Effect of a high temperature AlN buffer layer grown by initially alternating supply of ammonia on AlGaN/GaN heterostuctures*

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Abstract: The effect of a high temperature AlN buffer layer grown by the initially alternating supply of ammonia (IASA) method on AlGaN/GaN heterostructures was studied. The use of AlN by the IASA method can effectively increase the crystalline quality and surface morphology of GaN. The mobility and concentration of 2DEG of AlGaN/GaN heterostuctures was also ameliorated.

Key words: metal-organic vaporphase epitaxy; aluminum nitride; gallium nitride; AlGaN/GaN heterostructures
DOI: 10.1088/1674-4926/30/9/093001 **PACC:** 7280E; 7360L

1. Introduction

The GaN-based high electron mobility transistor (HEMT), as the next-generation RF power device, has been receiving much attention in the compound semiconductor industry because of its excellent high power handling capability in high frequency operations[1, 2]. However, finding a suitable substrate remains a challenge for GaN epitaxy growth. For cost considerations, *c*-plane sapphire is often used as a substrate despite a large lattice mismatch and a large difference in thermal expansion coefficients. The crystal quality of GaN has improved greatly since the two-step nucleation procedure was proposed by Amano *et al.* in 1986[3], although a high density of defects, vacancies or impurities still remain, especially at the region at a height of several hundred nanometers from the interfaces. Therefore, the electrical properties of the GaN-based HEMT with thin buffer layer are greatly degraded as a result of these crystal imperfections[4, 5]. Facet formation, which occurs during island growth at initial GaN buffer growth before coalescence, is thought to be the cause of these defects. In order to obtain decent GaN quality for electronic devices, coalescence of nuclei must be promoted to prevent facet formation. Recently, we successfully achieved a high temperature (HT) AlN layer by initially alternating supply of ammonia (IASA) directly grown on a sapphire substrate without a low-temperature AlN nucleation layer. Using this HT AlN layer as a buffer layer, a high quality GaN layer with a significant reduction in dislocation density was obtained, on which a high quality AlGaN/GaN HEMT structure was subsequently grown.

2. Experimental details

The growth of the GaN layer was achieced by metal-organic chemical vapor deposition (MOCVD) on a 3-piece-by-2-inch reactor. Triethylgallium (TEG), trimethylaluminum (TMAl) and high-purity ammonia (NH_3) sources were used as Ga, Al and N sources in the H_2 carrier gas. Basal plane sapphire substrates were heated in flowing H_2 at 1100 °C prior to growth in order to remove contamination from the sapphire. The growth temperature was measured by a thermocouple located at the center of the three susceptors. An HT AlN layer with a thickness of 100 nm was directly grown on a sapphire substrate at 1100 °C by the IASA method under a V/III ratio of 2000. The gas flow sequence used for the IASA growth is shown in Fig. 1. The duration and interruption time of the supply of NH_3 gas flow are both 20 s, and the number of pulses was 100. Afterwards, the temperature was lowered to 1000 °C to grow a 2 μm thick GaN layer, followed by 25 nm $Al_{0.25}Ga_{0.75}N$. For comparison, a reference sample was grown using the conventional two-step technique, which consisted of a 25 nm AlN nucleation layer grown at low temperature (LT), a 2 μm GaN layer and 25 nm $Al_{0.25}Ga_{0.75}N$ grown at high temperature.

The structural properties of the samples were characterized by high resolution X-ray diffraction (HRXRD) on a Bruker D8 system, delivering a CuKα1 line. A slit of 0.5 mm was placed in front of the detector in order to rule out broadening effects due to the limited sub-grain size and inhomogeneous strain in double-axis rocking scans. The surface morphology of AlGaN/GaN heterostructures was measured by atomic force microscopy (AFM) operating in contact mode with a SiN tip. The 2DEG electron density and mobility was

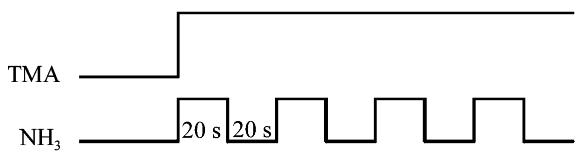

Fig. 1. Gas flow sequence used in NH_3 pulse-flow growth.

