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Study of anisotropic crystal and electrical properties for semipolar (11-22) GaN grown on m-sapphire

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We studied the anisotropic properties of semipolar (11-22) GaN thin film grown on m-plane sapphire substrate using a metalorganic chemical vapor deposition. Among many growth parameters, it was found that anisotropic crystal qualities and surface morphologies were significantly affected by growth pressure, growth temperature and NH_3 flow. The X-ray rocking measurements with different incident beam directions shows that anisotropic crystal properties of semipolar GaN, observed by two directions of [11-2-3] and [1-100], were improved by high temperature, high growth pressure and low NH_3 flow. In addition, anisotropic surface morphology was significantly improved by low growth temperature and low growth pressure. Particularly, low NH_3 flow would drastically reduce anisotropic crystal properties without changing anisotropic surface morphology. From I-V measurements for semipolar GaN with two different NH_3 flows, the resistance difference with two directions of [11-23] and [1-100] was decreased by reducing anisotropic crystal properties. Therefore, we believed that low NH_3 flow was one of major growth parameters to reduce anisotropic crystal and electrical properties of semipolar (11-22) GaN template.

Key words: GaN, Semipolar, HR-XRD, MOCVD.

Introduction

III-nitride semiconductors have attracted considerable attentions because of wide band gap energy with the variety of emission wavelengths from ultraviolet to infrared [1, 2]. It has been used for optoelectronic materials to achieve high power and high efficiency light emitting diodes (LEDs), laser diodes (LD) and electronic devices, etc [3, 4]. In general, GaN-based optoelectronic devices were grown by using polar c-plane GaN templates that represented strong internal electric field due to the spontaneous and the piezo-electric polarization effect. However, there are still some limits to develop high efficiency and power LD/LEDs because of polarization-induced quantum-confined stark effect (QCSE), which resulted in the decrease of luminous recombination efficiency. In addition, the emission wavelength of GaN-based LD/LEDs was significantly blue-shifted with increasing injection current because of the screening effect of spontaneous and piezoelectric polarization [2, 5-7].

In order to overcome physical limits of c-plane nitride semiconductors, many research groups have focused on non-polar and semipolar GaN-based light emitting devices. However, it has been reported that non-polar GaN faces have a tendency to represent low incorporation rate of In atoms during the growth of InGaN/GaN QWs region [8]. Moreover, it has often reported anisotropic surface structure, basal stacking faults (BSFs) and numerous dislocations in the m- and a-plane GaN layers [9-11]. For this reason, semipolar GaN-based LEDs have been additionally focused by a lot of research groups. Recently, it had been reported that semipolar (11-22) GaN grown on m-plane sapphire substrates represented a few problems such as anisotropic surface and crystal properties [12, 13], which could induce the poor optical and the electrical qualities of LEDs. In this study, we systematically investigated the anisotropic crystallinity and the electrical properties of semipolar (11-22) GaN films by controlling the growth parameters.

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Experiment

2.0 μm-thick semipolar (11-22) GaN epilayers were grown on the m-plane sapphire substrates by using metalorganic chemical vapor deposition (MOCVD). After the nitridation process on m-sapphire substrate using NH_3 gas at 1,050 °C for 5 min, semipolar (11-22) GaN templates were grown using the novel 1-step growth method without a low temperature GaN buffer layer [13-15]. Trimethylgallium (TMGa) and ammonia (NH_3) were used as Ga and N sources, respectively. To observe the effect of growth parameters on the anisotropic surface and the anisotropic crystal properties of semipolar GaN templates, growth temperature, growth pressure and NH_3 flow were controlled. First, growth pressure was changed from 100 to 300 mbar at the constant growth temperature of 1,000 °C. Second, growth temperature was varied from 1,000 to 1,050 °C. Lastly, NH_3 flow was changed from 11,600 to 14,500 sccm. The thickness of all samples was fixed to exclude the enhancement of crystal qualities with increasing film thickness. In addition, Si doping process was performed to measure the relationship between the electrical properties and the anisotropic crystalline of semipolar (11-22) GaN with different NH_3 flow rates of 11,600 (sample A) and 14,500 sccm (sample B). To observe anisotropic electrical properties, 100 nm-thick Ti electrodes were deposited toward two directions of [-1-123] and [1-100] from one point as shown in inset of Fig. 3.

