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Effective reduction of bowing in free-standing GaN by N-face regrowth with hydride vapor-phase epitaxy

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ABSTRACT

Free-standing GaN films prepared with hydride vapor-phase epitaxy (HVPE) technique usually show bowing resulting from the high densities of defects near the N-polar face after separation from the original substrates. To solve the problem, a simple technique has been developed. A GaN layer was regrown on the N-polar face of the free-standing GaN by HVPE. High-resolution X-ray diffraction (HRXRD) measurements were performed to compare the bowings among GaN films before laser lift-off (LLO), after LLO, and after regrowth. The apparent reductions of XRD full-width at half-maximum (FWHM), along with the increase of XRD peak intensity, after regrowth clearly demonstrate the effectiveness of this method to eliminate bowings of the free-standing GaN films.

1. Introduction

Gallium nitride substrate is the most suitable substrate for manufacturing high-performance nitride-based devices due to its homogeneity of lattice constant and thermal expansion coefficient with the overgrown device epitaxial layers [1,2]. It is highly favored as the substrate for making UV light-emitting diodes (LED), laser diodes (LD) and high-power devices [3,4]. Currently, the most mature way to manufacture GaN substrates is by using hydride vapor-phase epitaxy (HVPE) technology. In the HVPE growth, thick GaN layers are first grown on lattice- and thermal-mismatched substrates, such as sapphire [5], Si [6], SiC [7], GaAs [8] and $LiAlO_2$ [9]. However, the difference in thermal expansion coefficient between the GaN layer and the underlining substrate leads into severe bowing and bending [10].

Several techniques, such as laser lift-off (LLO) [11] and self-separation methods utilizing voids [12], WSiN [13], patterned GaN [14] and mechanical polish [15], have been proposed to separate the GaN thick films from the original substrates and form free-standing GaN substrates. It is noted that in such processes, the damage layer, with high densities of dislocations and microcracks, between GaN and the original substrate can make the bowing of the free-standing GaN films worse [16,17]. Furthermore, the surface damage of GaN substrates should be removed by chemical mechanical polish (CMP) before growth of device layers [18]. However, the bowing of GaN substrate makes the CMP process difficult. In this study, we have developed a simple technique to reduce the bowing of free-standing thick GaN films. In the process, a thick GaN film was originally grown on sapphire (0 0 0 1) utilizing HVPE and separated by LLO. Then another layer of GaN was grown on the N-face of the free-standing GaN using the same HVPE system to reduce the bowing phenomenon. A more detail description of the complete process is described as follows.

2. Experimental procedure

As shown in Fig. 1, 3 μm GaN templates were first grown by metalorganic chemical vapor deposition (MOCVD) on sapphire (0 0 0 1) substrates, followed by the deposition of a layer of SiO_2 using plasma-enhanced chemical vapor deposition (PECVD). Stripes of windows are then patterned on SiO_2 along the $(1\bar{1}00)$ direction for the following epitaxial lateral overgrowth (ELOG) of thick GaN films in a horizontal HVPE reactor. The HVPE growth was performed at 1050 °C with NH_3 and GaCl as the sources of nitrogen and gallium, respectively. A two-step growth was adopted, with the first step to enhance lateral growth at the growth pressure of 100 Torr and the second step was to promote fast vertical growth of thick GaN films at 700 Torr. Two samples, sample A and sample B, were prepared. While sample A has 250 μm of GaN after HVPE growth, sample B, with shorter duration of growth in the second step, has only 175 μm of GaN after growth. After cooling down to room temperature, the GaN thick films were separated from the sapphire substrates utilizing

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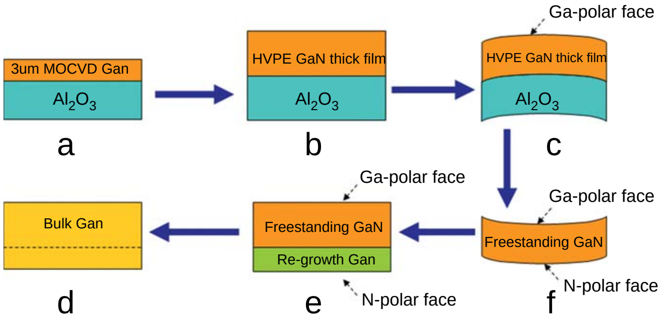

Fig. 1. Processing diagram of GaN growth: (a) GaN template with 3 μm MOCVD GaN thin film grown on sapphire (0 0 0 1). (b) Growth of GaN thick film at 1050 °C by HVPE. (c) GaN thick film on sapphire after cooling down to room temperature. (d) Free-standing GaN by removing sapphire substrate utilizing the LLO process. (e) GaN regrown on N-polar face of free-standing GaN at 900 °C by HVPE. (f) Bulk GaN after cooling down to room temperature.

