Surface Morphology of $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}/\text{Al}_2\text{O}_3$ -High Electron Mobility Transistor Structure

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We present surface properties of buffer films (AlN and GaN) and $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}/\text{Al}_2\text{O}_3$ -High Electron Mobility Transistor (HEMT) structures with/without AlN interlayer grown on High Temperature (HT)-AlN buffer/ Al_2O_3 substrate and Al_2O_3 substrate. We have found that the GaN surface morphology is step-flow in character and the density of dislocations was about 10^8 – 10^9 cm^{-2} . The AFM measurements also exhibited that the presence of atomic steps with large lateral step dimension and the surface of samples was smooth. The lateral step sizes are in the range of 100–250 nm. The typical rms values of HEMT structures were found as 0.27, 0.30, and 0.70 nm. HT-AlN buffer layer can have a significant impact on the surface morphology of $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}/\text{Al}_2\text{O}_3$ -HEMT structures.

Keywords: Metal Organic Chemical Vapor Deposition, AlGaIn/GaN High Electron Mobility Transistor, AlN Interlayer, Atomic Force Microscopy.

1. INTRODUCTION

Nitride semiconductor materials are of great interest for electronic device applications due to their attractive physical properties.¹ For instance, AlGaIn/GaN-HEMTs have been attracting much attention as a material for realizing high-power and high-frequency electronic devices due to their superior material features, such as wide band gaps, high peak and saturation electron velocities, and high two-dimensional electron-gas (2DEG) densities.² Despite improvements in GaN technology and material quality, HEMTs are not yet commercially available. Due to the lack of suitable GaN bulk single crystals, GaN is currently grown on heterosubstrates such as sapphire (Al_2O_3) and silicon carbide (SiC).³ However, since their lattice parameters and thermal expansion coefficients are not well-matched to GaN, the epitaxial growth generates huge densities of defects, with threading dislocations (TDs) being the most prevalent (10^7 – 10^{11} cm^{-2}).⁴ The lack of dislocation-free GaN-bulk substrates is one of the main issues hampering device progress.⁵ So far, most of III–V nitrides due to its low price, stability at high temperatures, and its mature growth technology are grown on Al_2O_3 substrates for epitaxial GaN growth. In this case, the standard growth procedure is that a thick GaN buffer layer has to be grown prior to any further devices structures. In order to avoid the extremely large

lattice mismatch between GaN and Al_2O_3 (~13.6%), a thin low-temperature (LT) GaN or AlN nucleation layer must be initially grown before the thick high-temperature (HT) GaN buffer layer.^{6,7} However, the crystalline quality of GaN epilayers is much improved over direct growth on Al_2O_3 substrate when an AlN nucleation layer is used.^{8,9} Since the AlN layer supplies nucleation centers and promotes lateral growth of the GaN films.¹⁰ It was recently reported that crystal quality of GaN epitaxial films grown on the HT-AlN buffer/ Al_2O_3 substrates are developed.^{11,12} On the other hand, insertion of the thin AlN interlayer between GaN buffer and AlGaIn ternary layers allowed to improve HEMTs with high performance.^{2,11,13} Although AlN buffer layers and AlN interlayer increase crystal quality and performance of AlGaIn-HEMTs, many questions still remain about the relationship between structural properties of HEMT structures of the AlN buffer layer and AlN interlayer.^{14,15}

In this study, we present surface properties of buffer films and $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}/\text{GaN}$ -HEMTs with/without AlN interlayer grown with MOCVD on Al_2O_3 substrates. We have found that LT-AlN nucleation and HT-AlN buffer can have a significant impact on the surfaces of the HEMT structures. Experimental results showed that the surface defect density and rms roughness of HEMT structures grown using by HT-AlN buffer smaller than without AlN buffer. In addition to, it also showed that the surface properties of HEMTs with/without AlN interlayer grown on the same buffer layers were similar to each other.

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2. EXPERIMENTAL DETAILS

The samples used in this study were grown on c-face (0001) Al₂O₃ substrates by low-pressure MOCVD. Hydrogen was used as the carrier gas and trimethylgallium (TMGa), trimethylaluminum (TMAI) and ammonia (NH₃) were used as the Ga, Al, and N sources, respectively. Prior to the epitaxial growth, Al₂O₃ substrates were annealed at 1100 °C for 10 min to remove surface contamination.

