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Effect of double AlN buffer layer on the qualities of GaN films grown by radio-frequency molecular beam epitaxy*

Li Xin-Hua(李新化)†, Zhong Fei(钟 飞),
Qiu Kai(邱 凯), Yin Zhi-Jun(尹志军), and Ji Chang-Jian(姬长建)

Key Laboratory of Material Physics, Institute of Solid State Physics, Chinese Academy of Sciences, Hefei 230031, *China*

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This paper reports that the GaN thin films with Ga-polarity and high quality were grown by radio-frequency molecular beam epitaxy on sapphire (0001) substrate with a double AlN buffer layer. The buffer layer consists of a high-temperature (HT) AlN layer and a low-temperature (LT) AlN layer grown at 800°C and 600°C, respectively. It is demonstrated that the HT-AlN layer can result in the growth of GaN epilayer in Ga-polarity and the LT-AlN layer is helpful for the improvement of the epilayer quality. It is observed that the carrier mobility of the GaN epilayer increases from 458 to 858 $cm^2/V{\cdot}s$ at room temperature when the thickness of LT-AlN layer varies from 0 to 20 nm. The full width at half maximum of x-ray rocking curves also demonstrates a substantial improvement in the quality of GaN epilayers by the utilization of LT-AlN layer.

Keywords: Gallium Nitride, buffer layer, carrier mobility, polarity
PACC: 6855, 6100M, 7280E

1. Introduction

Gallium nitride and its related alloys have attracted much attentions in recent years due to their promising applications in optoelectronic devices[1] and high-power electronics.[2] Various methods have been reported for the growth of epitaxial films of GaN, including hydride vapour phase epitaxy,[3,4] metal–organic vapour phase epitaxy[5,6] and radio-frequency molecular beam epitaxy(RF-MBE),[7−10] etc. In contrast to other III–V compound semiconductors such as GaAs and InP, it is much complicated to grow high quality GaN film, because of the large lattice mismatch and great difference in the thermal expansion coefficient between the epilayer and sapphire substrate.

For the growth of GaN epilayer by molecular beam epitaxy (MBE), a buffer layer is often used to control polarity and to improve the structural quality of epilayer.[11] It has been demonstrated that the qualities of GaN films depend on growth conditions of the buffer layer, such as growth temperature,[12] thickness and III/V ratio.[13,14] Buffer layer can restore the large difference between GaN epilayers and sapphire substrates. Furthermore, the polarity of the GaN surface grown on (0001) sapphire substrates can be controlled by adjusting the growth process of the buffer layers. Till now, the correlation between the polarity and buffer layer is one of the hottest topics in the GaN growth researches.

In this paper, we are focused on the polarity and structural quality control of MBE-grown GaN film by using buffer layer technology. A double buffer layer structure is introduced, which consists of a high-temperature (HT) AlN layer and a low-temperature (LT) AlN layer grown at 800°C and 600°C respectively.

2. Experimental

GaN films were grown on c-sapphire substrates by RF-MBE. Sapphire substrates were thermally cleaned at 850°C in an ultrahigh vacuum for 30 min and nitrided at 400°C for 1 hour with radio frequency (RF) power of 400 W. After that, the temperature was elevated to 800°C and an AlN (HT-AlN) buffer layer was grown with a thickness of about 15 nm, followed

*Project supported by the National Natural Science Foundation of China (Grant No 10574130).
†E-mail: lxhissp@163.com, xinhuali@issp.ac.cn

by thermal annealing at 880°C for 20 min. Before the deposition of about 1 μm GaN epilayer at 800°C, an LT-AlN layer was grown at 600°C. In order to study the effect of the LT-AlN buffer layer on the qualities of GaN epilayer, we varied the buffer thickness from 0 to 20 nm. Reflective high-energy electron diffraction (RHEED) was used to monitor the in-situ growth mode and polarity of epilayer. Wet chemical etching was used to further characterize the polarity of GaN films. The samples were placed in 1.8 M NaOH solution for 10 min at 100°C. Then the surface morphologies were observed by atomic force microscope (AFM). X-ray diffraction (XRD) measurements were made with a Philips Materials Research diffractometer. The full width at half maximum (FWHM) of the GaN $(10\bar{1}2)$ ω rocking curve was used as the measure of crystalline quality. The carrier mobility was tested by Hall-effect measurements in the conventional Van der Paouw method at room temperature.

