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Growth of GaN on porous SiC and GaN substrates

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GaN films were grown on porous SiC and GaN templates using both plasma-assisted molecular beam epitaxy (PAMBE) and metal-organic chemical vapor deposition (MOCVD) to evaluate possible advantage of epitaxy on a porous substrate. For the growth of GaN on porous SiC by PAMBE, transmission electron microscopy (TEM) observations indicate that the exposed SiC suface pores tend to extend into the GaN film as open tubes and to trap Ga droplets. The GaN layers grown on porous templates have fewer threading dislocations originating at the interface, but they have additional defects in the form of half-loop dislocations which act to relieve the strain in the films. For PAMBE of GaN on porous GaN, dislocations existing in the porous seed layer are seen to propagate through the porous layer into the overgrown GaN, resulting in no dislocation reduction. For MOCVD of GaN on porous GaN, the initial regrowth tend to bend laterally the dislocations and enhance their annihilation, resulting in 5-10× fewer dislocations in the overgrown film.

1 Introduction

Porous SiC has recently been explored as a promising substrate to grow epitaxial SiC and GaN with reduced dislocation density [1-2]. Such porous materials are produced by anodizing n-type SiC in hydrofluoric acid under ultra-violet illumination [3]. Elongated pores with diameters 10 to 30 nm are typically formed in 4H and 6H SiC depending on the etching conditions. Preliminary results for GaN growth on porous GaN have also shown some promise for improved GaN quality [4]. It has been speculated that a porous surface may serve as a template for nano-scale lateral epitaxial overgrowth, and that a porous substrate layer may be compliant to some extent to lattice and thermal mismatch strains.

Possible mechanisms for epitaxial improvement through growth on a porous template are illustrated in Fig. 1. If epitaxial growth begins at areas of sufficiently small size between pores [Fig. 1(a)], strain in the epitaxial film can be relieved elastically (i.e. without dislocation formation) [5]. If dislocations do form at the interface and extend vertically as threading dislocations, lateral growth of the islands might

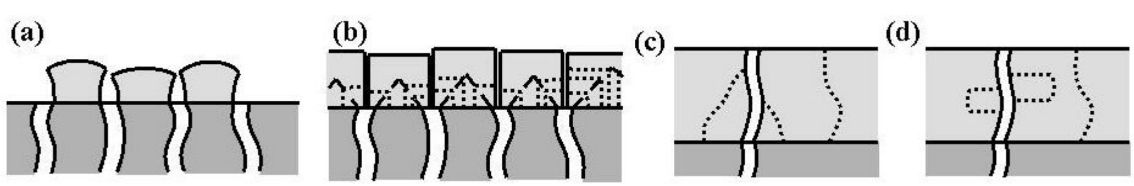


Fig. 1. Schematic illustration of various defect reduction mechanisms for a strained film (light gray) grown on a porous substrate (dark gray). Dislocations are indicated by dotted lines. Triangular facets in (b), formed in the initial stage of growth, are indicated by dashed lines.

cause these dislocations to bend horizontally [Fig. 1(b)] and annihilate each other. If the pores from the substrate extend into the film as open tubes, they can serve as sinks of dislocations [Fig. 1(c)] or as sources of dislocation half loops [Fig. 1(d)] for reducing residual strain in the film.

