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Nanoheteroepitaxy of GaN on a nanopore array of Si(111) surface

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Abstract

Nanoheteroepitaxial (NHE) growth of GaN using AlN/AlGaN as a graded buffer layer by metalorganic chemical vapor deposition has been demonstrated on the nanoporous patterned Si(111) substrates. The nanopore array on Si(111) has been fabricated by using anodized aluminum oxide membrane as an induced couple plasma dry etching mask. The reduction of the threading dislocation density and relaxation of the tensile stress in NHE GaN are revealed by transmission electron microscopy (TEM), micro-Raman spectrum and photoluminescence spectrum, respectively. Cross-sectional TEM analysis shows that dislocations nucleated at the interface are forced to bend into (0001) basal plane. Red shift in the E_2 (TO) phonon peak of micro-Raman spectrum indicates the relaxation of tensile stress in the nanoheteroepitaxial lateral overgrowth of GaN. A single step ELO without mask on nanopatterned Si(111) substrates is a simple and promising way for the improvement of the quality of GaN on Si substrates.

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1. Introduction

GaN-on-Si has been considered as a promising system and a platform technology for semiconductor devices applications. Combining the advantageous optoelectronic properties of GaN and the advantages of Si substrates, such as low cost, very large wafer size and good thermal conductivity, GaN devices can be readily integrated into Si-based circuits. GaN grown on Si substrates has been intensively studied, and GaN devices have been demonstrated on Si substrates including light emitting diodes (LEDs), UV detectors and high electron mobility transistors (HEMTs) [1–3]. However, due to the large mismatch in lattice constant and thermal expansion coefficient, GaN grown on Si are highly defective, compared to that on sapphire or SiC. Cracks along $(11\bar{1}00)$ due to high tensile stress in the film and a high density of threading dislocations around 10^{10} cm^{-2} highly deteriorate the performance of GaN-based devices [4]. For the commercialization of GaN-based devices on Si, many efforts have been made to acquire crack free and low defect density GaN. The low-temperature AlN interlayer [5], buffer engineering [6] and Si δ-doping technique [7] have been reported to reduce the dislocation density to $\sim 10^9$ cm^{-2} and stress being engineered to reduce the cracks. A further method for the reduction of the threading dislocation density has been demonstrated on sapphire by epitaxial lateral overgrowth (ELO) to $\sim 10^6$ cm^{-2} [8]. However, the patterning in conventional ELO is on the scale of micrometer and a very thick film has to be grown on the patterned template to obtain a continuous GaN layer after coalescence.

Theoretical study shows that nanoscale ELO growth will be an effective way to achieve low defect density and low residual stress due to three-dimensional stress relief mechanisms in the nanoscale growth [9,10]. GaN on nano-SOI [11], porous Si [12] and structured Si [13] have been attempted.

In this paper, we have demonstrated the NHE overgrowth of GaN on nanoporous Si substrate using graded AlN/AlGaN buffer layers. The NHE GaN nucleated on the Si(111) nanocrystallite surfaces coalesced to form truncated pyramids during intermediate growth stage, leaving behind nanoscale air bridges at the interface of the film and substrate. The reduction of the threading dislocation density and relaxation of the tensile

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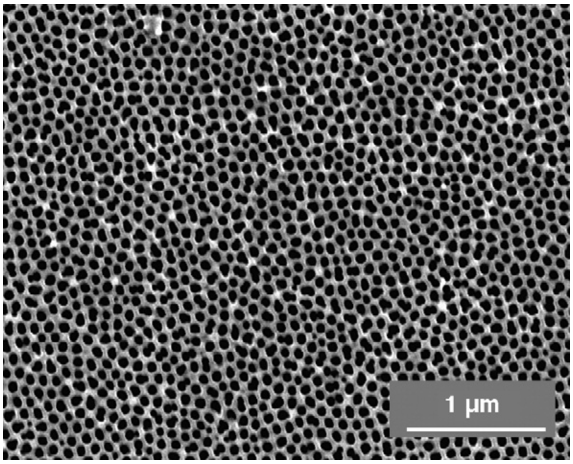

Fig. 1. SEM image of the nanopore arrays on the Si(111) surface.

stress in ELO GaN are revealed by transmission electron microscopy (TEM) and micro-Raman spectrum, respectively. The extent of stress relaxation and the reduction of the dislocation density by NHE approach are discussed based on the results obtained from optical spectroscopy and TEM.