For HT-AlN buffer film a 15 nm-thick AlN nucleation was deposited at 840 °C. After that, the reactor temperature was ramped to 1150 °C and an HT-AlN buffer layer was grown. The growth parameters of AlN are as follows: reactor pressure 25 mbar, growth rate 0.5 μm/h and gas total flow rate 8.0 L/min. For HT-GaN buffer film a 15 nm-thick AlN nucleation was deposited at 840 °C firstly. After that, the reactor temperature was ramped to 1150 °C and an HT-AlN buffer layer was grown, followed by two minutes growth interruption in order to reach growth conditions for GaN. The growth conditions of GaN were as follows: reactor pressure 200 mbar, growth temperature 1070 °C, H₂ carrier gas, and growth rate about 2 μm/h. We have grown AlN and GaN buffer film structures shown as schematic in Table I.

We have grown three HEMT structures shown as schematic in Table II. In terms of simplicity, the samples with AlN interlayer and without AlN interlayer grown on HT-AlN Buffer/LT-AlN nucleation layer/Al₂O₃ substrates were labeled as sample A and sample B, and the sample with AlN interlayer grown on LT-GaN nucleation layer/Al₂O₃ substrate was labeled as sample C.

For samples A and B, 15 nm-thick AlN nucleation layer was deposited at 840 °C. After that, the reactor temperature was ramped to 1150 °C and a HT-AlN buffer layer was grown, followed by two minutes growth interruption in order to reach growth conditions for GaN. Sample C was grown on semi-insulating GaN template. The semi-insulating GaN was prepared by two-step growth method with a 25 nm-thick LT-GaN nucleation deposited at 540 °C. The nucleation and annealing process were calibrated carefully to obtain the high resistance character of GaN. The growth conditions of GaN were as follows: reactor pressure 200 mbar, growth temperature 1070 °C, H₂ carrier gas, and growth rate about 2 μm/h.

Surface morphologies of buffer films (AlN and GaN), and sample A, sample B, sample C were performed by AFM technique. The AFM needle sensor measurements were carried out at room temperature and atmosphere pressure.

Table I. Schematic structures of AlN and GaN buffer films.

AlN buffer film	GaN buffer film
HT-AlN ~0.5 μm	HT-GaN ~2 μm
LT-AlN nucleation ~15 nm	HT-AlN ~0.5 μm
c-face Al ₂ O ₃	LT-AlN nucleation ~15 nm
—	c-face Al ₂ O ₃

Table II. Schematic structures of sample A, sample B, and sample C.

Sample A	Sample B	Sample C
GaN cap ~2 nm	GaN cap ~2 nm	GaN cap ~2 nm
Al _{0.3} Ga _{0.7} N ~25 nm	Al _{0.3} Ga _{0.7} N ~25 nm	Al _{0.3} Ga _{0.7} N ~25 nm
HT-AlN ~2 nm	—	HT-AlN ~2 nm
HT-GaN ~2 μm	HT-GaN ~2 μm	HT-GaN ~2 μm
HT-AlN buffer ~0.5 μm	HT-AlN buffer ~0.5 μm	—
LT-AlN nucleation ~15 nm	LT-AlN nucleation ~15 nm	LT-GaN nucleation ~25 nm
c-face Al ₂ O ₃	c-face Al ₂ O ₃	c-face Al ₂ O ₃

3. RESULTS AND DISCUSSION

As is well known, there are three general modes of growth of epilayers:

- (1) Atomic step-flow growth mode,
- (2) Layer-by-layer or 2D growth mode, and
- (3) 3D island growth mode.

Atomic step-flow growth mode allows fast adatom diffusion to intrinsic steps, a process which mediates step-flow. This growth mode creates a smooth surface morphology and can be achieved by high substrate temperature and low deposition rate.^{16, 17}

Fig. 1. (a) and (b) AFM surface images with 4 × 4 μm² scan area of AlN and GaN buffer films grown on (0001) Al₂O₃ substrate, respectively.