Anisotropic crystal qualities of semipolar (11-22) GaN templates were investigated by analyzing a full width at half maximum (FWHM) of high resolution X-ray rocking curves (XRC) with different azimuth angles from -90 to +90 °. The macroscopic and microscopic surface morphologies were observed by Nomarski optical microscopy (NOM) and atomic force microscope (AFM), respectively. I-V measurements were performed to compare anisotropic crystal properties with electrical properties of semipolar GaN templates.

Results and Discussion

Figs. 1(a-c) showed the FWHMs of XRCs as a function of azimuth angles from -90 to +90 ° for semipolar (11-22) GaN films grown by different growth pressures, temperatures and NH_3 flows, respectively. The azimuth is the angle between [-1-123] direction and the rotation axis of the Ω scan. As shown in Fig. 1(a), with increasing growth pressure from 100 to 300 mbar, FWHM values of the XRCs were decreased from 1,833 to 1,184 arcsec for the direction of [-1-123], while the difference of XRC FWHMs for [1-100] and [-1-123] was almost same. It implied that high growth pressure could improve overall crystal quality rather than anisotropic properties of semipolar GaN. Fig. 1(b) showed the XRC FWHMs of semipolar GaN grown at the different growth temperatures of 1,000 and 1,050 °C. XRC FWHMs for incident beam direction of [-1-123] were decreased from 1,339 to 1,093 arcsec with increasing the growth temperature. However, the difference of XRC FWHMs for [1-100] and [-1-123] was slightly decreased from 230 to 158 arcsec with increasing the growth temperature. It implied that high growth temperature could also enhance the overall crystal quality and reduce anisotropic crystallinity. With decreasing NH_3 flow from 14,500 to 11,600 sccm, XRC FWHM for [-1-123] was increased from 1,345 to 1,453 arcsec, while XRC FWHM for [1-100] was decreased from 1569 to 1,507 arcsec as shown in Fig. 1(c). It indicated that lower NH_3 flow would deteriorate the crystal quality for [-1-123] but improve the crystal quality for [1-100], resulting in the reduction of anisotropic crystal properties for two

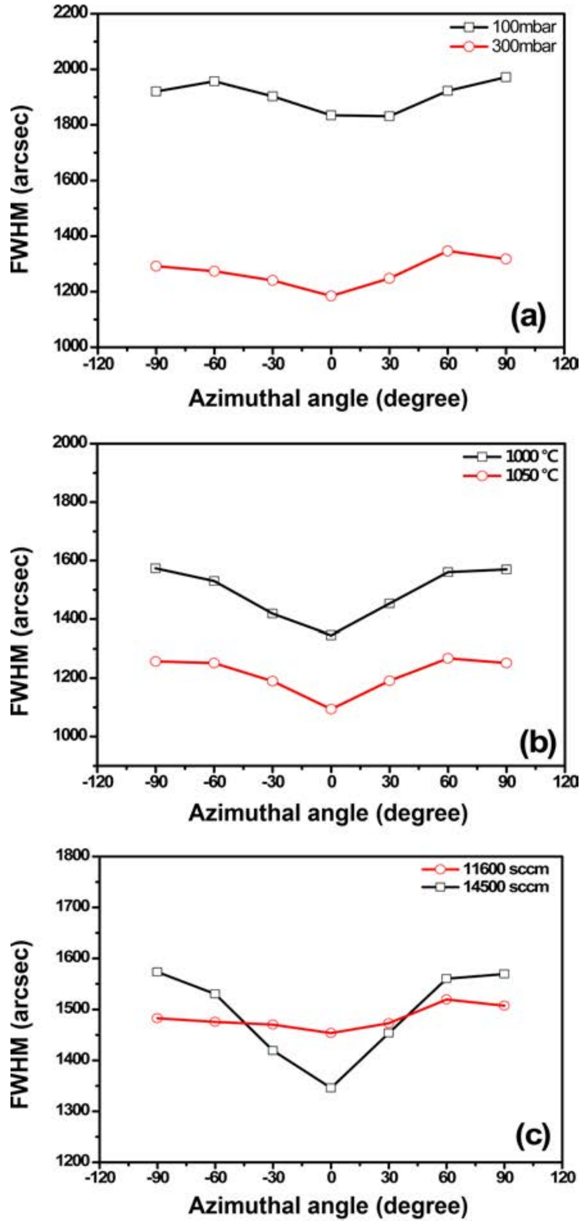

Fig. 1. XRC FWHMs of semipolar (11-22) GaN with different (a) growth pressures, (b) growth temperatures, and (c) NH_3 flows as a function of azimuth angles from -90 to +90°. The azimuth is the angle between [-1-123] direction and the rotation axis of the Ω scan.

directions. From these results, we believed that the high growth pressure and high growth temperature could improve overall crystal qualities rather than anisotropic crystallinity of semipolar (11-22) GaN. In addition, one can see that NH_3 flow rate could be one of major parameters to decrease the anisotropic crystal properties of semipolar (11-22) GaN template [16, 17].