* Project supported by the Key Program of the National Natural Science Foundation of China (No. 60736033), the National Key S&T Special Project (No. 2008ZX0101002-003), the National Defense Scientific and Technical Pre-Research Program of China (Nos. 51311050112, 51308030102, 51308040301).

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Received 18 February 2009, revised manuscript received 15 April 2009

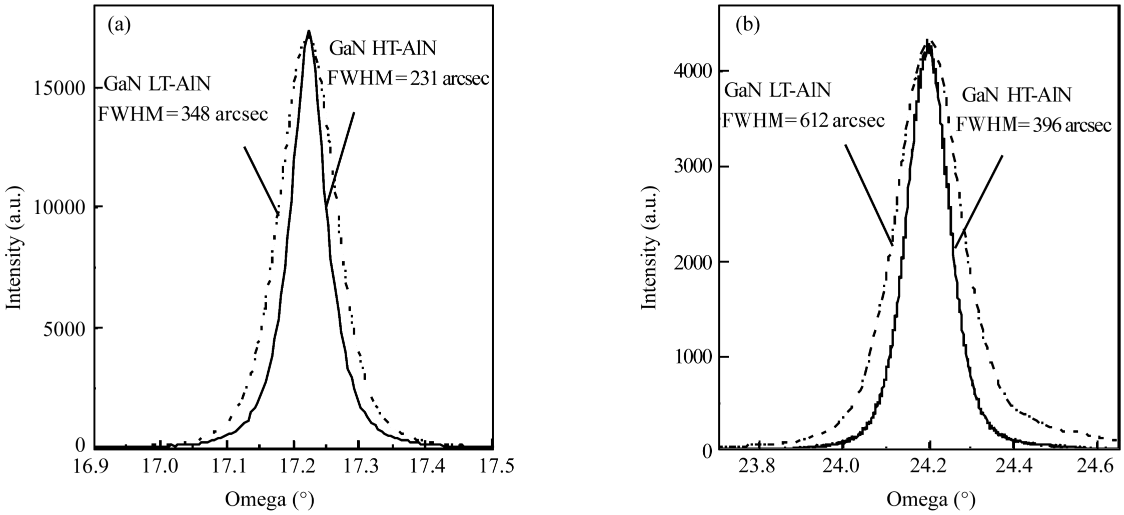

Fig. 2. (a) Double-axis X-ray omega rocking curves of the GaN film (002)-reflection. The FWHMs of GaN grown on HT-AlN and LT-AlN were 231 arsec and 348 arcsec; (b) Double-axis X-ray omega rocking curves of the GaN films (102)-reflection. The FWHMs of GaN grown on HT-AlN and LT-AlN were 396 arsec and 612 arcsec, respectively.

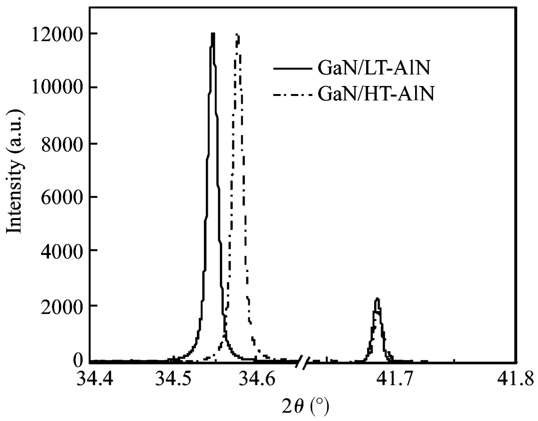

Fig. 3. Triple-axis X-ray 2theta–omega high-resolution X-ray deffraction for GaN films grown by MOCVD on LT-AlN and HT-AlN buffer layers on sapphire.

