Characterization of MOCVD Grown GaN on Porous SiC Templates

F. Yun[**], S. Doğan[††], Y. T. Moon, Y. Fu, J. Xu, D. Johnstone, and H. Morkoç

Virginia Commonwealth University, Department of Electrical Engineering, Richmond, VA 23284

Received zzz, revised zzz, accepted zzz

PACS 81.15Gh, 81.65.Cf, .78.55.Cr, 81.05.Rm

We have grown GaN layers by MOCVD on a set of nanoporous SiC templates with different porosity and morphology, produced by etching the anodized porous SiC starting material in a H_2 environment at temperatures ~1500°C, in an effort to attain improved films. The hydrogen etching serves to remove surface damage caused during mechanical polishing prior to anodization, remove the skin layer associated with anodization, tune the pore size, and consolidate pore geometry. Growth conditions favoring lateral overgrowth of GaN were employed on this set of samples to obtian GaN to a thickness of 2μm. Atomically smooth surfaces were obtained for the epitaxial GaN layers. The GaN quality is highly dependent on the specifics of the porous templates used. An intensity increase of up to a factor of 30 was observed in the GaN excitonic peak compared to GaN grown on standard SiC substrate. The I-V data indicated significant reduction in the leakage current (in reverse bias) compared to GaN grown on standard SiC. The dependence of optical properties, crystalline quality, and surface morphology on the particulars of porous SiC templates is discussed.

1 Introduction GaN is considered one of the well-suited materials for high-temperature and high-power electronic devices [1]. It has also found wide range applications in optoelectronic devices covering the visible to ultraviolet band of the electromagnetic spectrum. Due to a lack of native substrates for GaN homoepitaxy, most of the research and development effort has been focused on the use of foreign substrates [2]. Currently, heteroepitaxially grown GaN thin films are still characterized by a high density of defects (dislocations, point defects) caused primarily by the lattice and thermal mismatch between the wurtzitic GaN films and the foreign substrates. The most studied substrate so far is c-plane sapphire due to its low cost, large size, and available epi-ready surface preparation, despite its large lattice mismatch (~16%) which caused an in-plane rotation of GaN, and thermal mismatch to GaN.

SiC, on the other hand, offers smaller lattice mismatch (~3.4%), lack of in-plane rotation, and smaller thermal mismatch to GaN as compared to sapphire [3]. The smaller lattice mismatch, among others, has the benefit of eliminating the in-plane rotation observed on sapphire in addition to formation of less defective nucleation islands at the initial stages of growth. Absence of in-plane rotation allows minimization of mosaic structure. Overall, SiC is regarded as a more suitable substrate for reduced defect density associated with GaN heteroepitaxy.

A widely adopted scheme for defect reduction in GaN is lateral epitaxy overgrowth (LEO) [4]. However, additional and less complicated schemes which do not require photolithography and multiple growth runs are deemed necessary to further reduce cost and the defect density. For example, by using a nanoporous SiC template, the stress can be greatly relaxed at the early stage of growth, leading to the reduction of defect density. Another suggestion is to use the porous SiC substrate as a template for nanoscale lateral epitaxy overgrowth (nano-LEO), where nearly dislocation-free nanoscale islands (pores) are

---

[**] Corresponding author. Fax: +1-804-828-4269. E-mail address: fyun@vcu.edu.

[††] Also with Atatürk University, Faculty of Art & Science, Department of Physics, 25240 Erzurum, Turkey.

used as nucleation sites for lateral epitaxy overgrowth. It allows dislocations to bend, loop and annihilate, rather than propagate through the epilayer. We have previously reported on the improvement of GaN crystalline quality by using porous SiC templates for molecular beam epitaxy (MBE) growth with active ammonia N_2 source [5]. Sagar et al [6] have observed enhanced strain relaxation of GaN on porous SiC, during a plasma-assisted MBE growth of GaN on porous SiC. Recently, Jeong et al [7] reported MOCVD growth of GaN by adopting porous 4H-SiC substrates, showing an improved crystalline quality compared to the use of standard 4H-SiC and sapphire substrates. Evidently, we can expect the GaN quality to be sensitive to the details of the porous structure.