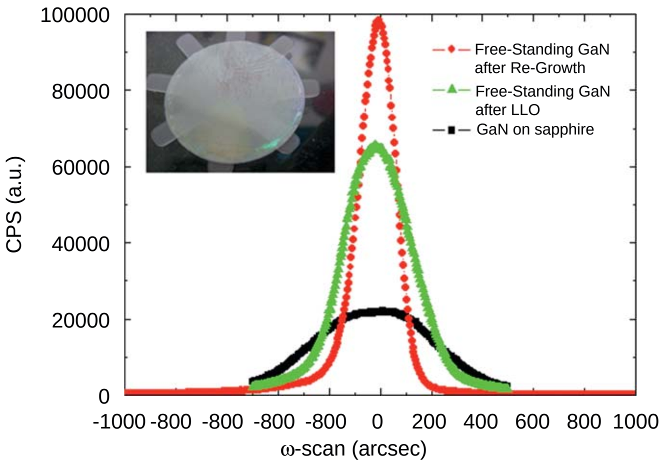

Fig. 2. ω-Scan of the HRXRD measurements in the (0 0 2) reflection for sample A. The inset picture is 250 μm free-standing GaN wafer in 1.5 in diameter of sample A.

LLO technique using a 355 nm Nd:YAG laser. Notably, the curvature of GaN changed from convex, before LLO, to concave, after LLO, as illustrated in Fig. 1(c) and (d). The Ga residue at the N-polar face of the free-standing GaN films resulting from decomposed GaN was subsequently removed using a solution of HCl/H_2O prior to the next HVPE regrowth. At last, a GaN layer of several tens of microns was regrown on the N-polar face of this free-standing GaN films at 900 °C by HVPE to reduce the bowing situation, as shown in Fig. 1(e) and (f). Both samples A and B produced free-standing GaN substrates with 1.5 in diameter.

To investigate the effects of GaN regrowth on the N-polar face, high-resolution X-ray diffraction (HRXRD) with the slit width of 1 mm, scanning electronic microscope (SEM) and cathodoluminescence (CL) measurements were performed to compare the crystal qualities at different stages of the process.

3. Results and discussion

Fig. 2 shows the rocking curves (ω-scan) of the HRXRD measurements on the Ga-face in the (0 0 2) reflection of sample A before the thick GaN film was separated from sapphire, after the GaN films was separated from sapphire, and after the regrowth of GaN on the N-polar face of separated GaN. It is seen that the XRD FWHM changed from 519 arcsec, before LLO, to 305 arcsec, after LLO. This reduction can be attributed to the relaxation of bowing and compressive strain after the GaN film is separated from sapphire. The reduction of FWHM by a factor of around 2 is in agreement with previous report [19]. Along with the reduced FWHM, the peak intensity was significantly increased as well, which is also an indication that bending of GaN was improved. However, it was found that the free-standing GaN after LLO is slightly bowing in the opposite direction, as illustrated in Fig. 1. This results from the high densities of defects at the N-polar face of the free-standing GaN after LLO, which is clearly revealed from the cross-sectional CL mapping near the SiO_2 mask above the GaN/sapphire boundary, as shown in Fig. 3. It has been reported that the bright CL emission in this region is associated with high densities of nonradiative recombination defects [20].

Compared to the XRD FWHM after LLO, the XRD FWHM of sample A after the regrowth of a GaN layer on the N-polar face was further reduced to only 166 arcsec. The XRD peak intensity simultaneously increased. It implies that the bowing of the free-standing GaN is again greatly eliminated. Similar trends were also observed on sample B which is thinner than sample A. Figs. 4

