Comparison study of GaN films grown on porous and planar GaN templates*

Shan Ding(丁姗), Yue-Wen Li(李悦文), Xiang-Qian Xiu(修向前)†, Xue-Mei Hua(华雪梅), Zi-Li Xie(谢自力), Tao Tao(陶涛), Peng Chen(陈鹏), Bin Liu(刘斌), Rong Zhang(张荣)‡, and You-Dou Zheng(郑有炓)

Key Laboratory of Advanced Photonic & Electronic Materials, School of Electronic Science & Engineering, Nanjing University, Nanjing 210093, *China*

(Received 24 November 2019; revised manuscript received 10 January 2020; accepted manuscript online 16 January 2020)

The GaN thick films have been grown on porous GaN template and planar metal-organic chemical vapor deposition (MOCVD)-GaN template by halide vapor phase epitaxy (HVPE). The analysis results indicated that the GaN films grown on porous and planar GaN templates under the same growth conditions have similar structural, optical, and electrical properties. But the porous GaN templates could significantly reduce the stress in the HVPE-GaN epilayer and enhance the photoluminescence (PL) intensity. The voids in the porous template were critical for the strain relaxation in the GaN films and the increase of the PL intensity. Thus, the porous GaN converted from β-Ga_2O_3 film as a novel promising template is suitable for the growth of stress-free GaN films.

Keywords: GaN, porous template, stress

PACS: 81.05.Ea, 81.05.Rm, 83.85.St **DOI:** 10.1088/1674-1056/ab6c48

1. Introduction

Gallium nitride (GaN) is a promising wide bandgap semiconductor that is widely used in optoelectronic and power devices.[1–3] Due to the lack of GaN native substrate, present most GaN is grown by heteroepitaxy on foreign substrates.[4,5] But the large lattice and thermal mismatches between GaN and its foreign substrates lead to large residual stress and high density of threading dislocations in the GaN epilayers, which greatly affect the performance of the devices. The free-standing GaN is the most suitable substrate for the epitaxial growth of high-quality GaN. The laser lift-off is a feasible technology for preparing free-standing GaN by laser scanning the interface between GaN and sapphire substrates.[6,7] Nevertheless, due to the large residual stress in GaN/sapphire, the laser lift-off process easily causes cracks and crystalline quality degradation in the GaN films,[8–10] resulting in high cost and low yield of the process.

Porous structures offer an attractive application as a template for the growth of high-quality GaN films, as the voids contribute to reducing the strain and the dislocation density in the GaN epilayer.[11] Some groups have reported on the fabrication of porous templates and the epitaxial growth of GaN films on the templates.[12,13] Earlier, our group reported that β-Ga_2O_3 can be converted into single-crystalline GaN porous templates after the nitridation.[14] In this paper, we grow GaN thick films on porous GaN and planar metal-organic chemical vapor deposition (MOCVD)-GaN templates by halide vapor phase epitaxy (HVPE), and their structural, optical, and electrical properties are systematically studied and compared.

2. Experimental details

The single-crystalline porous and stress-free GaN template was fabricated by nitriding β-Ga_2O_3 film in a quartz tube furnace for two hours,[14] the β-Ga_2O_3 film had been obtained by a home-made HVPE reactor.[15] Next, the porous template was used for the growth of GaN thick films by HVPE. For comparison, the 5 μm-thick MOCVD-GaN template was together placed into the HVPE system for the growth.

The structural properties of the samples were investigated by x-ray diffraction (XRD, Bruker D8 Discover), Raman spectroscopy (Raman, OLYMPUS-BX41), and scanning electron microscopy (SEM, GeminiSEM 500). The optical properties of GaN were characterized by photoluminescence (PL) spectra at room temperature. The carrier concentration and electron mobility were obtained from Hall measurements.

3. Results and discussion

Figures 1(a) and 1(b) show the top SEM images of the GaN films grown on porous GaN and planar MOCVD-GaN templates. A good smooth surface morphology with some typical hexagonal pits is observed. Cross-sectional SEM images are shown in Figs. 1(c) and 1(d). It can be seen that the HVPE-GaN films on the different templates are about 50 μm thick. The GaN/sapphire interfaces are also discriminated clearly. The insets show the magnified view of the corresponding GaN/sapphire interfaces. In addition to the sapphire sub-

*Project supported by the National Key R&D Program of China (Grant No. 2017YFB0404201), the State Key R&D Program of Jiangsu Province, China (Grant No. BE2019103), the Six-Talent Peaks Project of Jiangsu Province, China (Grant No. XCL-107), the Fund from the Solid-state Lighting and Energy-saving Electronics Collaborative Innovation Center, PAPD, and the Fund from the State Grid Shandong Electric Power Company.

