Advances in Homoepitaxial GaN grown by MOCVD for Vertical Electronic Devices

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Abstract

Homoepitaxial GaN growth using a production scale MOCVD reactor has been demonstrated. The epitaxial GaN threading dislocation density was very close to that of the different free-standing GaN substrates and uniform across large diameters. Incorporation of impurities to the low levels required for vertical electron drift layers was achieved by employing appropriate growth process conditions. Different surface analysis studies revealed near-perfect step flow growth over large areas of the wafers.

INTRODUCTION

Wide-bandgap semiconductors such as SiC, GaN, and Ga_2O_3 are promising candidates for high power and high frequency electronic applications. GaN with its increasing availability, quality, and acceptance in industry is an important semiconductor for new vertical electronic devices, which can have significant advantages over current lateral devices [1]. Those benefits include: 1) higher breakdown voltages, 2) much smaller chip sizes with respect to system performance, 3) better thermal management, 4) superior reliability, as the device surface does not need to endure peak electric fields. Several new vertical GaN device concepts, such as advanced MIS Schottky barrier diodes or vertical fin MOSFETs, do not require p-doping [2]. These avoid the technical difficulties of reduced breakdown voltage or low carrier mobilities, along with additional processes such as GaN regrowth or Mg ion implantation.

This work focuses on achieving high crystal quality of epitaxial GaN for applications in vertical electronic devices using a multi-wafer, production scale MOCVD reactor. The GaN growth initiation, defect incorporation, electrical properties, structural quality, and surface morphologies of GaN epilayers were analyzed using different characterization techniques.

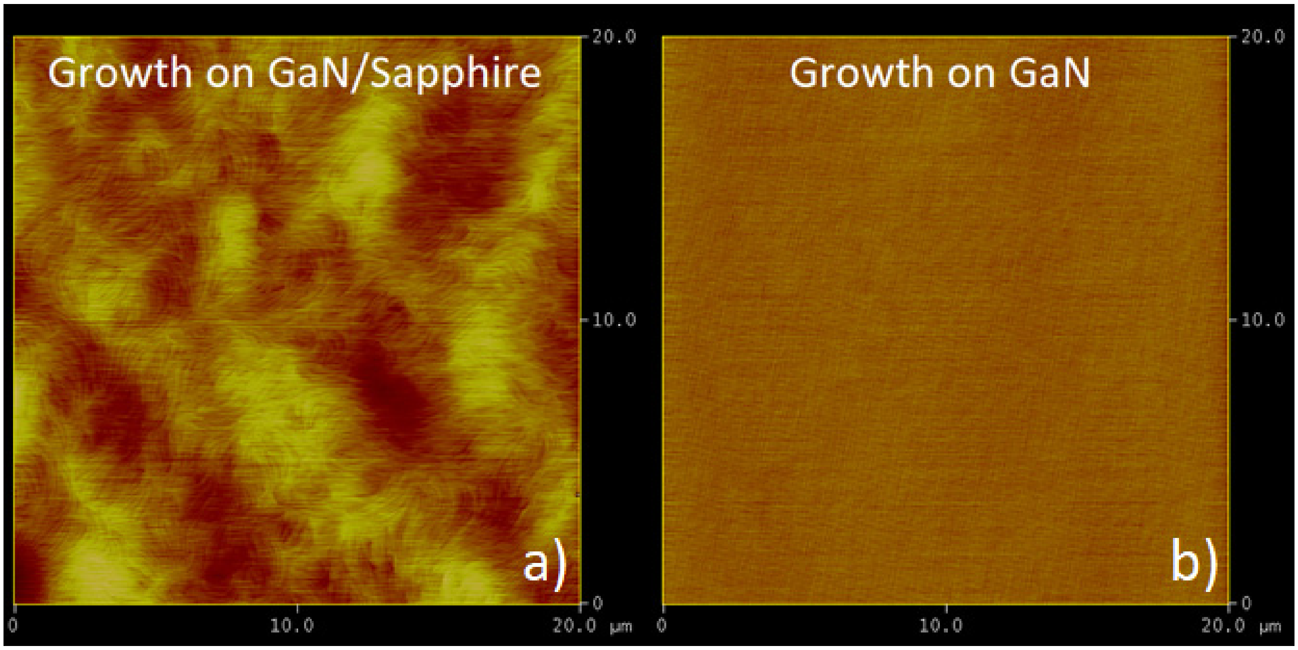

Fig. 1. (20 x 20) µm AFM images of a GaN epi layer stack grown on 100 mm a) GaN/sapphire template vs. b) free-standing GaN substrate (from the same production run): Image Z range is a) 22.0 nm vs. b) 2.3 nm; RMS roughness is a) 0.74 nm vs. b) 0.19 nm, respectively.