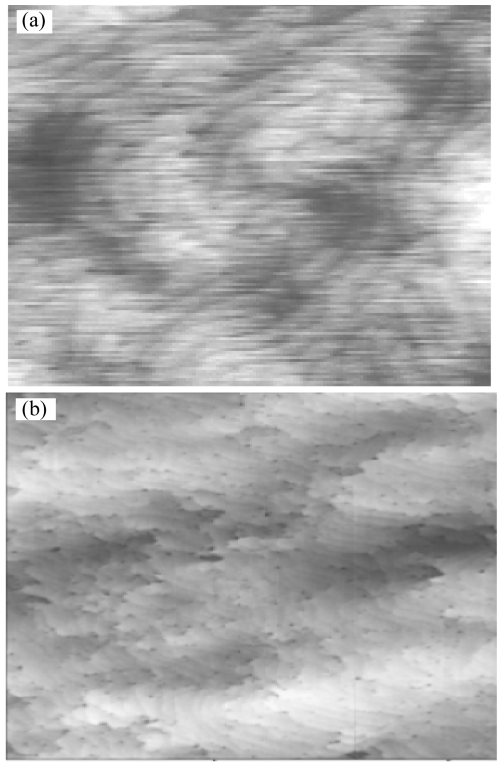

Fig. 4. AFM images of AlGaN/GaN (a) with an HT-AlN buffer and (b) with an LT-AlN buffer layer.

determined by Van der Pauw Hall measurements at 300 K. The background carrier concentration was analyzed by the captaincies –voltage (CV) method.

3. Results and discussion

The HRXRD results shown in Figs. 2(a) and 2(b) were examined by X-ray omega scan measurements carried out for both sysmetric (002) and skew (102) reflections. It is known that in wurtzite GaN crystals, the symmetric (002) reflection is most sensitive to the density of threading dislocations (TDs) with a screw component, while the skew (102) reflection is affected by all types of TDs. The FWHMs of (002) and (102) reflection for GaN grown on an LT-AlN buffer layer are wider than that grown on an HT-AlN buffer layer. In other words, the crystalline quality was improved with the HT-AlN buffer. Accordingly, the XRD results shown in Fig. 2 suggest that the HT-AlN reduced the TD density of the upper GaN film.

The *c*-axis lattice constant and stress in the GaN films were calculated from triple axis X-ray diffraction measurements. Figure 3 shows results of triple axis scans from GaN (002) reflections. The sapphire peaks are used as a reference signal. The *c*-axis lattice constant of GaN grown on HT-AlN and LT-AlN were obtained as 0.51901 and 0.51916 nm, respectively. As can be seen, the compressive stress in GaN grown on LT-AlN is larger than that in GaN grown on HT-AlN.

The surface morphology of AlGaN/GaN heterostructures grown on HT-AlN and LT-AlN were investigated by AFM. As shown in Fig. 4, the surface of the sample with the HT-AlN buffer layer was very smooth, and the atomic steps were clearly detected and regularly distributed. The root-mean-square (RMS) of AlGaN/GaN heterostructures grown on HT-AlN was only 0.18 nm in a 3×3 μm^2 scan area. The RMS of