†Corresponding author. E-mail: xqxiu@nju.edu.cn

‡Corresponding author. E-mail: rzhang@nju.edu.cn

 http://iopscience.iop.org/cpb http://cpb.iphy.ac.cn

strate, the porous GaN template is approximately 1.5 μm thick and includes the porous GaN layer converted from β-Ga_2O_3 with lots of small voids and an un-nitridated β-Ga_2O_3 layer, which is clearly visible in the inset of Fig. 1(c).

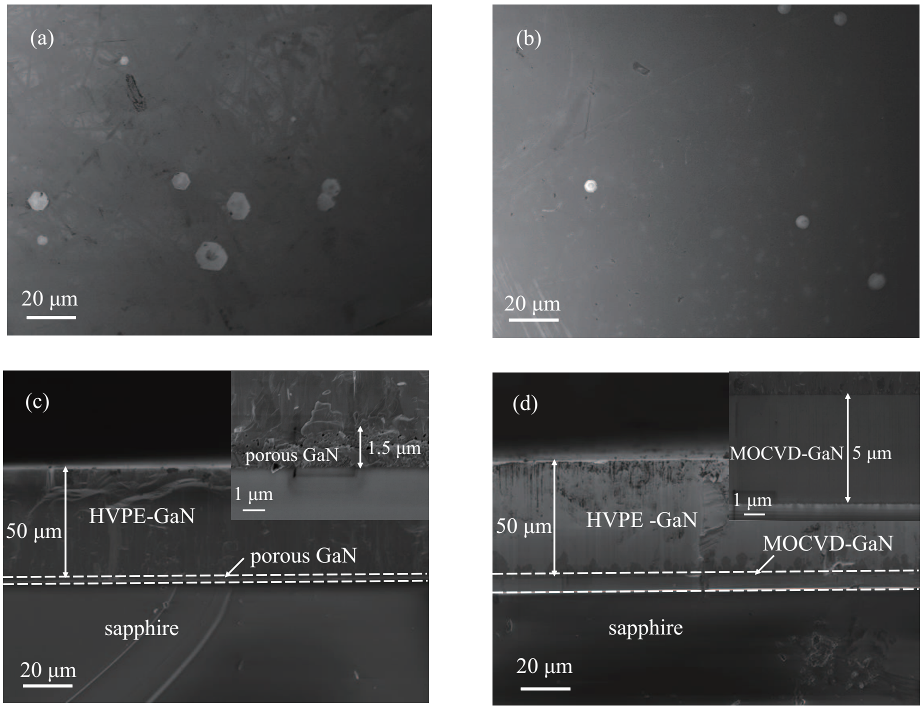

Fig. 1. Top SEM images of GaN grown on (a) porous GaN and (b) and MOCVD-GaN templates. Cross-sectional SEM images of GaN grown on (c) porous GaN and (d) MOCVD-GaN templates. Insets show the magnified view of the GaN/sapphire interfaces.

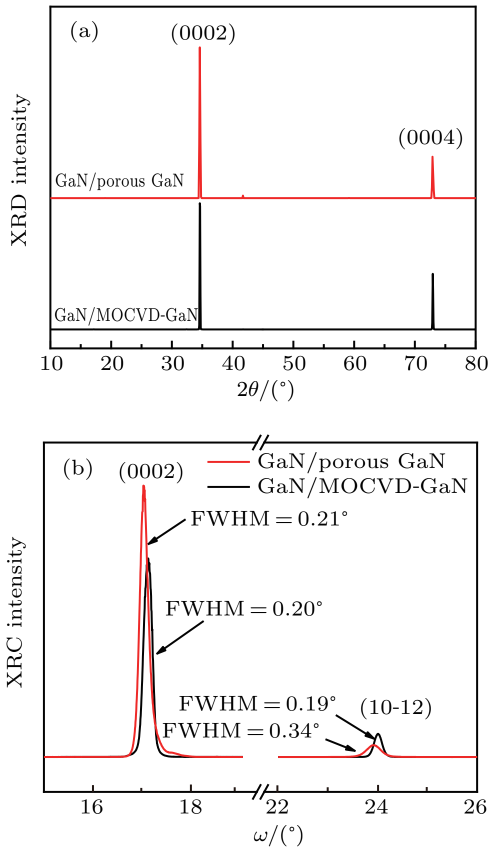

Fig. 2. (a) XRD patterns and (b) XRC of GaN films grown on the different templates.