3. Results and discussions

When the GaN samples were cooled to temperatures between 280 and 650°C, (2×2) reconstruction was observed on all samples with double AlN buffer layer. These phenomena indicate the presence of Ga-polarity surface according to Shen *et al.*[15] In our previous paper, we have demonstrated that Ga-polarity surface is resistant to etching in NaOH solution.[16] To confirm the polarity of GaN films grown on different AlN buffer, wet chemical etching was carried out. AFM images are shown in Figs.1(a)–1(d). Comparing with the as-grown surface, we find that both GaN films show little morphology changes after wet etching. The Ga-polarity is obtained in both

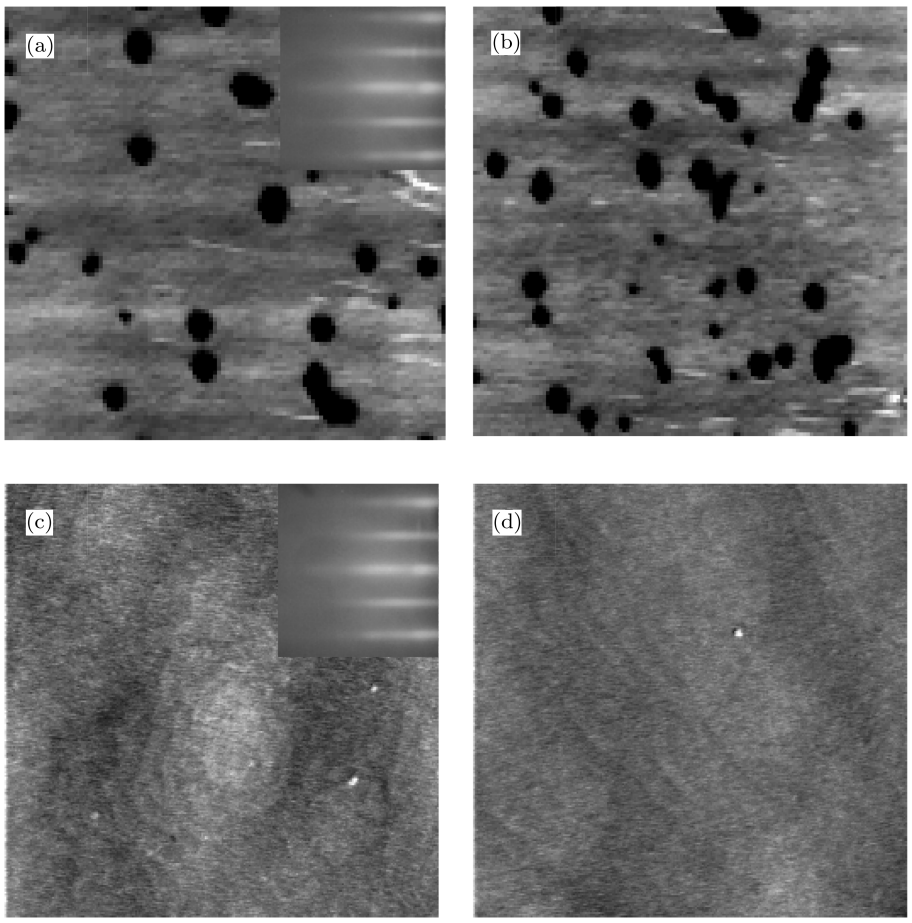


Fig.1. 2 μm $\times$2 μm surface morphologies observed by AFM: (a) a GaN film without LT-AlN buffer layer, the inset in (a) is the typical RHEED pattern when the films were cooled down at the temperatures between 280 and 650°C, (b) same GaN film shown in (a) after etching (c) a GaN film with 20 nm the secondary LT-AlN buffer layer, the inset in (c) is the typical RHEED pattern when the films were cooled down at the temperatures between 280 and 650°C, (d) the same GaN film shown in(c) after etching.

GaN films grown on AlN buffer with and without the insertion of LT-AlN layer. These facts indicate that the polarity control of GaN epilayer growth mostly depends on HT-AlN buffer. Therefore, the HT-AlN layer in double buffer structure can have the Ga-polarity control effect in the subsequent GaN epilayer growth.

It is found that GaN Films without the LT-AlN buffer show a rough surface with holes (Fig.1(a)). However, in the surface morphology of the as-grown GaN films grown on double buffer structure with 20 nm LT-AlN buffer (Fig.1(c)), atom steps are visible and the surface is rather flat with root mean square(RMS) roughness of 2 nm over a $2 \times 2\,\mu$m area. These results imply that the insertion of the LT-AlN buffer play a significant role in improving morphological quality of GaN film.

Meanwhile, one can find that highly concentrated holes exist on the etched surface of GaN films without the LT-AlN buffer (Fig.1(b)), which implies that high density dislocations exist in the overgrown films. These dislocations are considered propagating from the HT-AlN buffer layer. In order to reduce the dislocation density, the LT-AlN buffer is deposited to accommodate the defects in GaN films. From the surface morphology of the etched GaN films grown on double buffer structure with 20 nm LT-AlN buffer (Fig.1(d)), atom steps are still visible and no holes is observed in the area under investigation.