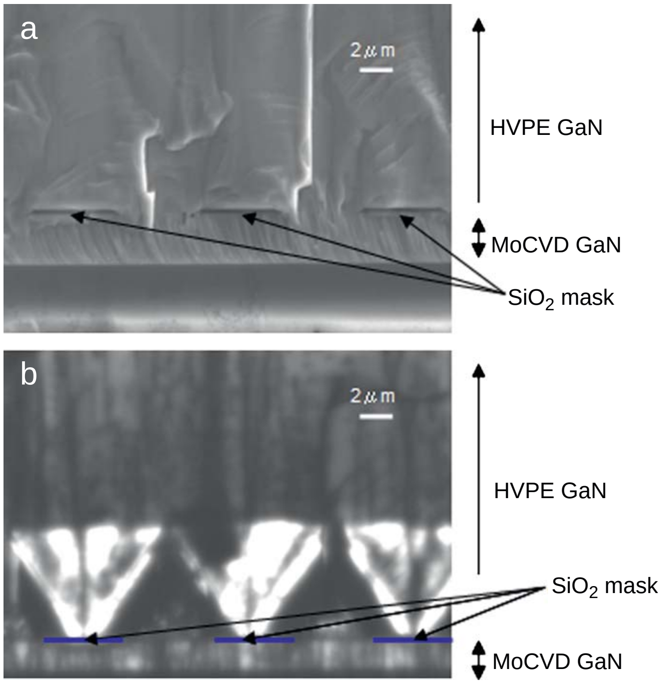

Fig. 3. (a) The SEM and (b) relative CL mapping by the cross-section view of GaN thick film on GaN template.

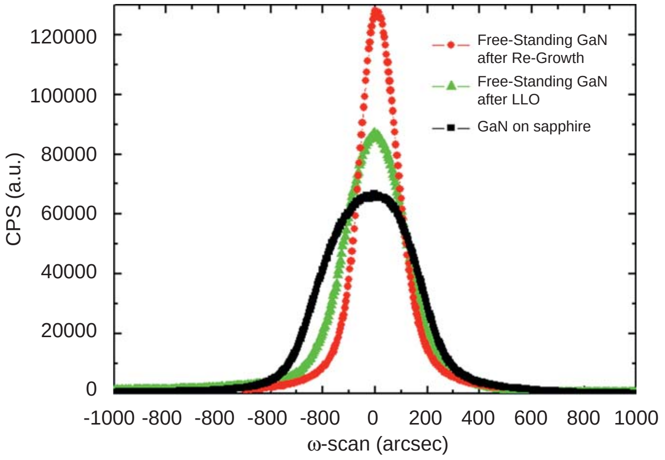

Fig. 4. ω-Scan of the HRXRD measurements in the (0 0 2) reflection for sample B.

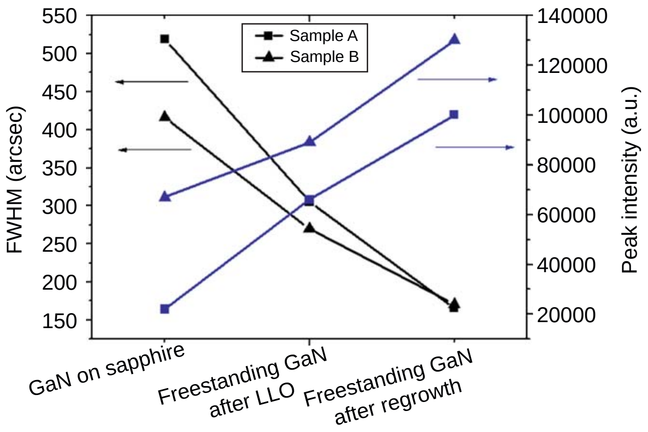

Fig. 5. Variation of FWHM and peak intensity for both samples A and B at different stages of growth by ω-scan of the HRXRD measurements in the (0 0 2) reflection.

and 5 summarize the changes in XRD FWHM and peak intensities of samples A and B before LLO, after LLO, and after regrowth. Although sample B initially showed a smaller XRD FWHM before LLO, due to its thinner GaN and hence less bowing, both samples A and B eventually have similar XRD FWHMs after regrowth, which indicates that both samples reached similar flatness. Moreover, the XRD peak intensities of both samples increased linearly after LLO and after regrowth.

4. Summary

Free-standing GaN films prepared with HVPE technique usually show bowing resulting from the high densities of point defects and dislocations near the N-polar face after separation from the original substrates. To solve the problem, a simple technique has been developed. A GaN layer was re-grown on the N-polar face of the free-standing GaN by HVPE. HRXRD measurements were performed to compare the bowings among GaN films before LLO, after LLO and after regrowth. The apparent reductions of XRD FWHM, along with the increase of XRD peak intensity, after regrowth clearly demonstrate the effectiveness of this method to eliminate bowings of the free-standing GaN films. This will provide advantages for following device processes, such as MOCVD growths and CMPs.

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