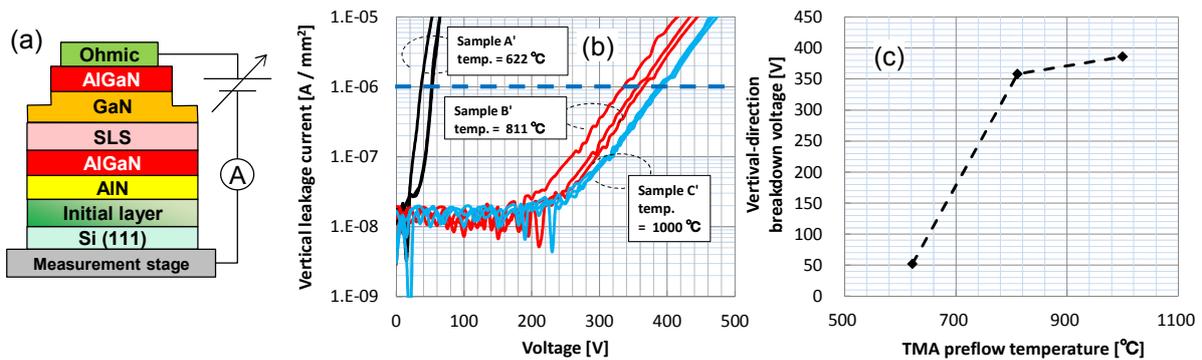


Figure 3. (a) Structure of the AlGaIn/GaN HEMT and the circuit for measuring the vertical leakage current. (b) Current–voltage characteristics of HEMTs on AlN/Si templates. (c) The VDBV of the HEMTs versus TMA preflow temperature.

To investigate the reason for the degradation in the VDBV, SEM observations were performed. Figure 4 shows cross-sectional SEM images of the SLS/AlGaIn/AlN interfaces of the HEMT structures. The interfaces between the initial AlN layer and the Si substrate are flat with no melt-back etching for the three samples. A large V-shaped defect in the AlGaIn layer and a fluctuation in the interface between the SLS and AlGaIn layer are observed for the HEMT structure grown on an AlN/Si template with a TMA preflow temperature of 622 °C; they decrease as the TMA preflow temperature increases. Narita et al. reported that the gate leakage current of AlGaIn/GaN HEMTs increased as the degradation in the interface of the SLS [9].

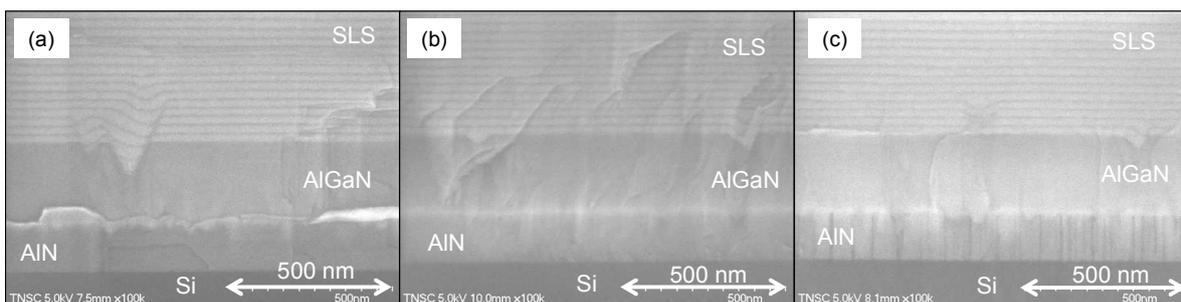


Figure 4. Cross-sectional SEM images of the SLS/AlGaIn/AlN interfaces of HEMT structures grown on AlN/Si templates with TMA preflow temperatures of (a) 622 °C, (b) 811 °C, and (c) 1000 °C.

Some V-shaped defects are observed at the interface between the SLS and AlGaIn layer. The fluctuation in the interface between the SLS and AlGaIn layer is caused by these V-shaped defects. As the TMA preflow temperature increases, the V-shaped defects become shallower as the dislocation density decreases. According to Sánchez et al., V-shaped defects are generated by

threading dislocations in InGaN/GaN MQWs [10]. It is supposed that the deep V-shaped defects are caused by the threading dislocation in the initial AlN layer. The kinetic mechanism of growth with TMA preflow technique is still under investigation.

CONCLUSIONS

AlN/Si templates and regrown AlGaIn/GaN HEMTs on AlN/Si templates were characterized. The relationship between the conditions for the formation of the initial layers and the VDBV of the AlGaIn/GaN HEMTs was investigated by simultaneously growing multiple HEMT structures on identical AlN/Si templates fabricated using different TMA preflow temperatures. An increase in the TMA preflow temperature decreased the density of screw- or mixed-type dislocations in the subsequently deposited AlN layers. This improved the flatness of the AlGaIn- and SLS-layer structures and the crystal quality of the GaN layers in the HEMT structures. In addition, it increased the VDBVs of the HEMT structures on the AlN/Si templates. Thus, the improvement in the crystal quality of the initial AlN layer affects the increase in the VDBV of the AlGaIn/GaN HEMTs on Si substrates.

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