Figs. 2(a-f) showed the NOM images of semipolar (11-22) GaN by controlling growth pressures, growth temperatures and NH_3 flows. All samples represented the arrowhead-like surface structures, which were typical surface structure of semipolar (11-22) GaN. However, the arrowhead-like surface morphology of semipolar

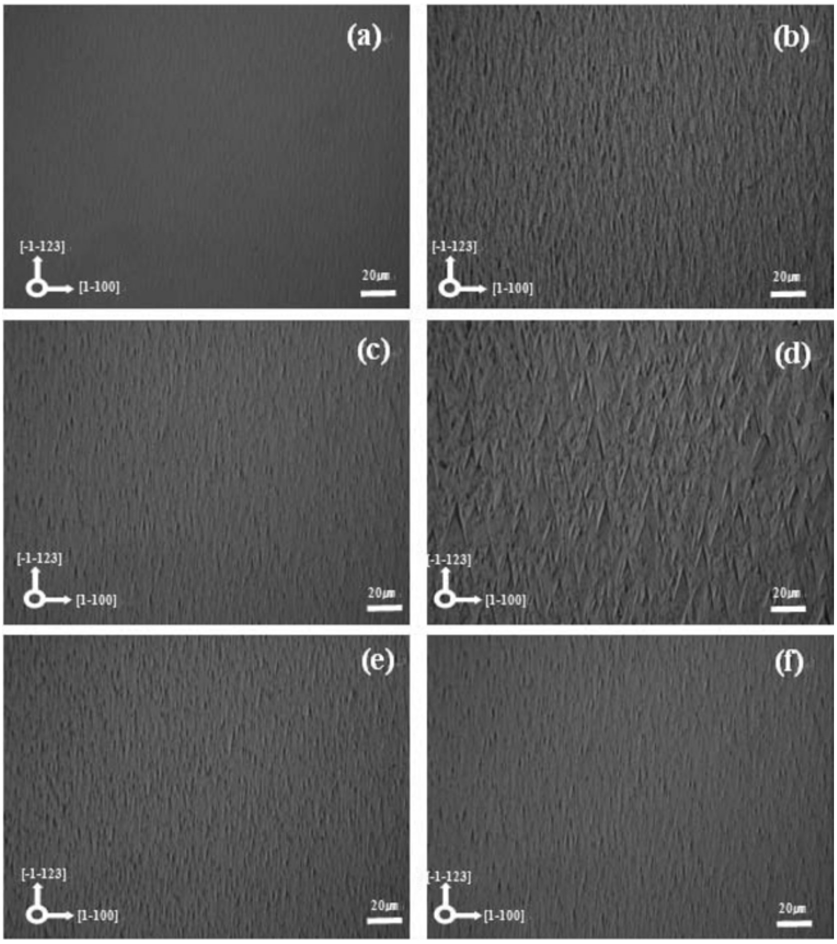

Fig. 2. Nomarski optical microscope images of semipolar (11-22) GaN with different growth parameters which were growth pressures ((a) 100 mabr and (b) 300 mbar), growth temperatures ((c) 1,000 °C and (d) 1,050 °C) and NH_3 flows ((e) 11,600 sccm and ((f) 14,500 sccm).

(11-22) GaN would be more clear and bigger facets with increasing the growth pressure, as shown Figs. 2(a-b). Especially, macroscopic surface morphology of semipolar GaN was surprisingly smoothed by decreasing growth pressure, which was comparable with that of c-plane GaN epilayer. From AFM measurements, root mean square (RMS) surface roughness of semipolar GaN with growth pressures of 100 and 300 mbar were 7.4 and 24.1 nm, respectively. As shown in Figs. 2(c-d), the arrowhead-like surface shape represented dipper and bigger with increasing growth temperature and RMS roughness was increased from 13.1 to 17.9 nm. Figs. 2(e-f) showed the images of semipolar (11-22) GaN with the NH_3 flows of 11,600 and 14,500 sccm, respectively. Both samples represented similar macroscopic surface structures and RMS roughness regardless of NH_3 flows. From these results, one can see that the anisotropic arrowhead-like structures and the surface roughness could be decreased by decreasing growth temperature and growth pressure. As shown in Table 1, the growth conditions to obtain smooth surface were contrary with those to improve crystal properties. It is often observed that higher crystal quality of GaN represented poorer surface morphology, which can be explained by relaxing internal stress to surface region. In particular, arrowhead-like surface structure would be due to the incorporation probability and the diffusion length difference of surface adatoms caused by difference in crystallographic anisotropy of [1-100] and [-1-123] between m-plane sapphire and semipolar (11-22) GaN.