Figure 2(a) shows the XRD ω–2θ scan patterns of the GaN films grown on different templates. The GaN (0002) and (0004) diffractions are observed for all the samples. The crystal quality of the GaN films is characterized by x-ray diffraction rocking curves (XRC) shown in Fig. 2(b). Note that the full width at half maximum (FWHM) of the (10-12) peak for the GaN film grown on the porous GaN template is larger than that on the MOCVD-GaN template, which may be due to the poor in-plane lattice reconfiguration during the nitridation-conversion process of the porous GaN.[16] The FWHM values of the (0002) peak of both the GaN films are similar but relatively high, and what is more, the growth conditions of the GaN epilayer must be further optimized to improve the crystal quality of the GaN epilayer, especially for the homogeneous epitaxial growth on GaN templates.

Figure 3 illustrates the Raman spectra for the GaN films at room temperature. The strain state in the GaN films is typically estimated from the frequency shift of the E_2 (high) phonon lines in Raman spectra. The E_2 (high) peaks of GaN grown on porous GaN and planar MOCVD-GaN templates are located at 567.8 cm^{-1} and 569.4 cm^{-1}, respectively. Compared with the E_2 (high) peak position (567.8 cm^{-1}) of stress-free thick GaN,[17] the GaN on porous GaN template is almost stress-free. The E_2 (high) phonon line of the GaN on MOCVD-GaN is blue-shift by about 1.6 cm^{-1}, the GaN on MOCVD-GaN possesses the higher compressive stress of about 0.419 GPa.[18] Besides, there is a weak shoulder peak E_1 (TO) mode near the E_2 (high) mode for both samples, which may be related to the defects in the GaN film.[19]

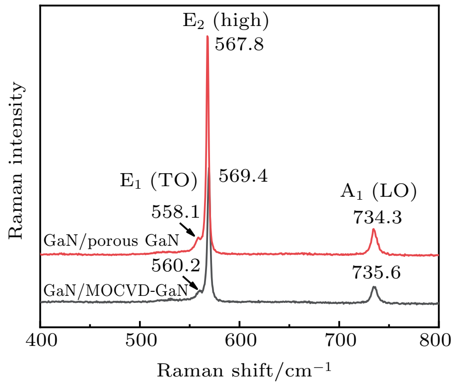

Fig. 3. Raman spectra of GaN films grown on porous GaN and MOCVD-GaN templates.

Figure 4 shows the room temperature PL spectra for the GaN films on different templates. The strong near band edge (NBE) emission peaks can be observed, and no yellow luminescence is observed. The NBE peaks of the GaN films grown on the porous GaN and MOCVD-GaN templates are observed at 3.408 eV and 3.422 eV, indicating that the GaN films are under compression at room temperature. The NBE peak of the GaN on porous GaN shows a 14 meV redshift compared with that of the GaN on MOCVD-GaN. According to the data, it is estimated that a compressive stress of about 0.66 GPa can be relaxed.[20] The PL spectra reveal that the porous GaN templates can effectively reduce the compressive stress, which is consistent with the Raman results. Besides, the stronger PL intensity is observed for the GaN on the porous GaN template, which can be attributed to the increase of the light extraction efficiency due to the presence of the porous GaN layer.[21]

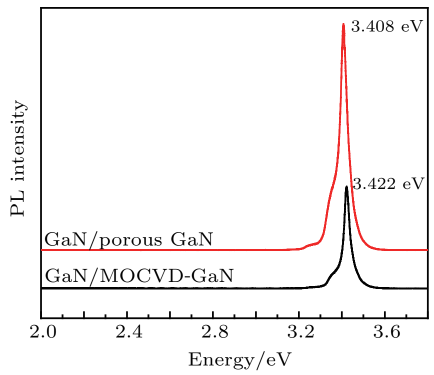

Fig. 4. Room temperature PL spectra of GaN grown on porous GaN and MOCVD-GaN templates.

The Hall measurement was performed for both samples at room temperature. The GaN on porous GaN has n-type conductivity with a carrier concentration of 7.798×10^{16} cm^{-3} and a mobility of 44.7 cm^2/V·s. And the GaN on MOCVD-GaN has n-type conductivity with a carrier concentration of 3.288×10^{16} cm^{-3} and a mobility of 39.2 cm^2/V·s. The relatively low mobility of both samples is attributable to the dislocation and defect scattering due to the lower crystalline quality.[22] The further optimization of the growth conditions would be performed to obtain higher quality GaN films.