The effects of double buffer layer on electrical quality of GaN films are evaluated by the room Hall measurement. It has been shown that many extended defects, especially threading dislocations, can introduce acceptor centres along the dislocation lines.[17,18] The dislocations become negative charged and scatter electrons travelling across, which results in the reduction of carrier mobility. In this way, the variation of carrier mobility can reflect the quality of the GaN epilayers. The experimental results are shown in Fig.2. The carrier concentrations for the GaN films grown on the double buffer structure with various LT-AlN buffer is around $5 \times 10^{16}\,\mathrm{cm}^{-3}$ according to the Hall measurement result. The typical electron mobility of GaN films grown without LT-AlN buffer is $458\,\mathrm{cm}^2/\mathrm{V{\cdot}S}$, which is relatively low in comparison with carrier mobility value reported in other groups. The reason of low carrier mobility is attributed to the existence of high density extended defects in the case of GaN films grown without secondary LT-AlN buffer. Most interestingly, the carrier mobility is found to increase substantially to $654\,\mathrm{cm}^2/\mathrm{V{\cdot}S$ by introducing a 5 nm thickness LT-AlN buffer. From Fig.2, we can find that the carrier mobility increases steadily with the thickness of LT-AlN buffer layers. The maximum value can reach $858\,\mathrm{cm}^2/\mathrm{V{\cdot}S}$, when a 20 nm LT-AlN is used. The significant improvement in carrier mobility implies the reduction of defect density and betterment of the GaN epilayer quality.

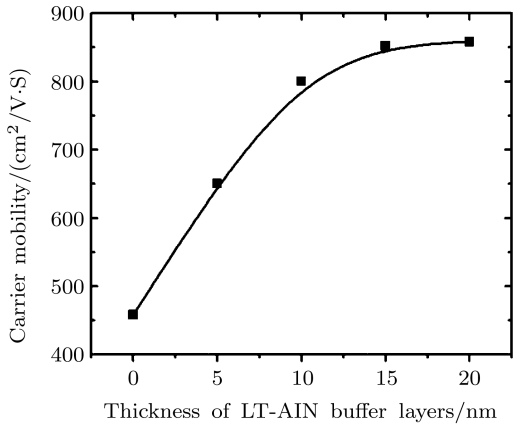


Fig.2. The relation between the carrier mobility and the thickness of the LT-AlN buffer.

As shown in Fig.3, we also demonstrated the x-ray rocking curves of $(10\bar{1}2)$ plane curves in the GaN films with 20 nm AlN buffer and without the LT-AlN buffer. The FWHM of the GaN $(10\bar{1}2)$ with 20 nm LT-AlN buffer is 351 arcsec, while the FWHM of GaN $(10\bar{1}2)$ without LT-AlN buffer is 1111 arcsec. The substantial decrease of FWHM of the GaN $(10\bar{1}2)$ reflection can be detected. It has been demonstrated by Heying *et al* that the FWHM of the GaN$(10\bar{1}2)$ is a reliable indicator of the threading dislocations concentrations in GaN thin films.[19] The decrease of FWHM of x-ray

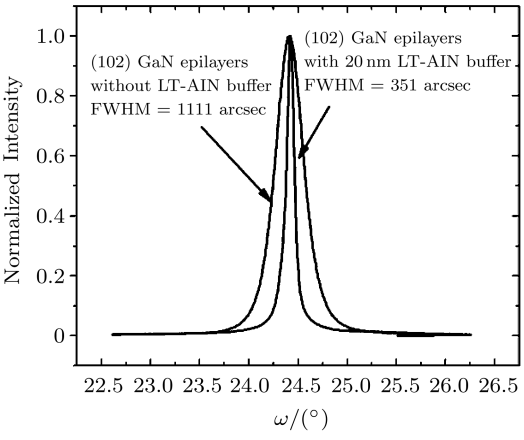


Fig.3. X-ray rocking curves of GaN films measured in ω-modus from (102) reflections of GaN films grown without LT-AlN buffer and with 20 nm LT-AlN buffer.

rocking curves reflects the reduction of threading dislocations by the introduction of LT-AlN buffer. This result agrees well with the increase of mobility in the GaN films grown on double buffer layer.

4. Conclusion

The influence of double AlN structure on the quality of GaN films is studied by RHEED, AFM, Hall-effect measurement and XRD. The Ga-polarity control of GaN films can be obtained by introducing the HT-AlN buffer. In order to improve the structural quality of GaN films, LT-AlN buffer is inserted. It is found that the morphological, electronic and structural quality is improved substantially by introducing LT-AlN. The mobility of electrons increases to $858\,\mathrm{cm}^2/\mathrm{V{\cdot}S}$ and FWHM of x-ray rocking curves reduce to 351 arcsec, when a 20 nm thickness LT-AlN buffer is used.

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