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Defect reduction in GaN on dome-shaped patterned-sapphire substrates

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This paper demonstrates the behavior of defect reduction in un-doped GaN (u-GaN) grown on a commercial dome-shaped patterned-sapphire substrate (CDPSS). Residual strain inside the u-GaN grown on the CDPSS have been investigated as well. As verified by the experimentally measured data, the limited growth rate of the u-GaN on the sidewall of the CDPSS enhances the lateral growth of the GaN on the trench region while increasing the growth time. This subsequently contributes to improve the crystalline quality of the GaN on the CDPSS. The more prominent dislocations occur in the u-GaN epilayers on the CDPSS after reaching the summit of the accumulated strain inside the epilayers. Such prominent bent dislocations improve their blocking abilities, followed by the achievement of the better crystalline quality for the growth of the u-GaN on the CDPSS.

1. Introduction

III-Nitride compound semiconductor have attracted much interest and achieved tremendous progress in recent years. GaN-based materials are typically grown on foreign substrates made of sapphire because the native GaN substrate with larger size is still not commercially available at low cost. Therefore, lots of defects are generated in GaN epilayers owing to the large mismatches in the lattice constants and in the thermal expansion coefficients between GaN and the sapphire substrate. These defects can dramatically deteriorate the electrical and optical qualities of GaN-based devices [1,2]. Currently, the single growth method of the patterned-sapphire substrate (PSS) can not only improve internal-quantum efficiency of devices by reducing defects but also enhance the light-extraction efficiency of optical devices [3–8].

Recently, a new popular type of the PSS curving the sidewall surface of each pattern is put forward, well-known as the dome-shaped PSS. Several pioneer works have investigated the effects of complicated geometrical features of the dome-shaped PSS on the luminous efficiency of optical devices [9,10]. However, few papers investigate the behavior of defect reduction inside GaN grown on the dome-shaped PSS. Nevertheless, in addition to defects, residual strains inside GaN grown on the dome-shaped PSS also impact the performance, reliability and stability of devices. Therefore, understanding in physical mechanisms of reducing defects and relaxing strain for the growth of GaN on the dome-shaped PSS is an urgent and important work. In addition, there are still few papers reporting the experimental correlation among the measurements of high-resolution X-ray diffraction (HRXRD), Raman, transmission micro-scope (TEM) and etch pit density (EPD).

In this paper, a commercial dome-shaped PSS (CDPSS) has been chosen for the growth of un-doped GaN (u-GaN). It is noted that the performance of following active epitaxial layers are determined by the quality of u-GaN epilayers. Various thickness of the u-GaN on the CDPSS has been designed for this study. Material properties of the u-GaN on the CDPSS with different epitaxial thickness are investigated through the use of HRXRD, Raman, TEM and EPD. The Raman line width is highly correlated to the HRXRD-calculated dislocation density. Moreover, the HRXRD and Raman experimental results show strong correlation in estimating biaxial strain. Through the investigation of TEM, lots of threading dislocations (TDs) bent to the sidewall surface of the CDPSS occur after reaching the summit of strain accumulation inside the u-GaN epilayers. EPD

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analysis confirms a reduction in TD densities crossing the GaN film to the surface region. In the following sections, the experimental results of HRXRD and Raman are described at first, followed by the analysis of TEM and EPD methods. The final parts are discussion and conclusion.

2. Experimental results

Surface morphologies and microstructural properties of the CDPSS and as-grown samples on the CDPSS were characterized by the instrument of focused-ion beam (FIB). Fig. 1(a) and (b) show the top-view and tilt-view FIB images, respectively, of the CDPSS where structures are arranged in periodic hexagons. The period of the CDPSS is 3 μm. Each hexagon has one dome-shaped post. Each post has the height of 1.65 μm and the bottom width of 2.8 μm.

A series of u-GaN on the CDPSS with various growth time were prepared by metal-organic chemical vapor deposition (MOCVD). Prior to the growth, CDPSSs were thermally baked at 1100 °C in hydrogen gas to remove surface contamination and desorb native oxide on the substrates. A 25-nm-thick GaN buffer layer was prepared at low temperature of 550 °C at the beginning of epitaxial growth. After that, the various thickness of u-GaN epilayers were grown on the CDPSS with different growth time. Trimethylgallium (TMGa) and ammonia (NH_3) were used as Ga and N precursors, with high purity hydrogen (H2) used as the carrier gas.

Fig. 1(c)-(j) show the cross-sectional FIB images of the u-GaN epilayers on the CDPSS with the growth time of 2, 5, 10, 20, 36, 52, 68 and 100 min. The related thickness of u-GaN epilayers measured with FIB are 0.14, 0.4, 0.74, 1.34, 1.94, 2.92, 4.06 and 4.81 μm. As shown in Fig. (c)-(f), the growth rate of the u-GaN on the trench of the CDPSS is faster than that on the sidewall of the CDPSS. Therefore, the u-GaN growth is blocked by the CDPSS structures because of the limited u-GaN growth rate on the sidewall of the CDPSS. This improves the lateral growth of the u-GaN on the trench region while increasing the growth time. The as-grown u-GaN samples on the CDPSS become 2D growth and reveal mirror-like smooth surface when the thickness is larger than the height of the dome-shaped post of the CDPSS as displayed in Fig. 1(g)-(j). In addition, the samples behave an easy coalescence since there are tiny voids along sidewall, and no large voids are seen in coalescent fronts.

