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Surface Morphology of $Al_{0.3}Ga_{0.7}N/Al_2O_3$-High Electron Mobility Transistor Structure

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Abstract : We present surface properties of buffer films (AlN and GaN) and $Al_{0.3}Ga_{0.7}N/Al_2O_3$-HEMT structures with 2nm-thick AlN interlayer and without AlN interlayer grown on Al_2O_3 substrates by using the atomic force microscopy (AFM). 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 of the order of 100-250 nm. The typical rms values of HEMT structures were found as 0.27, 0.30 and 0.70 nm.

Keywords: Metalorganic Chemical Vapor Deposition, $Al_{0.3}Ga_{0.7}N/Al_2O_3$-High Electron Mobility Transistor, AlN interlayer, Atomic Force Microscopy.

Nitride semiconductor materials are of great interest for electronic device applications due to their attractive physical properties [1]. For instance, AlGaN/GaN high electron mobility transistors (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 sapphire (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 GaN buffer layer grown at high temperature [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]. Although AlN nucleation layers have been widely used, many questions still remain about the relationship between the AlN layer and the structural and electronic properties of subsequent GaN or AlGaN/GaN layers [11,12]. For example, the electron mobility that important parameter for characterization of HEMT-based devices is related surface/interface defects (such as dislocations, nanopipes, GaN droplets) and roughness. On the other hand, the reduction of dislocation density is obtained in a wide range, depending on the nature of the interlayer (GaN or AlN) and growth conditions [5]. Shen *et al.* and Miyoshi *et al.* reported that HEMTs with a 1 nm-thick AlN interlayer grown on SiC and Al_2O_3 substrates shows high performance [2,13,14].

In this study, we present surface properties (such as step-flow growth, surface roughness, GaN droplets and screw type dislocation density) of buffer films (AlN and GaN) and $Al_{0,3}Ga_{0.7}N/Al_2O_3$-HEMT structures with 2nm-thick AlN interlayer and without AlN interlayer grown all samples were grown MOCVD having by different nucleation layer (GaN-AlN) on Al_2O_3 substrates. We have found that LT-AlN nucleation layer, high temperature (HT) AlN buffer layer, and AlN interlayer can have a significant impact on the surfaces of the $Al_{0,3}Ga_{0.7}N/Al_2O_3$-HEMT structures.

II. Experiments

The samples used in this study were grown on c-face (0001) Al_2O_3 substrates by low-pressure MOCVD. Hydrogen was used as the carrier gas and trimethylgallium (TMGa), trimethylaluminum (TMAl) and ammonia (NH_3) were used as the Ga, Al and N sources, respectively. Prior to the epitaxial growth, sapphire substrates were annealed at 1100 ºC for 10 min to remove surface contamination.

For 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 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. 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 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 ºC, H_2 carrier gas, and growth rate about 2 μm/h. We have grown AlN and GaN buffer film structures shown as schematic in Table 1.

We have grown three HEMT structures shown as schematic in Table 2. In terms of simplicity, the samples with AlN interlayer and without AlN interlayer grown on LT-AlN nucleation layer/Al_2O_3 were labeled as sample A and sample B, and the sample with AlN interlayer grown on LT-GaN nucleation layer/Al_2O_3 was labeled as sample C.

For sample A and sample B, 15 nm-thick AlN nucleation layer was deposited at 840 °C. After that, the reactor temperature was ramped to 1150°C and a high temperature 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 low temperature GaN nucleation deposited at 500 ºC. 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 ºC, H_2 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.

III. Results and Discussion

As is well known, there are three general modes of growth of epilayers: (i) Atomic step-flow growth mode, (ii) Layer-by-layer or 2D growth mode, and (iii) 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 [15,16].

A. Surface characterization of AlN and GaN buffer films

Figure 1 (a), and (b) shows AFM images with 4×4 μm^2 scan area on the surfaces of AlN and 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 [17]. 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 [6,17]. The density of dark spot (screw type dislocation) on GaN buffer film surface was approximately found 6.1×10^8. These dark spots on the GaN surface are approximately with 30 nm size (as shown in Figure 3).

The surface roughness closely related in lateral step size dimension on surface [18]. 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 3 summarizes values of screw type dislocation density, average lateral step size, and rms on surfaces of AlN and GaN buffer films.

B. Surface characterization of $Al_{0,3}Ga_{0.7}N/Al_2O_3$-HEMTs

Figure 2 (a), (b) and (c) shows AFM images with 5×5 μm^2 scan area of sample A, sample B and sample C, respectively. There are randomly oriented terrace steps, and dark spots on the GaN surface of samples. However, the nanopies and GaN 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 GaN droplets are deleterious to the device performance [18]. In addition to, the average step height different measured on sample A, sample B and sample 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 1nm-thick AlN interlayer and without AlN interlayer grown on a AlN(1μm)/Al_2O_3 template and Al_2O_3 substrate, shows 2.5×10^8 and 3×10^9 (cm^{-2}), respectively [2]. The dislocation densities of sample A, sample B and sample C were approximately found 2.5×10^8, 5.2×10^8 and 2×10^9 cm^{-2}. 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 [2,13] that the dislocation density in MOVPE-grown GaN films on AlN/Al_2O_3 templates 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 (with AlN nucleation and HT-AlN buffer). However, the highest dislocation density was found for sample C (with GaN nucleation and without HT-AlN buffer). 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(1μm)/Al_2O_3 template (without any low-temperature buffer layers) [2].

The average lateral step sizes of sample A, sample B and sample C are approximately 247, 190 and 128 nm, respectively. From these values, we can say that 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 sample A, B, and C, respectively. Table 4 summarizes thickness of top layer (GaN cap layer), density of screw type dislocation, average lateral step size, and rms on the surfaces sample A, sample B, and sample C.