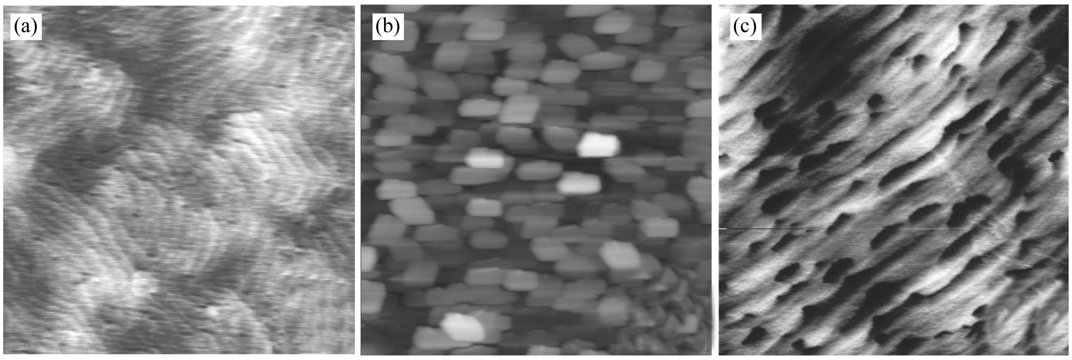

Fig. 5. (a) AFM image of the HT-AlN buffer layer grown by the IASA method; (b) AFM image of the HT-AlN buffer layer grown by the conventional method; (c) AFM image of 25 nm HT-AlN grown by IASA.

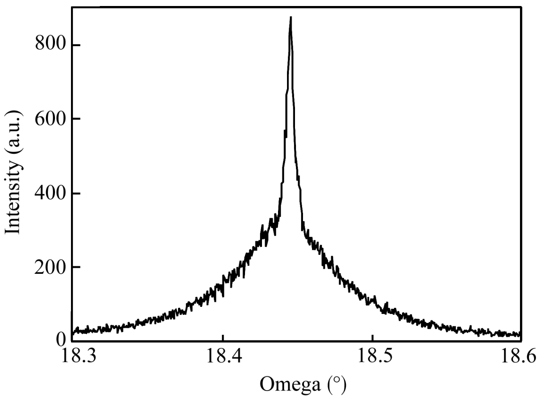

Fig. 6. Triple-axis X-ray omega rocking curves of the AlN film (002)-reflection. The FWHM was only 43 arsec.

a conventional sample is 0.6 nm with the same scan area. There were also many pits in the surface of the conventional sample, as shown in Fig. 4(b). Obviously, the HT-AlN grown by the IASA buffer technique can greatly increase the surface quality.

In order to more closely investigate the effects of the HT-AlN and IASA method on the AlGaN/GaN heterostructures, 100 nm high temperature AlN by IASA and the conventional method were grown at the same temperature. The crystal quality and surface morphology of HT-AlN were characterized by HRXRD and AFM. Figures 5(a) and 5(b) show the AFM images of the AlN grown at high temperature. The HT-AlN grown by IASA is continuous and homogeneous, with roughness under 5 nm, and the atomic level can be clearly seen. However, the islands of HT-AlN grown by the conventional method were not combined. This phenomenon was similar to an AlN layer grown at low temperature. It is well known that the pre-reaction of TMAl and NH_3 was very strong at high temperature. The separation of TMA and NH_3 by IASA could decrease this pre-reaction. The IASA technique also promoted buffer layer coalescence. The two dimensional (2D) layer-by-layer growths basically dominated the HT-AlN growth even at the early stage. Consequently, a high surface quality of the secondary layer can be obtained. The effect of HT-AlN thickness was also studied. HT-AlN with 25 nm thickness was grown by the IASA method, as shown in Fig. 5(c). It can be seen that the complete coalescence of islands was not achieved. Figure 6 shows the HRXRD curves of the HT-AlN grown by IASA method. The FWHM of (002) reflection of the IASA HT-AlN was only 43 arcsec. The transition from a wide base to a narrow central feature demonstrates significant diminution of the threading dislocation density from the bottom accommodation sublayer to the top of the layer[6]. The FWHMs of (002) reflection of the conventional HT-AlN and 25 nm HT-AlN grown by IASA were much larger, although not shown here. This indicates that the 100 nm HT-AlN grown by IASA method had high crystal quality. As can be seen, the thicker HT-AlN grown by the IASA method could decrease the pre-reaction of TMAl and NH_3, and achieve better crystal quality and surface morphology. The lattice mismatch between GaN and AlN is only 2%. Therefore the higher crystal quality of GaN grown on HT-AlN can be achieved.