Next, various thickness of the as-grown u-GaN samples on the CDPSS were analyzed by HRXRD. Diffraction data is acquired by exposing samples to X-ray radiation with a characteristic wavelength (λ) of 1.5418 Å. Fig. 2(a) and (b) represent HRXRD ω scans of rocking curve for the symmetrical (002) and asymmetric (102) reflections, respectively, of the as-grown u-GaN samples on the CDPSS. The intensity of both rocking curves keeps increasing with thicker GaN epilayers. Moreover, the full-width of half-maximum (FWHM) of the asymmetric (102) rocking curve refers to the lattice distortion from pure edge and mixed dislocations. Screw and

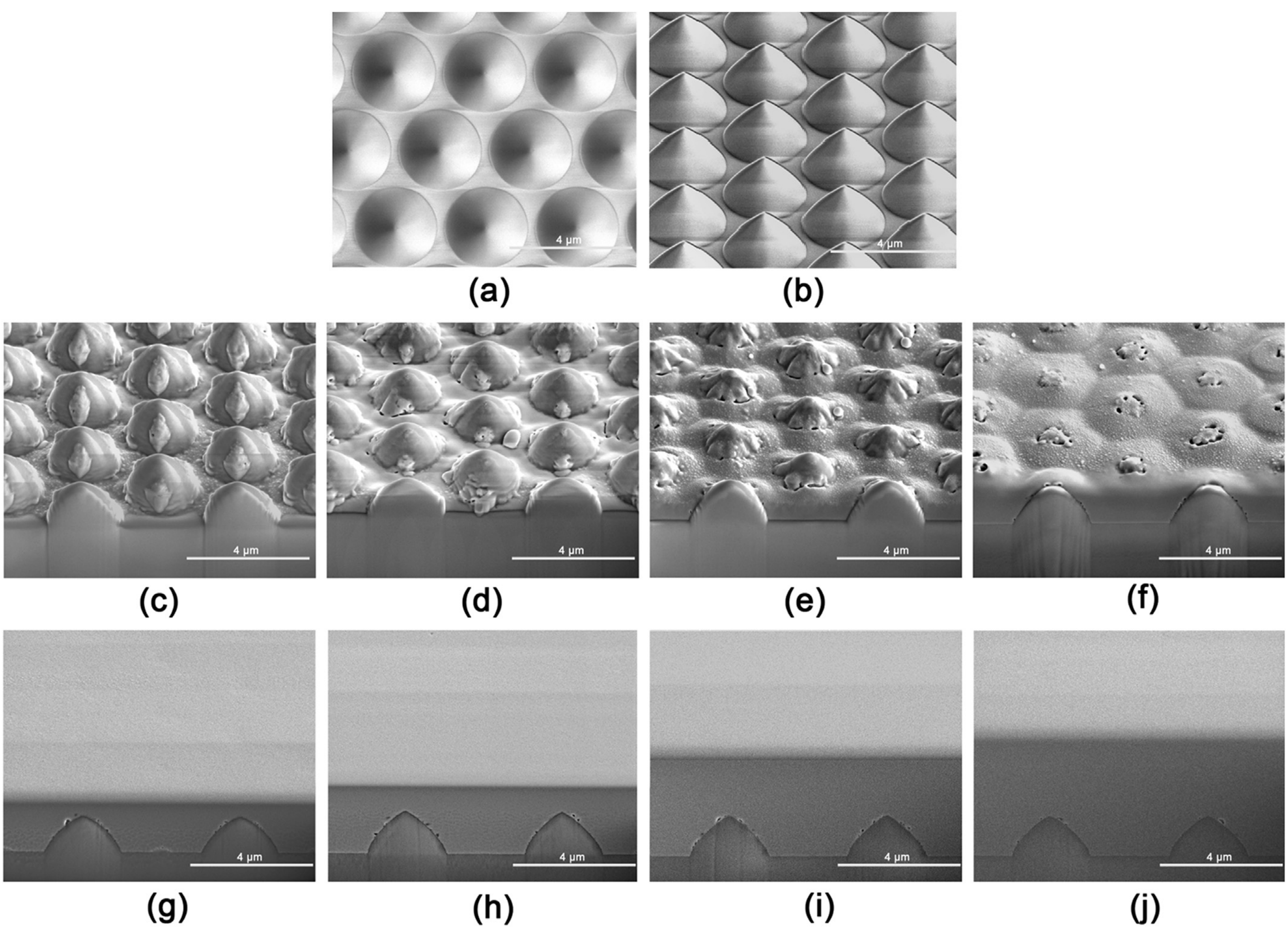

Fig. 1. The FIB images of (a) the top-view and (b) the tilt-view of the CDPSS, respectively. The cross-sectional FIB images of the as-grown u-GaN on the CDPSS with the growth time of (c) 2 min, (d) 5 min, (e) 10 min, (f) 20 min, (g) 36 min, (h) 52 min, (i) 68 min and (j) 100 min, respectively.