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Beyond 10 μm Thick Crack-Free GaN Growth on Si for High Power Device Applications

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Abstract

We demonstrated beyond 10 μm thick crack-free GaN growth on Si substrate using selective area growth technique. Systematic characterization by scanning electron and optical microscopy on the grown samples revealed that cracks nucleate and propagate on $\{1\bar{1}00\}$ planes in $[1\bar{2}10]$ directions. By developing $\{1\bar{1}01\}$ facet planes in selective area growth, thermal mismatch strain relief at facet surfaces eliminate cracking and enable over 10 μm thick crack-free GaN growth on Si. These grown structures exhibited high crystalline quality throughout the thickness of the structure as validated by selective area diffraction in high resolution transmission electron microscopy, with a dislocation density of 2-3 x 10^8 cm^{-2} at the GaN surface.

1. Introduction

GaN holds a great potential for next generation efficient high power devices due to a number of attributes including the large bandgap which can support high breakdown fields and small thermally generated leakage currents, and high carier density and mobility/saturation velocity which provide low on-resistance. However, due to the relatively high cost of bulk GaN and the lack of appropriate substrate for its monolithic integration, the full potential of GaN for commercial applications is yet to be realized. One approach that has potential for a disruptive high power GaN technology is its growth on cheap and technologically well-developed substrates such as Si. However, the growth of thick GaN layers on Si is hindered by the thermal (and lattice) mismatch which results in generating cracks in the GaN layer for thicknesses exceeding ~3 μm[1] and using well-optimized AlGaN transition layers[2,3].

In this work, we analyzed the selective area growth (SAG) of GaN on Si and performed mechanistic studies to understand cracking associated with thermal stresses and created structures to accommodate them in order to grow over 10 μm thick crack-free GaN on Si.

2. Experiments

SAG GaN samples were prepared by depositing and patterning 200nm SiO_2 on top of a GaN on a Si template substrate which consists of a high quality 500nm GaN thin layer followed by AlGaN and AlN buffer layers atop. The

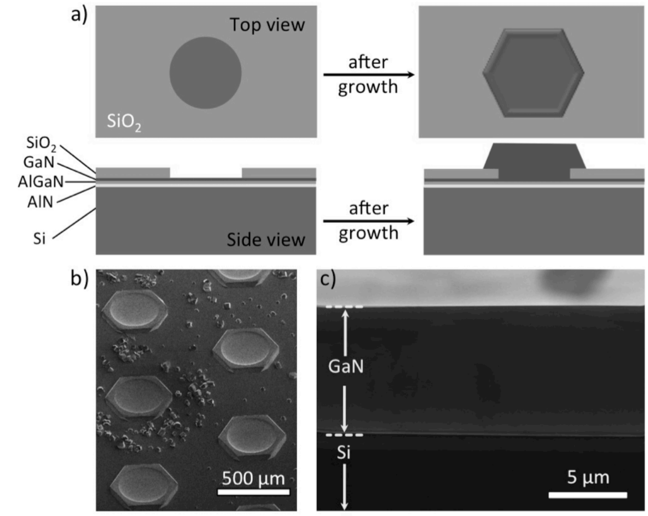

Fig. 1 (a) Schematic structure and process for the growth of SAG GaN on Si. (b) 45° angle-view SEM image for the grown crack-free GaN structures on Si with mask opening diameter of 450 μm and edge-to-edge spacing of 450 μm. The edge height is 32 μm and the center height is 12 μm. (c) Cross-sectional SEM view of 9μm thick crack-free GaN layer on Si.

SAG growth pattern was a 5x5 hexagonal array of SiO_2 circular openings with the diameters of 450 μm with edge-to-edge spacing of 450 μm. SAG GaN was grown in the circular openings by metal organic chemical vapor deposition (MOCVD) with different times from 1hour to 3 hours. Fig. 1a shows top and side view schematics before (left) and after (right) growth and Fig. 1b shows 45° scanning electron microscopy image (SEM) of representative grown sample with > 12μm thick crack-free GaN on Si. Fig. 1c shows a cross-sectional SEM view of 9μm thick GaN layer on Si.

3. Results

The 3 hour grown sample was characterized by High resolution transmission electron microscopy (HRTEM). Fig. 2a shows a top-view SEM image of the 3 hours grown sample subject of HRTEM. Fig. 2b shows the focused ion beam (FIB)-cut sample that underwent additional thinning into 100nm thick GaN on Si lamellas. The thickness of the GaN was over 10 μm as evident from Fig. 2b. There were no surface (Fig. 2a) or buried (Fig. 2b) cracks in the GaN on Si. The selective area diffraction (SAD) pattern was taken in in 1-2 μm steps from bottom (interface with Si) to top (free GaN surface) of the structure and displayed well resolved SAD spots without indications of polycrystalline grains or stacking faults. TEM analysis in dark and bright fields yielded a dislocation density count of 2-3 x10^8 cm^{-2} at the GaN surface, comparable to and lower than the density of threading dislocation in highly efficient GaN light emitting diodes on sapphire[4].