In this paper, we have fabricated a set of nanoporous 6H-SiC templates with different porosity and morphology. GaN epitaxy was performed on these porous templates with identical conditions by MOCVD. The dependence of the GaN film on porosity was characterized in terms of surface morphology, optical properties, crystalline quality, as well as current-voltage (I-V) characteristics.

2 Experimental The as-received n-type anodised porous 6H-SiC [8] wafer was on axis along the (0001) Si-face. The porous SiC was subjected to a H_2 etching process at 1500°C for a duration between 1 to 30 minutes, with a H_2 flow rate of ~10 l/min. A set of five nanoporous SiC templates with different porosity and morphology was produced after etching for 1, 5, 10, 15, and 30 min, respectively. For MOCVD growth, trimethylgallium (TMG) was used as the Ga source, and NH_3 as the N_2 source, with H_2 as the carrier gas. A low temperature GaN buffer layer (100 nm) was first grown at 950°C, followed by a 2 μm GaN epilayer grown at 1050°C using conditions favoring lateral growth which was optimized on a standard (nonporous) 6H-SiC substrate (control sample) which showed atomic steps after the hydrogen annealing treatment.

Scanning electron microscopy (SEM) and atomic force microscopy (AFM) were used to examine the surface morphology. Photoluminescence (PL) was measured using a He-Cd laser (325 nm) as the excitation source. High-resolution x-ray diffraction rocking curves were taken on GaN films by a diffractometer equipped with a 4 x Ge (220) crystal as x-ray monochrometer. The full width at half maximum (FWHM) was recorded for both the symmetric (0002) and asymmetric (10$\underline{1}$2) diffraction peaks. I-V characteristics were measured on Schottky junctions fabricated on the GaN films.

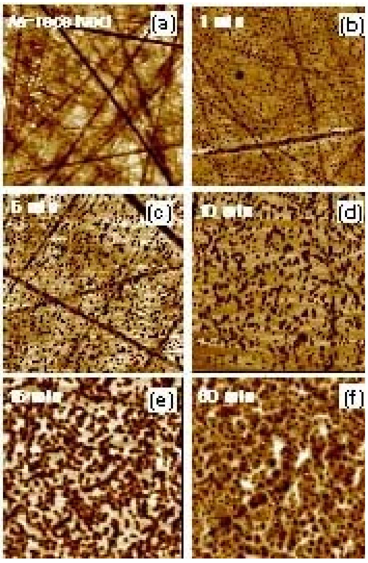

Fig. 1. AFM images of as-receive porous SiC with surface scratch lines and skin layer covering most of the pores (a), and the change of porosity after H_2 etching at 1500°C for (b) 1min, (c) 5 min, (d) 10 min, (e) 15 min, and (f) 30 min. The scale of all images is 5x5 μm.

3 Results and Discussions For nonporous 6H-SiC wafer, the H_2 etching treatment removes surface scratch lines caused by mechanical polishing, and exposes the smooth surface of SiC with well-aligned bi-atomic steps. In addition to this effect, H_2 etching of porous SiC at ~1500°C serves to remove the anodization related “skin layer” [3], which caps most of the pores. With progressive H_2 etching, the pore size was further enlarged, and the pore geometry was consolidated. Fig. 1 shows AFM images of both as-received porous SiC, with surface scratch lines visible and a skin layer (Fig. 1(a)), and the change of surface pore morphology after H_2 etching for different amounts of time. After 1 min. of etching (Fig. 1(b)), the skin layer began to etch, exposing a much higher density of pores. After 5 min. (Fig. 1(c)) and 10 min, (Fig. 1(d)) of etching, the scratch lines gradually diminished, and pore size enlargement was clearly observed with the pore density almost unchanged. Further H_2 etching of 15 min. resulted in a considerable change in the pore density as well as size, as shown in Fig. 1(e). Finally, a drastic change in the pore shape, size and surface roughness was observed after 30 min. of etching, as shown in Fig. 1(f). A quantitative definition of porosity is not given here due to the ambiguous nature of such pores, which entails size, density and geometry. Instead, we use the H_2 etching time as an indicator of porosity, with longer time indicating higher porosity.