2. Experimental

A 1-μm aluminum layer was deposited on Si substrate by electron beam evaporator. The alumina films were anodized at 3 °C in 0.3 M oxalic acid and subsequently subjected to wet treatment (with 5 wt.% H_3PO_4 for 60 min) to widen the pore size. This procedure allows fabrication of nanopores with high reproducibility and uniformity due to good adhesion of the template to the substrate. CF_4-based inductively coupled plasma (ICP) etching conditions are employed to duplicate the nanopores of AAO template onto the Si substrates as shown as Fig. 1. The etching depth in Si(111) was around 160 nm. GaN overgrowth was then carried out on the nanoporous Si substrates by MOCVD at 1010 °C. The MOCVD was carried out in EMCORE-D125 system. Trimethylgallium (TMGa), trimethylaluminium (TMAl) and ammonia were used as source materials for Ga, Al and N, respectively. Hydrogen was used as the carrier gas. A 30 nm AlN was firstly grown on the nanoporous substrates to prevent the direct reaction of Ga with Si, followed by the growth of a 70 nm AlGaN as the buffer layer. Subsequently, nanoheteroepitaxial growth of GaN was carried out. The flow rates of TMGa and ammonia are 50 sccm and 12 slm, respectively. The reactor pressure was maintained at 200 torr for GaN over-growth. The samples were characterized by field emission scanning electron microscopy (JEOL 6700FESEM) and cross-sectional transmission electron microscopy (Philips CM300 FEG TEM). The optical properties of NHE GaN were examined by room temperature micro-photoluminescence measurement. The Raman spectra from the samples under 514.5 nm excitation were recorded using a JY-T64000 micro-Raman system under the $z(x\_)\bar{z}$ backscattering configuration with the scattering light parallel to the *c*-axis of GaN films. The laser light was focused to a 1.0-μm spot size on the sample surface. The spectral resolution of the micro-Raman set up is 0.2 cm^{-1}.

3. Results and discussion

Fig. 1 shows the SEM image of the nanopore arrays which are patterned on Si(111) after CF_4 ICP etching using AAO template as a mask and after removal of the AAO template. The diameter of the pores is around 60 nm with an interpore distance of about 110 nm, which is almost the same dimension as in the original AAO template. AAO produced with ordered nanopores with a narrow distribution of tunable diameter pores ranging from ~10 to 500 nm is a promising template for nanofabrication, such as nanopores, nanodots and nanopillar arrays. This nanopatterning method is a good alternative to lithographic techniques because it is simple and inexpensive and can be employed to pattern large substrate areas.

Fig. 2a presents a SEM cross-sectional image of the nanoheteroepitaxial GaN sample. It can be seen that there was no nucleation of GaN inside the pores of the Si. Deposition selectively occurred on the top surfaces of porous Si, and then the growth proceeded laterally and vertically. We can see nanoscale air-bridges at the top surface of the Si interface. It might be due to the combining of the high aspect ratio and the nanosized pores in our case. Fig. 2b shows the plan-view SEM of the NHE GaN on nanoporous Si substrates. The top view of NHE GaN truncated pyramids is observed from the images. The white contrast in the image is the side facet of the GaN pyramids, indicated as arrows. A schematic growth mode of the NHE GaN on nanoporous Si is

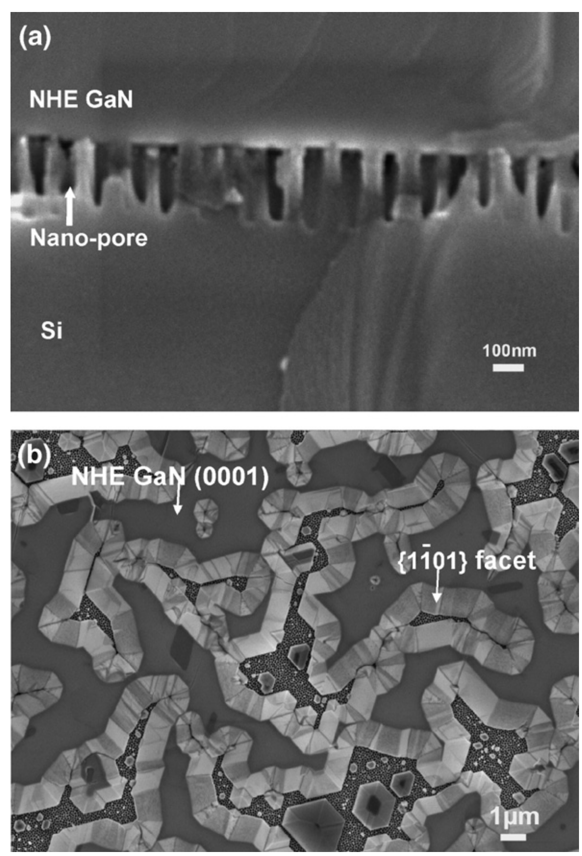

Fig. 2. (a) Cross-sectional SEM image of NHE-GaN on nanopatterned porous Si (111); (b) top-view SEM image of NHE-GaN on nanopatterned porous Si(111).