EXPERIMENTAL

GaN layers between 1 µm and 16 µm total thickness were simultaneously grown on GaN/sapphire templates and on commercially available free-standing GaN substrates of either 2- or 4-inch diameter. The GaN/sapphire templates for the companion wafers were produced at IQE via MOCVD.

Trimethyl-gallium (TMG) and ammonia (NH_3) were used as the Ga and N precursor, respectively. Disilane (Si_2H_6) was used for intentional doping of parts of the structures. Both N_2 and H_2 were used as a carrier gas for the growth and for the in-situ surface preparation of the GaN substrates.

The surface morphology of the GaN wafers was studied using AFM in tapping mode: i) prior to epitaxy, ii) after in-situ annealing, and iii) post-epitaxy. Figure 1 shows typical (20 x 20) µm scans of the post-epitaxy GaN surface. The RMS surface roughness of GaN on a) GaN/sapphire template and b) free-standing GaN substrate was 0.74 nm and 0.19 nm, respectively. The latter is close to the theoretical limit for the observed 2D step-flow growth morphology. The quality of commercially available GaN substrates is continually improving. Today, excellent 2-inch GaN substrates are available, 4-inch GaN substrates typically exhibit macro defects such as pits or inclusions, where a subset of these defects can have an impact on usable wafer area. A sample image of a 100 mm GaN wafer after thick homo-epitaxy is given in Figure 2.

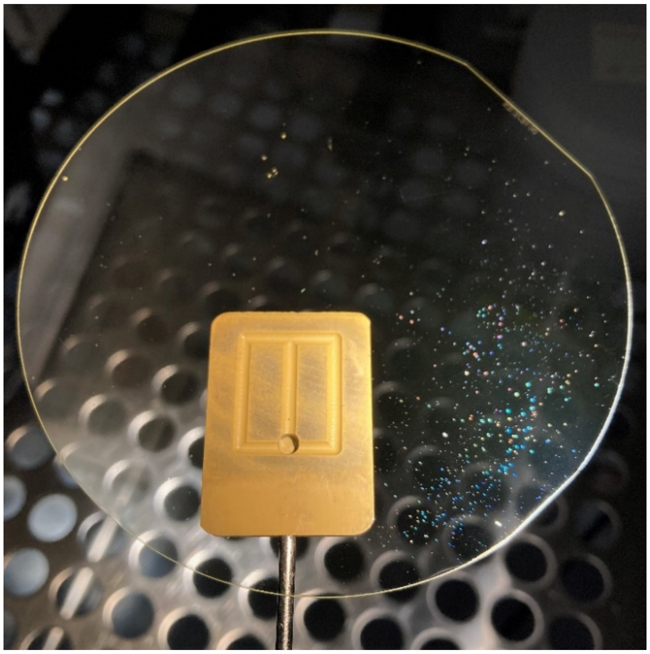

Fig. *2*. Photo of a 100 mm GaN wafer after a 13 um thick GaN homoepitaxial growth run.

The flatness of a 4-inch homoepitaxial GaN wafer was analyzed using a standard capacitance-based contactless wafer measurement tool. The wafer bow and warp were measured to be 22.7 µm and 28.7 µm, respectively, which is consistent with typical flatness requirements for device fabrication [4].

Since there is no substantial refractive index contrast between the GaN substrate and the epitaxial film, traditional growth rate metrology tools relying on interferometry cannot be used for thickness measurements.

Figure 3 shows cross sectional SEM of companion wafers grown on GaN/sapphire templates that was used to analyze the thickness and structural uniformity of the GaN layers grown under different conditions. This was correlated with white-light thickness measurements of the GaN/sapphire template before and after the run and SIMS measurements from selected samples. The total GaN thickness (epitaxial and template) of this sample is measured to be 16.3 um, which is in excellent agreement with a simple optical ex-situ Fabry-Perot interference measurement of the epi-stack. In the SEM scan, the GaN/GaN overgrowth interface cannot be identified, which should be at around 5 um distance from the GaN/sapphire interface of the initial template growth. This finding is expected for an optimized GaN surface preparation before initiating the GaN overgrowth.

Before/after wafer weight measurement for the GaN on GaN growths was also evaluated. The expected weight change for a 100 mm GaN/GaN product wafer with a 10 um thick GaN homoepi would be approximately 0.5 g, corresponding to a wafer weight change of around 2%. This was confirmed and tested as a production control technique for high wafer volumes.

The GaN epiwafers were measured using HRXRD, revealing rocking curve FWHM values around 60 arcsec for the (002) and as low as 40 arcsec for the (102) peak of the epitaxial GaN layers. A typical example of a rocking curve scan is shown in Figure 4.