Table 1. XRC FWHMs and AFM RMS roughness of semipolar (11-22) GaN with different growth parameters.

Growth parameters		XRC FWHM (arcsec)		RMS roughness (nm)
		[-1-123]	[1-100]	
Growth pressure (mbar)	100 mabr	1833	1972	7.4
	300 mbar	1184	1318	24.1
Growth temperature (°C)	1000 °C	1339	1569	13.1
	1050 °C	1093	1251	17.9
NH_3 flow (sccm)	11,600 sccm	1453	1507	14.2
	14,500 sccm	1345	1569	13.1

To investigate the effect of anisotropic crystalline on the electrical properties of semipolar GaN regardless of surface morphology, we prepared two Si-doped n-type semipolar (11-22) GaN template which were grown by

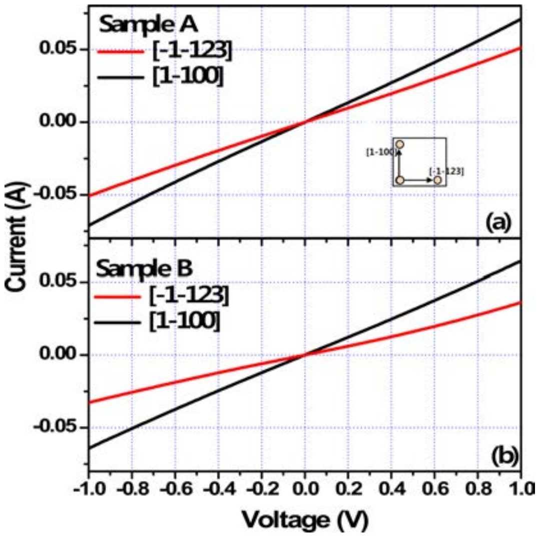

Fig. 3. I-V curves of (a) samples A and (b) sample B were measured by two directions of [-1-123] and [1-100]. Samples A and B were grown by using NH_3 flow of 11,600 and 14,500 sccm, respectively.

using two different NH_3 flows of 11,600 (sample A) and 14,500 sccm (sample B). From Hall measurement, we obtained the high electrical properties ($n_e = 1.03 \sim 1.13 \times 10^{19}/cm^3$, $\mu_e = 98.5 \sim 106.6\ cm^2/Vs$) of both samples, indicating that the carrier concentration of sample A was slightly higher than sample B but both samples represented similar electrical properties. In addition, both samples represented similar surface morphology but large difference of anisotropic crystalline. Figs. 3(a-b) showed the I-V curves of samples A and B, respectively, which were measured toward two different crystal directions such as [1-100] and [-1-123]. I-V curves toward [1-100] represented better linearity and lower resistance than [-1-123] regardless of samples A and B. It implied that the electrical properties with the direction of [1-100] was much better than [-1-123]. In heteroepitaxial growth of semipolar GaN, it is often observed that basal stacking faults (BSF) were developed toward [1-100] [13]. We would guess that BSFs would play a role in disturbing the carrier transport between both contact regions due to the defect scattering effect. In addition, the resistance difference of two directions was 5.4 Ω for sample A, which was lower than that (14.6 Ω) of sample B. From these results, we believed that the anisotropic crystal properties of semipolar GaN (sample B) would significantly affect high anisotropic electrical properties, which could deteriorate the performance of semipolar GaN-based optoelectronic devices.

Conclusion

We investigated anisotropic crystal, surface and electrical properties of semipolar (11-22) GaN grown on m-plane sapphire by controlling growth pressure, temperature and NH_3 flow rate. The high growth pressure and the high growth temperature would improve crystallinity but deteriorate surface morphology. However, low NH_3 flow would significantly decrease anisotropic crystal properties without deteriorating surface morphology. From I-V measurements, GaN template with lower anisotropic crystal properties represented more uniform resistance for two crystal directions of [1-100] and [-1-123]. Therefore, we suggested that low NH_3 flow would decrease anisotropic crystallinity of semipolar GaN, resulting in the reduction of anisotropic electrical properties.

Acknowledgement

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