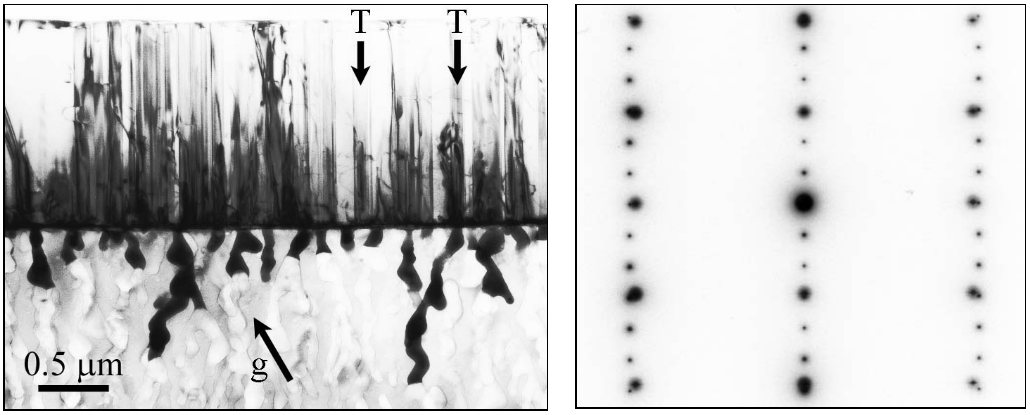
2 Experimental

All porous SiC substrates used in this study were 6H polytype with a 3.5° miscut angle, etched at a current density of 7 mA/cm^2 under 250 W Hg lamp illumination by TDI, Inc. The porous SiC substrates contain a ~50-nm-thick skin layer with few exposed pores at the surface. H-etching at 1700°C for 1-2 minutes and/or reactive ion etching in SF_6 were used to remove the skin layer prior to the growth [6]. Using this combination of RIE and H-etching we have prepared a series of porous substrates with pore density ranging from ~3 to ~13 μm^{-2} [7]. The PAMBE growth of GaN was performed at 750°C under an Ga rich condition optimized for growing low dislocation density GaN films on non-porous substrates; such films on non-porous substrates are known to have Ga-polarity [8]. The MOCVD growth was performed at 1050°C using trimethyl gallium and ammonia. The porous GaN templates used in this work are etched PAMBE- or HVPE-grown GaN seed layers [9], each with a surface layer of vertical pores of about 20-80 nm in diameter. Both seed layers contain threading dislocations, mostly edge type, and grain/domain boundaries. Transmission electron microscopy (TEM), electron and x-ray diffraction, and stylus profilometry were used to characterize the structural quality of the overgrown layers.

3 Results and discussion

Our early attempts at PAMBE of GaN on porous SiC were performed on substrates for which the skin layer had not been fully removed [2]. For the low surface pore density (<1 μm^{-2}) of those samples, TEM observations indicate that the epitaxial GaN growth initiates primarily from surface areas between pores. The exposed surface pores tend to extend into the GaN as open tubes, and trap Ga droplets. A slight reduction (by about a factor of two) in dislocation density was found for the growth on porous substrates, and electron diffraction patterns indicate a greater relaxation of mismatch strain in the films grown on the porous substrates. However, some uncertainty in these early results occurred since the substrate temperatures for the films grown on the porous substrates were greater by 30-40°C than for the films on non-porous substrates (due to a reduced effective emissivity of the former [7]). More recent experiments have been performed in which this difference in sample temperatures between substrates was minimized, and also for which the surface pore density was varied by the combination of H-etching and RIE [7]. As the surface pore density increases, more open tubes are produced in the overgrown GaN layers, with fewer threading dislocations emerging from the initial growth surface. Figure 2 shows a typical growth morphology on a SiC surface with pore density ~12 μm^{-2} and pore size ~70 nm. All pores are filled with Ga during growth, and each pore produces an open tube in GaN extending all the way to the top surface. Most dislocations observed in GaN are dislocation half loops with **b** = $1/3\langle 11\bar{2}0\rangle$ glided in from the tube sidewalls, like those depicted schematically in Fig. 1(d). Diffraction pattern indicates that the GaN layer containing tubes and dislocation half loops is fully relaxed ($\Delta a/a \approx 3.6\%$).

Similar growth morphology was observed on a porous SiC surface of comparable pore density but with a much larger pore size. As shown in Fig. 3(b), the growth surface between large pores is not flat and GaN lateral growth occurs at the edge of each pore covering part of the pore opening. Considerable c-plane stacking faults are found in this lateral growth region, although the film regions above the lateral growth is relatively free of threading dislocations. These large surface pores have thus enabled a new growth mode, i.e. lateral growth, of the film. The open tubes emerging from the pores are much smaller in

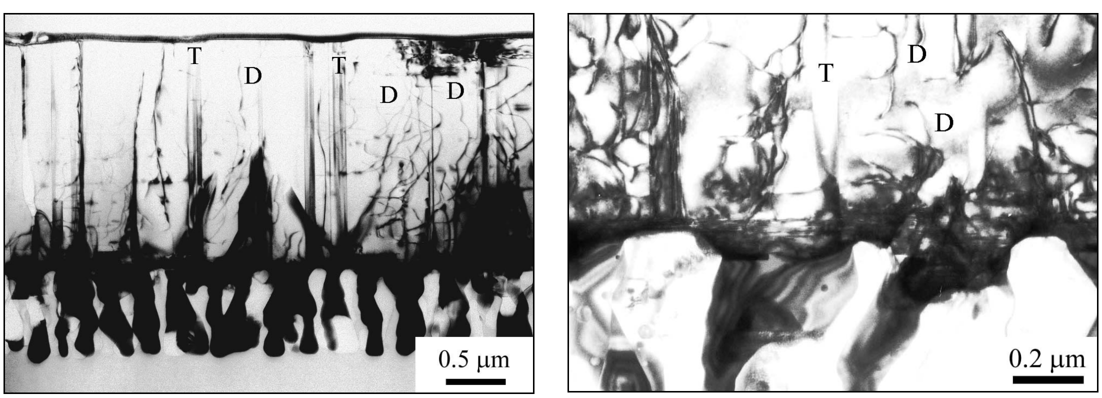


(a) (b)

Fig. 2. (a) GaN grown by PAMBE on a porous SiC surface with a pore density ~12 μm^{-2} and pore size ~70 nm. Each pore produces an open tube extending to the GaN top surface. Some of these vertical tubes are marked by “T”. (b) Electron diffraction pattern of (a) indicates that the GaN overgrown layer containing tubes is fully relaxed.

diameter than the original pore opening because of the lateral growth. The dislocations found in regions between the tubes are mostly half loops originated from the tubes, similar to that seen in Fig. 2. Wafer curvature measurements for all the films grown on porous substrates clearly reveal a substantial relaxation of the mismatch strain in the film, which we attribute to the presence of the half loops [7].