After a 2-µm GaN growth on top of the porous templates, the surface of GaN is characterized by a smooth step-flow morphology (AFM not shown here), decorated with varying density of hexagonal pits, as shown by the SEM images inserted in Fig. 2. The presence of hexagonal pits indicates incomplete lateral coalescence during the GaN growth on porous SiC templates, and it is found to be highly dependent on porosity. Fig. 2 plots the hexagonal pit density against the H_2 etching time, i.e. porosity. We can discuss the dependence of lateral growth conditions on porosity in three zones with respect to Fig. 2. At low porosity (Zone I), the substrate surface is characterized by a partially removed skin layer and scratch lines. The resulting density of hexagonal pits on GaN surface is higher by more than an order of magnitude as compared to the control sample. With the increase of porosity mainly by pore enlargement, and the elimination of surface scratch lines (Zone II), the template surface is characterized by a contiguous nanoporous network with a relatively smooth surface and pore size ranging from 10 to 100 nm. The smooth surface regions in-between the pores provide good templates for epitaxial growth, and the pore size is favorable for enhanced lateral growth. Therefore, hexagonal pit density due to incomplete lateral coalescence is a minimum on the GaN surface. When the porosity continues to increase (Zone III) by H_2 etching, the enlargement of pore size is accompanied by a notable change in pore geometry, leaving a very rough skeleton of porous SiC surface and a significant broadening in pore size distribution. The overgrowth of GaN on etched for 30 min. in H_2 shows a sharp increase in hexagonal pit density (Fig. 2).

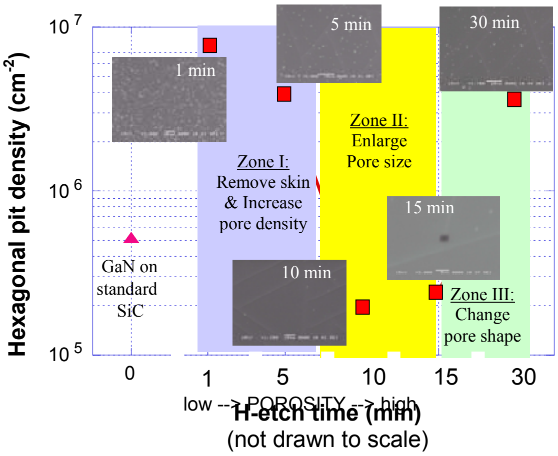

Fig. 2. Inset shows SEM images of smooth GaN surface decorated with hexagonal pits, grown on different porosity templates. The density of hexagonal pits is plotted against hydrogen etch time (or porosity).

At both room temperature and 15K, the PL intensity of GaN bandedge emission showed a strong

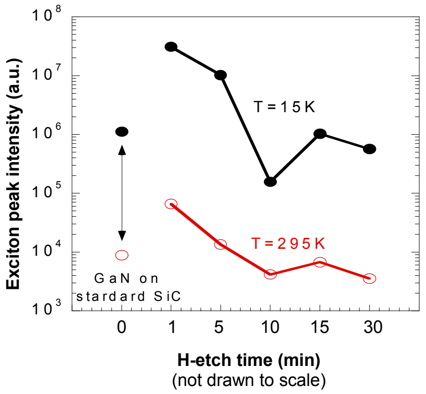

Fig. 3. Intensity of GaN exciton peak as a function of porosity (in terms of hydrogen etching time), both at room temperature and T=15K. The intensity for the control sample is also plotted as a reference.

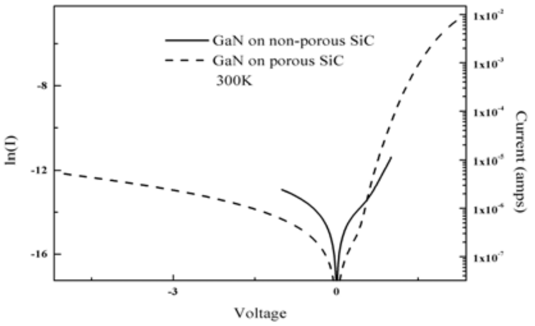

Fig. 4. I-V characteristics of Schottky diodes on GaN films grown on porous SiC template (5 min hydrogen etched), and on nonporous SiC substrate. The leakage current has improved significantly when porous template was used.

dependence on the porosity of SiC templates. Fig. 3 plots the GaN exciton peak intensity as a function of porosity in terms of H_2 etching time. For both RT and LT spectra, an increase of intensity can be seen for moderate to short etching times (≤ 5min), compared to the control sample grown on nonporous SiC substrate. At T=15K, the increase can be ~30 times as compared to the control sample. For high porosity templates, however, the intensity is relatively lower. Since the PL spectra are sensitive to the quality of the top few hundreds of nanometers of the GaN films, this implies the reduction of non-radiative recombination centers which are in turn associated with the reduction of defect density at least at the top portion of the GaN epilayer, with the use of low to medium porosity templates.