This was found to be slightly narrower than the pre-epi substrate peak width in some cases. The total threading dislocation density of the GaN films can be estimated to be around $1 \cdot 10^6$ cm^{-2}, which is mostly dependent on the quality of the GaN substrate used [3].

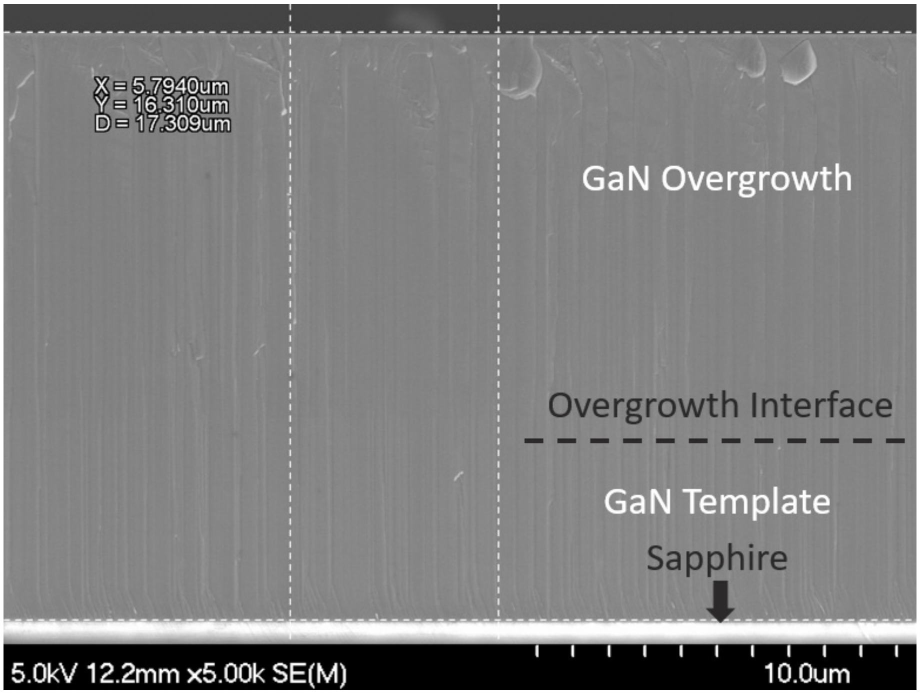

Fig. 3. Cross-sectional SEM image of a companion wafer grown on a GaN/sapphire template, total GaN epi thickness is 16.3 µm (including template). This measurement determines the growth rate for different conditions during epitaxy and helps improve overall wafer uniformity.

The unintentional incorporation of chemical impurities was investigated using high-precision SIMS analysis, carried out by Eurofins EAG Laboratory. When optimized growth conditions are used, the defect levels of unintentional C and O for the electron drift layer could be limited to concentrations in the mid 10^{15} cm^{-3} and low 10^{15} cm^{-3} range, respectively [5]. This is consistent with the requirements on ionized impurity background in the low 10^{16} cm^{-3} range or below, to ensure proper control of the electric field in the drift layer. This limits the ionized impurity scattering and enables free electron mobility of 1000 cm^2/Vs and above for carrier transport in direction of the c-axis.

For the growth of thick drift layers, it is important to optimize the incorporation of impurities and various defects along with the best stability for the overall wafer structure. Especially the balance of O, Si, and C_N impurities along with structural and native GaN defects may contribute to variations in the volume free carrier concentration, following the principle of charge balance. This is especially important to control for GaN drift layers, which often require a free electron concentration around $1 \cdot 10^{16}$ cm^{-3} for the first-generation of vertical GaN power devices.

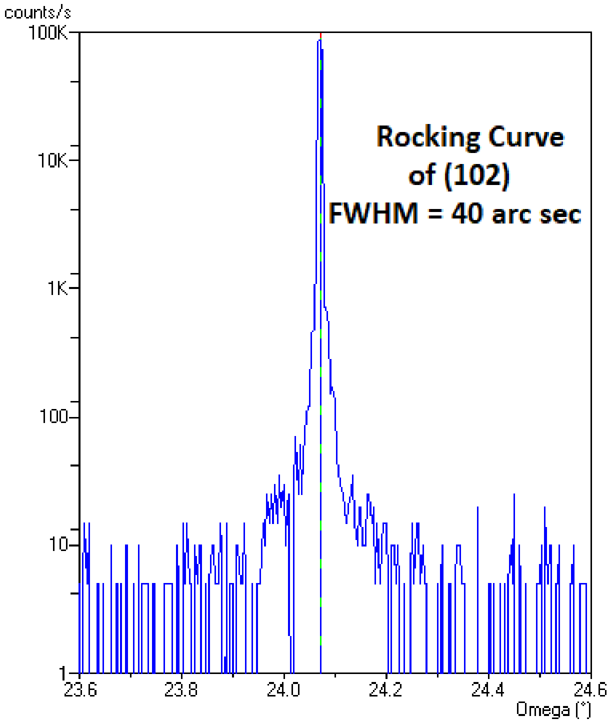

Fig. 4. Rocking curve scan of the (102) peak of a typical GaN homoepitaxial film. The high structural quality of the epi film typically matches the substrate.