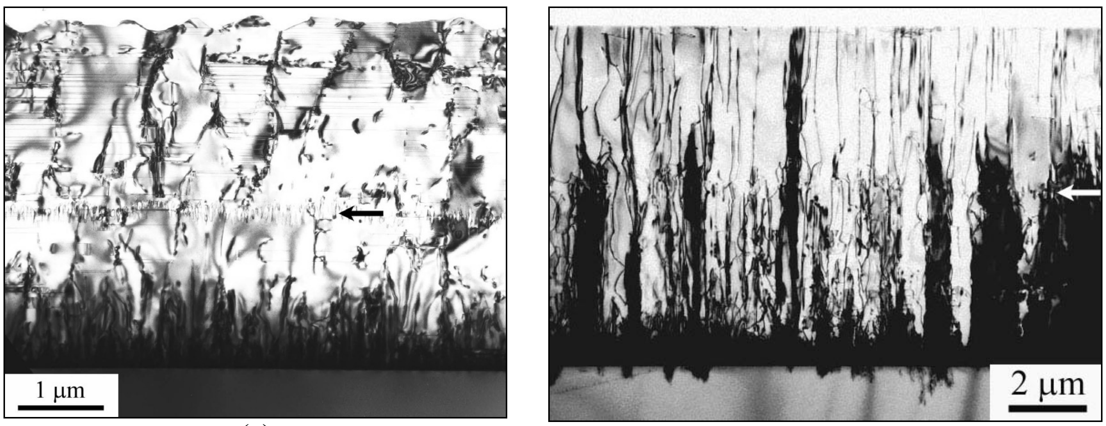
For the case of GaN growth on porous GaN, the overgrown layer tends to replicate the underlying dislocation structure (although considerable dislocation reduction can occur as this overgrowth proceeds, independent of the presence of the porous layer). The porous GaN templates used in this work are etched PAMBE- or HVPE-grown GaN seed layers [9], each with a 0.25-μm-thick surface layer of vertical pores of about 20-80 nm in diameter. For PAMBE overgrowth [Fig. 4(a)], dislocations existing in the seed layer are seen to propagate through the porous layer into the overgrown film, resulting in no dislocation reduction. X-ray diffraction also reveals similar values of rocking curve widths (within 20%) for the seed layers and the overgrown films.



(a) (b)

Fig. 3. (a) GaN grown by PAMBE on a porous SiC surface with a pore density ~13 μm^{-2} and pore size ~250 nm contains open tubes, marked by “T”, extending to the top surface and dislocation half loops, marked by “D”, glided in from the tubes. (b) GaN lateral growth occurs at each pore over the filled Ga.

For the MOCVD overgrowth of GaN on a porous GaN template, however, a notable 5-10× reduction in threading dislocations is observed in GaN in the vicinity above the surface pores [Fig. 4(b)]. The improved structural quality of the MOCVD films compared to the seed layers is also revealed by a significant reduction (~40%) in x-ray rocking curve widths of the (0002) reflection. TEM images similar to Fig. 4(b) taken at higher magnifications indicate that dislocations from the seed layer after propagation through the porous layer tend to bend laterally and thereby encounter other nearby dislocations and combine or annihilate each other [Fig. 1(b)]. It is important to note that similar lateral movements of dislocations were also observed during initial MOCVD overgrowth of GaN on a HVPE non-porous seed layer, which also result in some dislocation combination and/or annihilation.



(a) (b)

Fig. 4. (a) GaN film grown by PAMBE on a porous GaN seed layer marked by an arrow. (b) GaN film grown by MOCVD on a porous GaN seed layer. The overgrown layer contains 5-10× less dislocations.

4 Conclusions

We have evaluated the effect of using porous SiC and GaN templates for GaN overgrowth by PAMBE and MOCVD. For PAMBE growth of GaN on porous SiC we observe qualitatively a reduction in the density of threading dislocations originating at the GaN/SiC interface, since misfit dislocations produced at the interface can either terminate at the pores or bend into laterally grown GaN over the pores [Figs. 1(b) and 3(b)]. Lateral growth of the GaN is found over large surface pores. We also find that the GaN films are more strain relaxed than those grown on non-porous substrates, by the mechanism shown in Fig. 1(d). The PAMBE growth of GaN on a porous GaN seed layer produces no dislocation reduction. MOCVD growth of GaN on porous GaN substrates can, however, bring forth a notable (5-10×) reduction in defect density via a lateral dislocation bending mechanism similar to that depicted in Fig. 1(b).

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