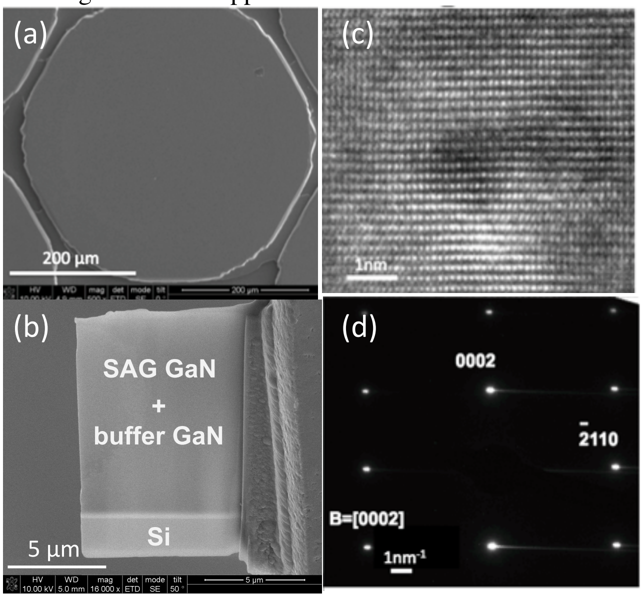

Fig. 2 (a) Top-view SEM image of a single dot with diameter of 450 μm and thickness of 10 μm obtained in SAG on Si with flat surface. (b) Cross section SEM image of the sample on a TEM grid. (c) HRTEM image of the GaN crystal and (d) its SAD pattern at 5 μm distance away from the Si interface.

Our analysis point to an intriguing behavior in GaN thermally induced cracking that can be avoided with appropriate crystallographic engineering of the growth patterns in SAG. Our time-dependent growth studies also sheds light on the growth and cracking behavior. Fig. 2a and Fig. 2b show optical microscope images for 1 hour growth (sample A) and 2.5 hours growth (sample B) samples whose corresponding thicknesses were 5 μm and 15 μm at the center of the structures, respectively. Interestingly, even though the thickness of sample B is much thicker than sample A, no crack was generated in sample B while sample A has some cracks initiated on $\{1\bar{1}00\}$ planes and propagating in $[1\bar{2}10]$ directions. From these observation, we hypothesized that grown structures that have $\{1\bar{1}01\}$ facets can share dislocation Burgers vectors with $\{1\bar{1}00\}$ planes and therefore relieve the thermal stresses by dilating the free $\{1\bar{1}01\}$ surface in the $[1\bar{2}10]$ directions. As Fig. 2a and Fig.2b show, sample B has shaper and well developed facet planes which help relieving the thermal stresses and enable to grow crack-free thick GaN film on Si.

4. Conclusions

We demonstrated the growth of thick crack-free GaN on Si where the maximum thickness was 15 μm at the center of the dot. The HRTEM image verified high crystalline quality of the grown layer and the dislocation density of 2-3x10^8 cm^{-2} at the GaN surface was achieved by the stress reduction due to selective area growth with well developed $\{1\bar{1}01\}$ facets. Time dependent growth result showing cracks in non-faceted structure and no-crack in well faceted structure validated our hypothesis. The 10 μm thick GaN on Si has potential to have very high breakdown voltages in excess of 1kV which paves the way for monolithically integrated efficient high power GaN devices on Si. We will report fabrication and brekadown voltage characterization of Schottky and p-n junction diodes on these thick GaN on Si structures..

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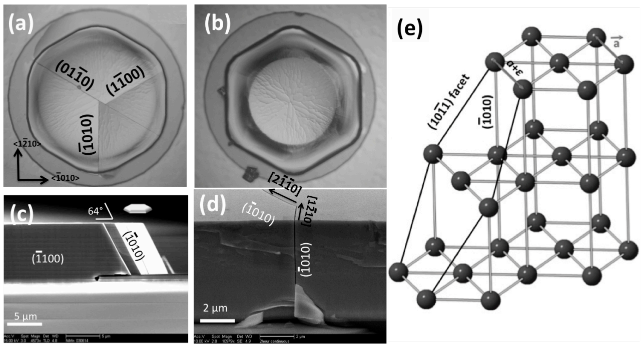

Fig. 3 (a) Optical microscope image of sample A showing cracked GaN grown on Si and (b) sample B having no crack in GaN. The facet planes are $\{1\bar{1}01\}$ type with free surfaces in (b) and (c) help relieve the stress by dilating in the $[1\bar{2}10]$ directions, which is the direction in which the cracks generated on $\{1\bar{1}00\}$ planes propagate as verified in the cross-section SEM image in (d).

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