The 2DEG mobilities of the AlGaN/GaN heterostructures grown on HT-AlN and LT-AlN were obtained by Hall measurements at room temperature, which were 1700 and 1500 $cm^2/(V{\cdot}s)$, respectively. This indicates that the adoption of HT-AlN is helpful to improve the AlGaN/GaN heterostructures' electrical characteristics. As mentioned above, the HT-AlN grown by the IASA technique can decrease the surface roughness and the dislocations density of AlGaN/GaN heterostructures, and hence reduce the surface roughness and dislocation scattering. So higher 2DEG mobility can be achieved.

It is well known that GaN exhibits a high unintentional n-type doping level due to residual oxygen donors introduced during heteroepitaxy. This effect is particularly evident in GaN on sapphire, where oxygen can be incorporated directly from the substrate[7]. Mercury probe C–V measurements were carried out to evaluate the 2DEG depth profile in AlGaN/GaN heterostructures. Figure 7 shows the carrier depth profiles in AlGaN/GaN heterostructures using LT-AlN and HT-AlN buffer layers. It is noted that the background carrier concentration in GaN grown on HT-AlN is lower. Figure 5(a) shows that the HT-AlN grown using the IASA technique had formed an atomically flat layer. This compact buffer layer may have blocked the diffusion of oxygen atoms from the sapphire.

4. Conclusion

HT-AlN deposited at high temperature by the IASA technique directly on sapphire showed high crystal quality and better surface morphology. Therefore, better crystalline quality and surface morphology of AlGaN/GaN heterostructures

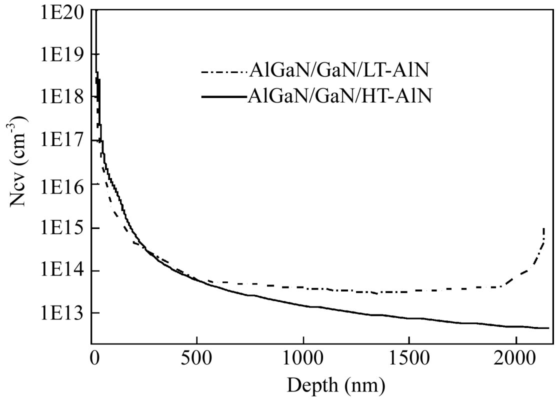

Fig. 7. Carrier concentration depth profile in AlGaN/GaN heterostructures grown on HT-AlN and LT-AlN.

grown on this buffer layer also can be achieved The diffusion of oxygen atoms wase blocked by the compact HT-AlN buffer layer and background carriers in GaN decreased. The surface roughness and the dislocation density of AlGaN/GaN heterosructures grown on the HT-AlN buffer layer using the IASA method were reduced and higher 2DEG mobility was achieved.

References

[1] Ando Y, Okamoto Y, Hataya K, et al. 12 W/mm recessed-gate AlGaN/GaN heterojunction field-plate FET. IEDM Tech Dig, 2003: 563

[2] Kikkawa T, Mitani E, Joshin K, et al. An over 100 W CW output power amplifier using AlGaN/GaN HEMTs. CS MANTECH Tech Dig, 2004: 97

[3] Amano H, Saaki N, Akasaki I, et al. Metalorganic vapor phase epitaxial growth of a high quality GaN film using an AlN buffer layer. Appl Phys Lett, 1986, 48: 353

[4] Amano H, Kito M, Hiramatsu K, et al. P-type conduction in Mg-doped GaN treated with low-energy electron beam irradiation (LEEBI). Jpn J Appl Phys, Part 2, 1989, 28: L2112

[5] Nakamura S. GaN growth using GaN buffer layer. Jpn J Appl Phys, Part 2, 1991, 30: L1705

[6] Faleev N, Lu H, Schaff W J. Low density of threading dislocations in AlN grown on sapphire. J Appl Phys, 2007, 101: 093516

[7] Look D C, Molnar R J. Degenerate layer at GaN/sapphire interface: influence on Hall-effect measurements. Appl Phys Lett, 1997, 70: 3377