Fig. 2. AFM GaN surface image with $2 \times 2 \mu\text{m}^2$ scan area of sample B. The dark spots (screw type dislocation) on the GaN surface are approximately with 30 nm size.

3.1. Surface Characterization of AlN and GaN Buffer Films

Figures 1(a) and (b) show AFM images with $4 \times 4 \mu\text{m}^2$ scan area on the surfaces of HT-AlN and HT-GaN buffer films, respectively. There appears an array of relatively straight and parallel terraces on the AlN surface, which is quite different from the GaN surface. Instead of parallel terraces on AlN surface there are randomly oriented terraces on the GaN surface. The parallel and straight terraces suggest the typical step-flow growth mode, meaning that the two-dimensional (2D) layer-by-layer growth basically, dominates the AlN growth even at an early stage, which is totally different from the GaN growth. This correlates with the growth conditions of epitaxial AlN and GaN.⁶ In addition to, the average step height different measured on AlN and GaN surfaces are 0.15 and 0.27 nm, respectively.

Many of the terrace steps shown on the GaN surface are pinned, generally appearing dark spots in the AFM images. The pinned steps should be associated with the screw threading dislocations (TDs) since a pinned step

must form when a TD with a screw component intersects a free crystal surface and causes a surface displacement normal to the surface.¹⁸ Thus, the fact that nearly no pinned steps can be observed for AlN indicates a very low density of screw TDs, which is consistent with the previously reported AFM, TEM, and XRD results.^{6, 18} The density of dark spot (screw type dislocation) on GaN buffer film surface was found to be as $\sim 6.1 \times 10^8$ ($\pm 0.20 \times 10^8$).

Fig. 3. (a), (b), and (c) AFM GaN surface images of sample A, sample B, and sample C, respectively (with $5 \times 5 \mu\text{m}^2$ scan area). Step-flow growth has been observed on HEMT structures. The many of the terrace steps shown on the sample A, sample B, and sample C are pinned, generally appearing dark spots, which are associated with dislocations with screw components.

Table III. The values of dislocation density, average lateral step size, and rms on surfaces of AlN and GaN buffer films.

Buffer film surface	Dislocation density (cm^{-2}) ($\pm 0.20 \times 10^8$)	Lateral step size (nm)	rms (nm)
AlN (0.5 μm)	—	130	0.10
GaN (2 μm)	6.1×10^8	200	0.55

Table IV. The dislocation densities, average lateral step sizes, and rms for the samples A, B, and C.

Structures	Substrates	Dislocation density (cm^{-2}) ($\pm 0.20 \times 10^8$)	Lateral step size (nm)	rms (nm)
This work				
GaN(2 nm)/AlGaN(25 nm)/AlN(2 nm)/ GaN(2 μm): sample A	AlN(0.5 μm)/LT-AlN(15 nm)/ Al_2O_3	2.5×10^8	247	0.27
GaN(2 nm)/AlGaN(25 nm)/GaN(2 μm): sample B	AlN(0.5 μm)/LT-AlN(15 nm)/ Al_2O_3	5.2×10^8	190	0.30
GaN(2 nm)/AlGaN(25 nm)/AlN(2 nm)/ GaN(2 μm): sample C	LT-GaN(25 nm)/ Al_2O_3	2.0×10^9	128	0.70
Miyoshi et al. [2]				
AlGaN(25 nm)/AlN(1 nm)/GaN(2 μm)	AlN(1 μm)/ Al_2O_3	2.5×10^8	—	0.12–0.16
AlGaN(25 nm)/GaN(2 μm)	AlN(1 μm)/ Al_2O_3	2.5×10^8	—	0.13–0.16
AlGaN(25 nm)/AlN(1 nm)/GaN(3 μm)	Al_2O_3	3.0×10^9	—	0.47–0.53

These dark spots on the GaN surface are approximately with 30 nm size (as shown in Fig. 2).

