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Effects of High-Temperature AlN Buffer on the Microstructure of AlGaN/GaN HEMTs[1]

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Abstract—Effects on AlGaN/GaN high-electron-mobility transistor structure of a high-temperature AlN buffer on sapphire substrate have been studied by high-resolution *x*-ray diffraction and atomic force microscopy techniques. The buffer improves the microstructural quality of GaN epilayer and reduces approximately one order of magnitude the edge-type threading dislocation density. As expected, the buffer also leads an atomically flat surface with a low root-mean-square of 0.25 nm and a step termination density in the range of 10^8 cm^{-2}. Due to the high-temperature buffer layer, no change on the strain character of the GaN and AlGaN epitaxial layers has been observed. Both epilayers exhibit compressive strain in parallel to the growth direction and tensile strain in perpendicular to the growth direction. However, an high-temperature AlN buffer layer on sapphire substrate in the HEMT structure reduces the tensile stress in the AlGaN layer.

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1. INTRODUCTION

The GaN-based high-electron-mobility transistors (HEMTs) are strong candidates for high-power and high-frequency applications owing to the excellent properties of group-III nitride semiconductor materials [1–4]. The GaN-based HEMT structures are commonly grown on sapphire substrates on account of the lack of large native substrate. However, the lattice constant and thermal coefficient discrepancy between GaN and sapphire brings about a high dislocation density in the GaN and overgrown epitaxial layers, which adversely affects the performance of devices. In order to reduce the dislocation density in the epilayers, several techniques such as the lateral epitaxy overgrowth and various buffer layers growth have been used [5–7]. In recent years, the growth of GaN and AlGaN films on an AlN buffer layer or multi-buffer layers have been attracting interest [7–10].

On the other hand, a semi-insulating (SI) thick-GaN main layer is a necessity for HEMTs because it decreases parallel conduction between the source and the drain, and ensures a sharp channel pinch off [11, 12]. A SI-GaN is usually achieved by means of intentional doping or tuning the growth conditions [12–14]. Apart from these methods, Yu et al. [15] developed a SI-GaN layer for AlGaN/GaN HEMT applications by using an AlN buffer layer on sapphire substrate. Consequently, the AlN buffer layer has a critical important for the device performance, and thereby its effects on the heterostructures needs to be understood.

In case of heteroepitaxial growth, a strong influence of the buffer layer on the structural properties and the character of the growth of subsequent layers has been well known [7, 9, 16, 17]. We, too, had confirmed this in one of our previous studies [18]. In this study, we report the effects on the crystalline quality, dislocation density, and surface morphology of AlGaN/GaN-HEMTs of an HT-AlN (high-temperature AlN) buffer layer on *c*-plane sapphire substrate. We also evaluated the strain status of GaN and AlGaN epitaxial layers in the HEMT structures.

2. EXPERIMENTAL METHOD

The unintentionally doped AlGaN/GaN-HEMTs used in the present study were grown on *c*-plane sapphire substrates in a low-pressure MOCVD reactor (Aixtron 200/4 HT-S) by using standard trimethylgallium (TMGa), trimethylaluminum (TMAl), and ammonia (NH_3) as Ga, Al, and N sources, respectively. Prior to the epilayer growth, the substrates were annealed at 1100°C for 10 min to remove the surface oxides. For sample with the buffer layer, the growth was initiated with the deposition of a 15-nm-thick low-temperature AlN nucleation layer (NL) at 840°C. Then, the reactor temperature was ramped to 1150°C

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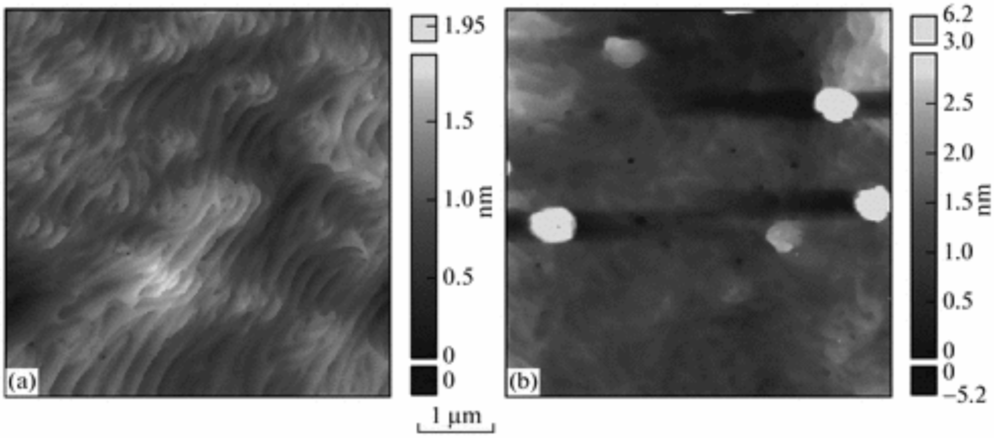

