Good Repeatability of AlGaN/GaN HEMT on 4” Si Substrate by 5x4” Multi-Wafer Production MOCVD System

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Abstract

This paper presents crack-free AlGaN/GaN heterostructures grown on 4 inch Si(111) by the production scale 5x4” (19x2”) multi-wafer Thomas Swan MOCVD system that was once used for GaN-based LEDs and purchased in 2009. The two dimensional electron gas is formed at the AlGaN/GaN interface with average Hall mobility values more than 2100 cm^2/v·s and sheet resistance less than 400 Ohm/☐. Optimized in-situ baking process was used to insure the RtR repeatability. Run to run repeatability of AlGaN/GaN structural qualities, the trace of *in situ* optical reflectivity, wafer bow, and 2DEG properties show the potential manufacturing possibility with the epitaxial process stability for MOCVD systems which were once used for LEDs production but no longer cost-effective now. The result is meaningful for LED fabs to utilize the obsoleted MOCVD systems.

INTRODUCTION

AlGaN/GaN HEMT on Si have emerged as a promising solution for high frequency power amplification and high voltage power switching applications, as they can utilize the production lines in a CMOS fab and the availability of low cost Si substrates in larger diameters comparing to SiC and GaN substrates. Encouraged by the recent device performance results achieved for AlGaN/GaN HEMT on Si aided by the advancement of high quality crack-free GaN growth on large substrates, the power electronics industry is currently engaged in pilot production of those devices. With the large mismatch of lattice constant and thermal expansion coefficients between Si and GaN, GaN epitaxy on Si leads to problems such as cracks, high-density misfit and threading dislocations. Many techniques have been utilized to relieve this stress and create crack-free GaN, such as using a low-temperature AlN layer [1], graded AlGaN buffer layers [2-3], AlN/GaN superlattices [4], and a SiN interlayer [5]. In addition, large wafer bow caused by the compressive stress from GaN during growth hinders the uniform temperature control across the wafer, which results in the non-uniform composition/thickness, layer stress and device performance. With the growth challenges of heteroepitaxy of GaN on Si, device quality GaN and its manufacturability have to be demonstrated for the potential mass production of AlGaN HEMTs on Si. We have tested repeated runs of GaN/Si and HEMT on 4” Si (111) substrates to confirm the repeatability and stability in large scale production MOCVD. Run to run repeatability of AlGaN/GaN structural qualities, wafer bow, and 2DEG properties show the potential manufacturing possibility with the epitaxial process stability.

EXPERIMENT

The epitaxy process is carried out in 5x4” and 19x2” multi-wafer Thomas Swan Close Coupled Showerhead production MOCVD systems that were purchased in 2009 and once used for GaN-based LEDs production. Trimethylgallium, trimethylaluminium, and ammonia were used as precursors for gallium, aluminum, and nitrogen, respectively. Hydrogen was used as the carrier gas. The Si wafer was first annealed at 1050 °C under hydrogen ambient for about 5 minutes to remove native oxide from the surface, which was followed by the pre-flow of TMAl without the presence of ammonia. First 15-30 nm low temperature AlN buffer layer was grown at 1000 °C. Then a high temperature AlN nucleation layer with the thickness of about 150 nm was grown, and followed by a single layer of low Al composition $Al_xGa_{1-x}N$ buffer layers with the content of about 25%. The thickness of the AlxGa1-xN interlayer was 300 nm. The growth conditions for AlN and AlGaN buffer layer were above 1000 °C at a pressure of 75–100 Torr. A high resistance GaN buffer layer with self-Carbon doped, about 2-3 µm, was grown on top of the AlxGa1-xN interlayer. About 300 nm thick high quality GaN channel layer was overgrown on a high resistance

GaN buffer. The unintentionally doped $Al_{0.25}Ga_{0.75}N$ barrier layer is grown with a GaN cap in order to protect the AlGaN surface morphology. A 1 nm thick AlN spacer was inserted between the AlGaN barrier and GaN to improve the performance of the 2DEG. Three repeat runs, named sample A, B, C, were carried out in one day without any interruption except in-situ baking to clean the showerhead and carrier at high temperature in H2 atmosphere. The in-situ baking process was optimized to insure the RtR repeatability. By using 625 µm thick Si (111) substrates, we could easily achieve crack-free epilayers with total nitride stack thickness 3.0±0.1 µm, and with a significantly reduced wafer bowing <30 µm.