The surface roughness closely related in lateral step size dimension on surface.¹⁹ The average lateral step sizes on the surface AlN and GaN are approximately 130, 200 nm, respectively. On the other hand the root-mean square (rms) is important parameter to definite surface/interface roughness. The rms of AlN and GaN surfaces were found to be 0.10 and 0.55 nm, respectively. From these values, we can say that the AlN has atomically flat surface. Table III summarizes values of screw type dislocation density, average lateral step size, and rms on surfaces of AlN and GaN buffer films.

3.2. Surface Characterization of $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}/\text{Al}_2\text{O}_3$ -HEMTs

Figures 3(a, b, and c) show AFM images with $5 \times 5 \mu\text{m}^2$ scan area of samples A, B, and C, respectively. There are randomly oriented terrace steps, and dark spots on the GaN surface. However, the nanopipes and Ga droplets were not observed. There appears step-flow morphology on the GaN surface of samples. While the step-flow growth is beneficial, the nanopipes and Ga droplets are deleterious to the device performance.¹⁹ In addition to, the average step height different measured on samples A, B, and C are 0.24, 0.24, and 0.27 nm, respectively. These measured values are very close to one monolayer of (002) GaN. Miyoshi et al. reported that dislocation density of HEMT structures with a 1 nm-thick AlN interlayer and without AlN interlayer grown on a AlN buffer (1 μm)/ Al_2O_3 substrate, and Al_2O_3 substrate, shows 2.5×10^8 , and $3 \times 10^9 \text{ cm}^{-2}$, respectively.² The dislocation densities of samples A, B, and C were found to be as $\sim 2.5 \times 10^8$, $\sim 5.2 \times 10^8$, and $\sim 2 \times 10^9 \text{ cm}^{-2}$ ($\pm 0.20 \times 10^8$). The dislocation density in the sample A approximately one order of magnitude lower than in sample C, and twice that in sample B. This is in agreement with the previously reported results^{2,11} that the dislocation density in MOVPE-grown GaN films on AlN buffer/ Al_2O_3 substrates is one or more orders of magnitude lower than in GaN films grown on Al_2O_3 substrates with and without LT-buffer

layer. As seen above values the lowest dislocation density has been found for the sample A grown on the HT-AlN buffer/LT-AlN nucleation/ Al_2O_3 substrate. However, the highest dislocation density was found for sample C grown on the LT-GaN nucleation/ Al_2O_3 substrate. It is interesting to say that Miyoshi et al. found that the dislocation densities are the same for their samples with AlN interlayer and without AlN interlayer grown on AlN buffer (1 μm)/ Al_2O_3 substrates (without any low-temperature buffer layers).²

The average lateral step sizes of samples A, B, and C are about 247, 190, and 128 nm, respectively. From these values, the sample A has less rough than the others. The rms values were found to be as 0.27, 0.30, and 0.70 nm for samples A, B, and C, respectively. Table IV summarizes thickness of top layer (GaN cap layer), density of screw type dislocation, average lateral step size, and rms for the samples. The values of dislocation density, average lateral step size, and rms measured on surface of HT-GaN buffer film are close to samples A and B, but different from C. Finally, the present AFM results clearly indicate that samples A and B improved the film quality compared to sample C due to presence of LT-AlN nucleation layer and HT-AlN buffer layer in the heterostructures.

4. CONCLUSION

We have investigated the surface properties of buffer films (AlN and GaN), and $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}/\text{Al}_2\text{O}_3$ -HEMT structures with AlN interlayer and without AlN interlayer grown on Al_2O_3 substrate by using AFM. The AFM images of GaN cap layer surfaces showed the step-flow morphology. The screw type dislocation density on GaN surface which has no GaN droplets and nanopipes was found to be about 10^8 – 10^9 cm^{-2} . AFM measurements also exhibited that the presence of atomic steps with large lateral step dimension and the surfaces of samples were smooth. The lateral step sizes of samples are of the order of 100–250 nm and typical rms values were found as 0.27, 0.30, and 0.70 nm. Finally, we have found that LT-AlN nucleation and HT-AlN buffer layer can have a significant impact on the surface morphology of $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}/\text{Al}_2\text{O}_3$ -HEMT structures grown on Al_2O_3 substrates. In addition

to, it also showed that the surface properties of HEMTs with/without AlN interlayer grown on the same buffer layers were similar to each other.

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