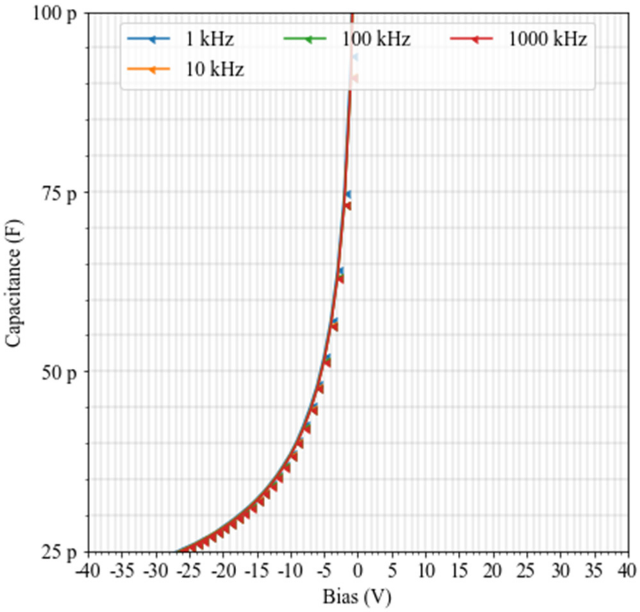

Fig. 5. Capacitance-Voltage measurement at different frequency settings.

Capacitance-voltage profiling was used to probe the effective carrier concentration in the electron drift layer. The C(V) dependence is shown in Figure 5. A near constant slope of $1/C^2$ vs V was observed. As shown in Figure 6, the calculated free carrier concentration vs depth was near flat over the entire range of applied voltages and the probed region of the GaN drift layer. Such profiles are critical for successful drift layer incorporation in vertical GaN devices.

By applying a similar methodology, it was shown that intentional n-doping could be controlled in a range between low 10^{16} cm^{-3} to low 10^{19} cm^{-3} for specific layers of the different homoepitaxial structures.

CONCLUSION

Homoepitaxial growth on free-standing GaN substrates was carried out using production scale MOCVD reactors. High crystalline quality and low defect incorporation into the electron drift layers were demonstrated. The realized capability, in conjunction with anticipated improvements in GaN substrate quality, represents a key step for future volume production of vertical GaN devices.

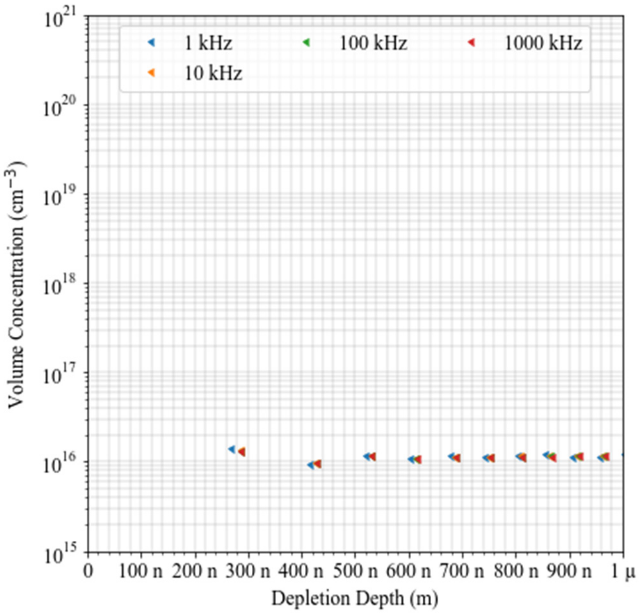

Fig. 6. Free electron volume concentration in an optimized GaN drift layer as derived from C-V measurements.

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ACRONYMS

MOCVD: Metal-Organic Chemical Vapor Deposition
MIS: Metal Insulator Semiconductor
MOSFET: Metal Oxide Semiconductor Field Effect Transistor
HRXRD: High-Resolution X-ray Diffraction
FWHM: Full Width at Half Maximum
AFM: Atomic Force Microscopy
SIMS: Secondary Ion Mass Spectroscopy
SEM: Scanning Electron Microscopy
RMS: Root Mean Square