The crystalline quality of GaN layer was performed by HRXRD for (002) symmetrical and (102) asymmetrical Bragg reflections. The thickness of epilayers was measured by the trace of in situ optical reflectivity with monitoring wavelength of 950 nm during the sample growth which is shown in Fig.1 and Al composition by photoluminescence and HRXRD. The surface morphology of the AlGaN HEMT barrier was studied by AFM, and the electrical properties of the 2DEG were evaluated by Van der Pauw-Hall measurement using Ti/Al/Ti/Au as the ohmic contact with rapid thermal annealing at 850 °C for about 3 min.

Fig. 1. shows the trace of in situ optical reflectivity with monitoring wavelength of 950 nm during the sample growth. AlN, AlGaN, and GaN growths exhibit different oscillation periods in the figure due to their reflectivity differences at different growth conditions. Nearly no damping of the oscillation amplitude with increase of the nitride layer thickness indicates a good crystal quality.

Fig. 2. shows the optical microscope images of the sample with smooth surface morphology and free of cracks except only 2 mm of the edge which is acceptable. The corresponding AFM image presents atomic-step terraces, as shown in Fig. 3. The root mean square roughness is 0.24 nm in a scanned area of 5×5 μm^2, which indicates that the surface of the GaN layer is very smooth.

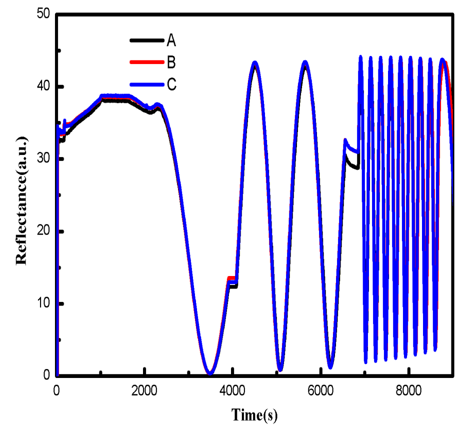

Fig. 1. The *in-situ* 950 nm-optical reflectivity of the growth process.

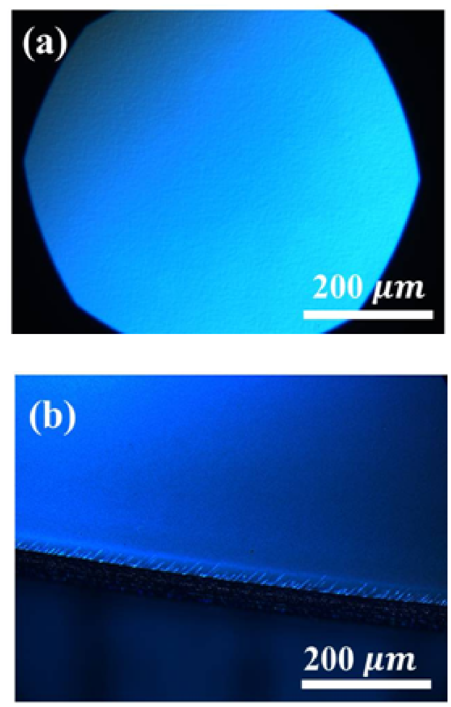

Fig. 2. Optical microscope images of the as-grown heterostructure: (a) middle; (b) edge.

TEM were carried out across sample to further reveal the mechanisms of stress relaxation and their relationships with dislocation inclination. From Fig. 4, we can see that the dislocations begin to incline abruptly at the interface between the AlN layer and AlGaN layer. The edge dislocations incline to project onto the (0001) growth plane along <100>lines, which lie perpendicular to the b¼ a Burgers vector of the dislocations. The projected length of the inclined dislocation acts as a misfit-dislocation segment to relax the compressive strain. The inclination of these dislocations is associated with the compressive stress induced by the lattice mismatch between AlN and AlGaN layers. From the TEM images, we can see clearly that large bend angles enhance the probability of dislocations to encounter and react with other ones. Dislocation annihilation indeed occurs with the aid of dislocation reaction [6].

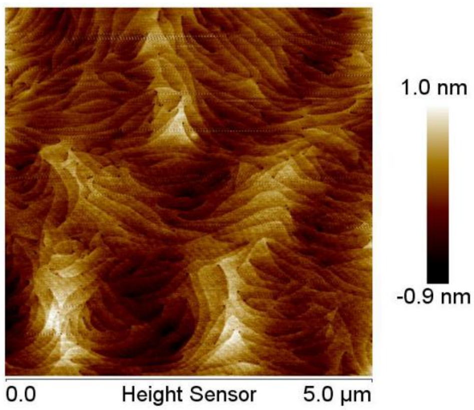

Fig. 3. AFM image of the GaN layer (5×5 µm^2).