The values of dislocation density, average lateral step size, and rms measured on surface of GaN buffer film are close to sample B. However, the values of dislocation density, average lateral step size, and rms measured on sample A are lower than both GaN buffer film surface and sample B. This means that AlN interlayer improves the surface properties of HEMT structures. In addition to, the dislocation density, average lateral step size, and rms values measured on sample A and sample C, it is possible to say that surface properties of sample A are better than sample C. Finally, the present AFM results clearly indicate that sample A improved the film quality compared to sample B and sample C due to presence of LT-AlN nucleation layer, HT-AlN buffer layer, and a thin AlN interlayer in the heterostructures.

IV. Conclusion

We have investigated the surface properties of buffer films (AlN and GaN) and $Al_{0,3}Ga_{0.7}N/Al_2O_3$-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 was 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 HT-AlN buffer layer, and 2nm-thick AlN interlayer can have a significant impact on the surface morphology of $Al_{0,3}Ga_{0.7}N/Al_2O_3$-HEMT structure grown on LT-AlN nucleation/Al_2O_3 substrate.

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Figure Captions:

Fig.1: (a) and (b) AFM surface images with 4x4 μm^2 scan area of AlN and GaN buffer films grown on (0001) Al_2O_3 substrate, respectively.

Fig.2: (a), (b) and (c) AFM GaN surface images of sample A, sample B and sample C, respectively (with 5x5 μm^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.

Fig.3: AFM GaN surface image with 2×2 μm^2 scan area of sample B. The dark spots (screw type dislocation) on the GaN surface are approximately with 30 nm size.

Table Captions:

Table 1: Schematic structures of AlN, and GaN buffer films.

Table 2: Schematic structures of samples A, sample B, and sample C.

Table 3: The values of dislocation density, average lateral step size, and rms on surfaces of AlN and GaN buffer films.

Table 4: The thickness of top layer, dislocation density, average lateral step size, and rms on surfaces of Sample A, sample B, and sample C.

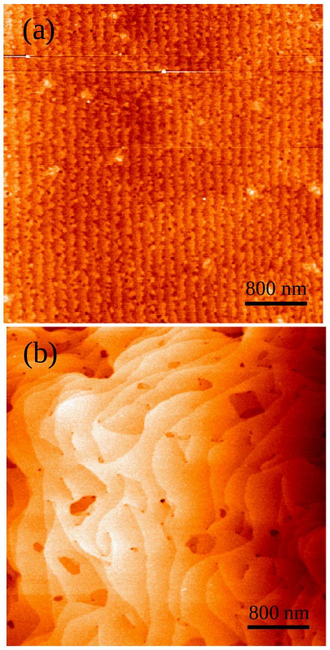

Fig.1

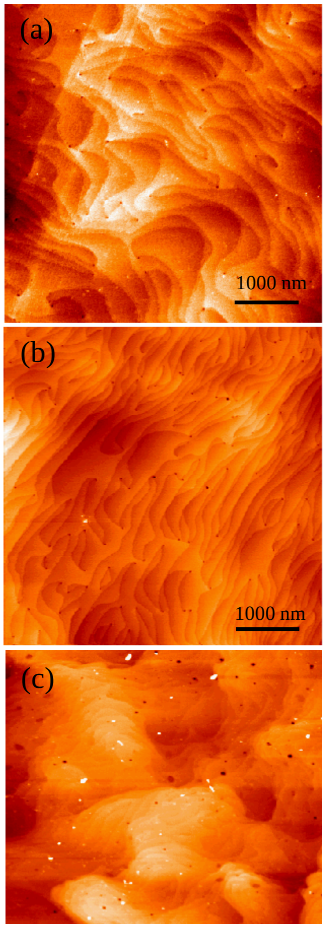
(a)
1000 nm
(b)
1000 nm
(c)

Fig.2

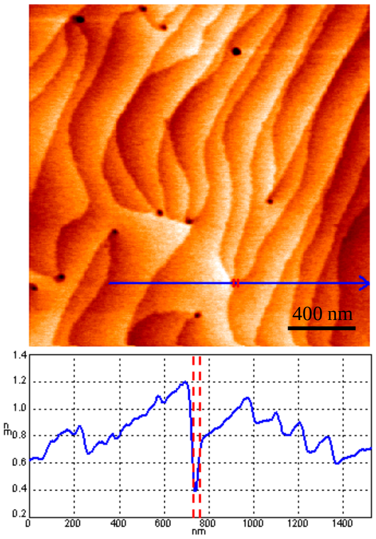
400 nm
1.4
1.2
1.0
0.8
0.6
0.4
0.2
nm
0
200
400
600
800
1000
1200
1400
nm

Fig.3

Table 1:

AlN buffer film
HT-AlN ~ 0.5 µm
LT-AlN nucleation ~ 15 nm
c-face Al_2O_3
--

GaN buffer film
HT-GaN ~ 2 µm
HT-AlN buffer ~ 0.5 µm
LT-AlN nucleation ~ 15 nm
c-face Al_2O_3

Table2:

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_2O_3	c-face Al_2O_3	c-face Al_2O_3

Table 3:

Buffer film surface	Dislocation density (cm^{-2})	Lateral Step Size (nm)	RMS (nm)
AlN(0.5 µm)	--	130	0.10
GaN(2 µm)	6.1×10^8	200	0.55

Table 4:

	Structures	Substrates	Dislocation density (cm^{-2})	Lateral Step Size (nm)	rms (nm)
This work	GaN(2 nm)/AlGaN/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/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/AlN(2 nm)/GaN(2 µm): *sample C*	LT-GaN(25 nm)/Al_2O_3	2×10^9	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	3×10^9	--	0.47-0.53