However, from x-ray rocking curve analysis, we did not see any improvement in the overall crystalline quality over that of GaN grown on nonporous SiC substrate, although there seems to be a dependence of FWHM on porosity. The narrowest FWHM for (0002) is 6.47 arcmin for the 5-min etched sample, and the narrowest for $(10\underline{1}2)$ is 10.0 arcmin for the 1-min etched sample. The control sample has a remarkable (0002) FWHM of 1.83 arcmin, and $(10\underline{1}2)$ of 7.90 arcmin. This is partly due to the fact that the MOCVD growth conditions adopted here were optimized for the best GaN crystalline quality on standard SiC. Another factor in play is that the structural information gained from XRD data is indicative of a weighted average quality of the total layer thickness. For the case of a 2--μm layer here, it reflects more of the quality of inferior interior layer. In this sense, PL is a more useful tool in assessing the top layer quality, at least in terms of optical emission properties.

Fig. 4 shows the I-V characteristics at room temperature, for Schottky diode structures fabricated on the 2-μm GaN films with 5-min H_2 etched porous template, as well as with the standard SiC substrate (control). The figure clearly shows an improved Schottky junction characteristics for the GaN film on porous template, indicating a GaN epilayer with reduced point defect density near the top surface. To be specific, the current for a reverse bias of -5V was ~10 μA for the GaN on non-porous SiC, as compared to < 1 μA for GaN on Porous SiC, from an average of some 10 diodes. This improvement in leakage current is consistent with the LT-PL results, which showed an increase in the intensity of exciton peak.

4 Conclusion A set of porous SiC templates was prepared with different porosity by H_2 etching a SiC wafer at 1500°C, previously made porous by anodization. The quality of GaN epitaxial layers grown on these porous templates was found to be sensitive to the properties of the porous templates in terms of the pore size, density, and shape. The hexagonal pit density on GaN surface due to incomplete coalescence can be tuned by porosity. The intensity of GaN exciton peak increases up to 30 times with the use of low porosity template. The I-V characteristics indicate reduced leakage current for reverse bias in GaN on porous SiC as compared to that on nonporous SiC, consistent with a less defective GaN near the top portion of the epilayer when selected porous SiC templates were used.

Acknowledgements This work has been funded by ONR as part of a Defence University Research Initiative on Nanotechnology (DURINT) program and is monitored by Dr. C. E. C. Wood of ONR. The authors thank Prof. Randy M. Feenstra for many helpful discussions.

References

[1] H. Morkoç, Nitride Semiconductors and Devices, Springer, 1999. Second edition in press.
[2] L. Liu and J. H. Edgar, Mater. Sci. Eng. **R37**, 61 (2002).
[3] C. D. Lee, A. Sagar, R. M. Feenstra, C. K. Inoki, T. S. Kuan, W. L. Sarney, and L. Salamanca-Riba, Appl. Phys. Lett. **79**, 3428 (2001).
[4] D. Kapolnek, S. Keller, R. Vetury, R. D. Underwood, P. Kozodoy, S. P. DenBaars, and U. K. Mishra, Appl. Phys. Lett. **71**, 1204 (1997).
[5] F. Yun, M. A. Reshchikov, L. He, H. Morkoç, C. K. Inoki, and T. S. Kuan, Appl. Phys. Lett. **81**, 4142 (2002).
[6] A. Sagar, C. D. Lee, R. M. Feenstra, C. K. Inoki, and T. S. Kuan, J. Vac. Sci. Technol. **B21**, 1812 (2003).
[7] J. K. Jeong, Hyun J. Kim, H-C. Seo, Hee J. Kim, E. Yoon, C. S. Hwang, and Hyeong J. Kim, Electrochemical and Solid-State Letters, **7**, C43 (2004).
[8] wafers purchased from TDI, Inc. Silver Spring, MD 20904, USA.