Fig. 1. AFM scans with a 5×5 µm^2 area of the samples: (a) A and (b) B. Dark to white color variance corresponds to pit to hill variance on the surface of the samples.

and a 500-nm-thick HT-AlN buffer layer was grown. A sample without the buffer was deposited on a 25-nm-thick low-temperature GaN NL, for comparison. The NL thickness and annealing process of this sample were carefully calibrated to obtain highly resistive character. Finally, for both samples, an undoped 2000-nm-thick GaN main layer, 25-nm-thick AlGaN barrier layer, and 3-nm-thick GaN top layer were grown at same growth temperature and reactor pressure. The HEMT structures with and without the HT-AlN buffer were labeled as samples A and B.

The structural quality and strain state of the samples were examined by XRD measurements using a Bruker D8-Discover high-resolution diffractometer system. The surface morphology of the samples was characterized by AFM observations using an Omicron variable temperature (VT) STM/AFM instrument.

3. RESULTS AND DISCUSSION

In order to understand the surface properties of the samples, AFM scans were performed over a small area of 5×5 µm^2. Figure 1 shows AFM images obtained from the GaN top surfaces of the HEMT structures. As seen from these images, sample A with the buffer has a well- defined step-terrace structure. However, sample B without the buffer displays pits and hillocks on the surface besides unclear step terraces. The pit and hillock densities of this sample were estimated as 5.6×10^7 and 2.4×10^7 cm^{-2} by the number of pits and hillocks from the image of 5×5 µm^2, respectively. The observed step-terrace formation on the surfaces of the samples reveals step-flow growth. On the other hand, the majority of the steps on the surfaces were terminated at darks spots in the images. It is rather well known that there are three kinds of threading dislocations (TDs) in a GaN epilayer: pure screw (c-type), pure edge (a-type), and mixed ($c + a$)-type. The intersection of a TD except for the pure edge one with the free surface leads to a step termination on a single crystal surface and hence, the step termination density is related to the screw or mixed TD density [19]. The density of step terminations is in the rang of 10^8 cm^{-2} on the surface of sample A. The step termination density was not distinguishable from sample B, on account of its rough surface. However, from the step-terrace structure and lateral sizes of the terraces, it is apparent that the step termination density of sample A is lower than that of sample B. Additionally, the root-mean-square (rms) values of samples A and B were obtained as 0.25 and 0.66 nm over a scan area of 5×5 µm^2, which are in agreement with the lateral sizes of the terraces on the surfaces. Consequently, AFM observations clearly indicated that sample A grown by using an HT-AlN buffer layer on sapphire substrate has a good- quality surface with an rms value of 0.25 nm and a regular step-terrace structure as opposed to the inferior surface of sample B grown by a low-temperature GaN NL only.

Figure 2 shows Bragg reflections from the symmetric plane (0002) and asymmetric plane $(10\bar{1}2)$ of the GaN layers in the samples. Gaussian type (0002) reflections result from the mosaicity of the layers [20, 21]. In this case, it is clear that GaN main layer without the buffer in sample B has a more mosaic structure because of the wide spread of the reflection. As is already well known, the broadening of the X-ray reflections is related to the crystalline quality of epitaxial layers, which is denoted by the full-width at half-maximums (FWHMs) of the peaks. The FWHMs of samples A and B were determined as 0.078°, 0.116° for the GaN(0002) reflections and 0.104°, 0.342° for the GaN$(10\bar{1}2)$ reflections as listed in table. As is clearly seen, the FWHM values of sample A are lower than those of sample B. These results show that the GaN in sample B has a poor quality, which seems in harmony