From the above results, GaN films grown on porous and planar GaN templates under the same growth conditions have similar structural, optical, and electrical properties. But the GaN porous templates can significantly reduce the stress in the HVPE-GaN epitaxial layer. Besides, the porous template can facilitate not only the release of stress but also the self-separation of GaN thick films.[16]

4. Conclusion

In summary, we have grown the GaN thick films on the porous and planar GaN templates by HVPE. The Raman measurement revealed that the GaN film grown on the porous GaN template is almost stress-free. Compared with GaN on the planar MOCVD-GaN template, the PL intensity of GaN on the porous template was significantly enhanced due to the presence of lots of voids in the porous template. We think that the porous GaN template would be beneficial for the preparation of high-quality stress-free GaN substrates after further growth optimization.

References

[1] Kim M H, Schubert M F, Dai Q, Kim J K, Schuberta E F, Piprek J and Park Y 2007 *Appl. Phys. Lett.* **91** 183507

[2] Steigerwald D A, Bhat J C, Collins D, Fletcher R M, Holcomb M O, Ludowise M J, Martin P S and Rudaz S L 2002 *IEEE J. Sel. Top. Quantum Electron.* **8** 310

[3] Shen L, Heikman S, Moran B, Coffie R, Zhang N Q, Buttari D, Smorchkova I P, Keller S, DenBaars S P and Mishra U K 2001 *IEEE Electron Device Lett.* **22** 457

[4] Zhang Y H, Dadgar A and Palacios T 2018 *J. Phys. D: Appl. Phys.* **51** 273001

[5] Liu L and Edgar J H 2002 *Mater. Sci. Eng. R-Rep.* **37** 61

[6] Kelly M K, Ambacher O, Dimitrov R, Handschuh R and Stutzmann M 1997 *Phys. Status Solidi A* **159** R3

[7] Wong W S, Sands T, Cheung N W, Kneissl M, Bour D P, Mei P, Romano L T and Johnson N M 1999 *Appl. Phys. Lett.* **75** 1360

[8] Monemar B, Larsson H, Hemmingsson C, Ivanov I G and Gogova D 2005 *J. Cryst. Growth* **281** 17

[9] Tong X L, Li L, Zhang D S, Dai Y T, Lv D J, Ling K, Liu Z X, Lu P X, Yang G, Yang Z Y and Long H 2009 *J. Phys. D-Appl. Phys.* **42** 045414

[10] Lipski F, Wunderer T, Schwaiger S and Scholz F 2010 *Phys. Status Solidi A* **207** 1287

[11] Hartono H, Soh C B, Chow S Y, Chua S J and Fitzgerald E A 2007 *Appl. Phys. Lett.* **90** 171917

[12] Jang L W, Jeon D W, Polyakov A Y, Govorkov A V, Sokolov V N, Smirnov N B, Cho H S, Yun J H, Shcherbatchev K D, Baek J H and Lee I H 2014 *J. Alloy. Compd.* **589** 507

[13] Zhang L, Dai Y B, Wu Y Z, Shao Y L, Tian Y, Huo Q, Hao X P, Shen Y N and Hua Z 2014 *Crystengcomm* **16** 9063

[14] Li Y W, Xiu X Q Xiong Z N, Hua X M, Xie Z L, Tao T, Chen P, Liu B, Zhang R and Zheng Y D 2019 *Mater. Lett.* **240** 121

[15] Xiong Z N, Xiu X Q, Li Y W, Hua X M, Xie Z L, Chen P, Liu B, Han P, Zhang R and Zheng Y D 2018 *Chin. Phys. Lett.* **35** 58101

[16] Li Y W, Xiu X Q, Xiong Z N, Hua X M, Xie Z L, Chen P, Liu B, Tao T, Zhang R and Zheng Y D 2019 *Crystengcomm* **21** 1224

[17] Melnik Y V, Vassilevski K V, Nikitina I P, Babanin A I, Davydov V Y and Dmitriev V A 1997 *MRS Int. J. Nitride Semicond. Res.* **2** e39

[18] Tripathy S, Chua S J, Chen P and Miao Z L 2002 *J. Appl. Phys.* **92** 3503

[19] Kushvaha S S, Kumar M S, Shukla A K, Yadav B S, Singh D K, Jewariya M, Ragam S R and Maurya K K 2015 *RSC Adv.* **5** 87818

[20] Zhao D G, Xu S J, Xie M H, Tong S Y and Yang H 2003 *Appl. Phys. Lett.* **83** 677

[21] Vajpeyi A P, Tripathy S, Chua S J and Fitzgerald E A 2005 *Physica E* **28** 141

[22] Ng H M, Doppalapudi D, Moustakas T D, Weimann N G and Eastman L F 1998 *Appl. Phys. Lett.* **73** 821