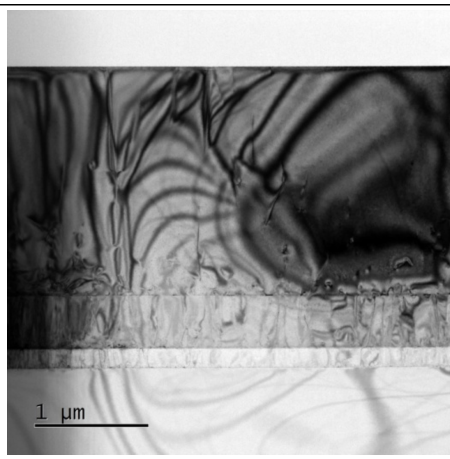

Fig. 4. Cross-sectional TEM images of the AlGaN/GaN heterostructure on 4-inch Si (111) substrate.

The full widths of half maximum of the XRD rocking curve symmetric (002) and asymmetric (102) ω-scans in the GaN layer are 541 arcsec and 667 arcsec, respectively shows in Fig.5. XRD FWHM average values for (002) and (102) planes are less than 500” and 1000” for sample A, B, C respectively for GaN layers with highly auto Carbon doped with < 2% in 1σ (within measurement limit), respectively.

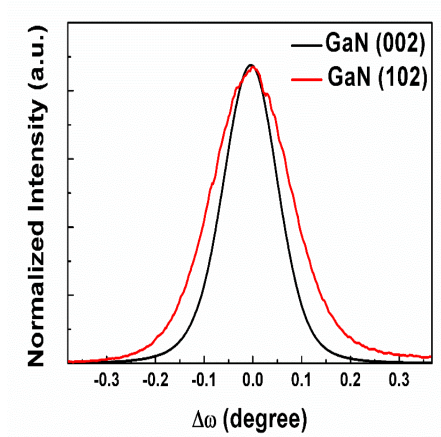

Fig. 5. HRXRD rocking curves of (002) and (102).

Hall measurements were conducted at room temperature on three samples taken from wafer edge to wafer middle by using Van der Pauw configuration. HEMT samples with 25 nm $Al_{0.25}Ga_{0.75}N$ barriers exhibit an average 2DEG mobility greater than 2100 cm^2/ v·s. The two-dimensional electron gas mobility of the sample is in the range of 2110 to 2140 cm^2/ v·s. with the sheet carrier concentrations higher than 8.0x10^{12} cm^{-2} and the sheet resistance less than 400 Ohm/□. The post growth wafer bow at room temperature is consistently less than 30µm, for ~3µm stacks. The sheet resistance across the wafer is as low as 356± 7Ω/□, and thus the uniformity value is 2.0%. The high electron mobility and low sheet resistance indicate the high quality of the AlGaN/GaN heterostructures. The AlGaN/GaN HEMT fabricated with a gate-to-source distance, gate-to-drain distance and gate length of $L_{GS}/L_{GD}/L_G$=1.5 µm/3 µm/1.5 µm delivers excellent DC characteristics with a maximum drain current density (I_{Dmax}) of 490 mA/mm, which further suggests the high quality of the material.

CONCLUSIONS

In summary, we report here the repeated growths of crack-free AlGaN/GaN HEMT on 4” silicon by large scale production MOCVD using a single AlGaN layer with low Al composition. Optimized in-situ baking conditions were used to insure the RtR repeatability. By balancing the compressive stress induced and consumed during the growth, and the thermal tensile stress induced during the cooling down process, the GaN layers are nearly strain-free with a lower wafer bow. Upon the GaN epi layers, high uniformity and high quality AlGaN/GaN hetero-structures with a low sheet resistance of 356 ± 7Ω/□ (±2% variation) have been obtained. The HEMT runs show good run-to-run repeatability, demonstrating the potential manufacturing possibility for MOCVD systems which were used for LEDs fab but no longer cost-effective now. The result is meaningful for LED fabs to utilize the obsoleted MOCVD systems.

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Acronyms

HEMT: high electron mobility transistor
MOCVD: metal organic chemical vapor deposition
AFM: atomic force microscope
TEM: transmission electron microscope
HRXRD: high resolution X-Ray Diffraction
2DEG: two-dimensional electron gas
RtR: run to run