Orientation Control of Bulk GaN Substrates Grown via Hydride Vapor Phase Epitaxy

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Abstract

The growth of GaN bulk crystals via the HVPE process and the manufacturing of orientation controlled substrates from the GaN crystals are presented. An HVPE process has been produced for growth of bulk GaN on sapphire with an AlN interfacial seed layer. This process has allowed for the production of GaN substrates up to 2 inches in diameter. Due to the stress associated with the growth of GaN on sapphire, orientation control can be problematic. However, a method for orientation control has been implemented that employs XRD for identification of the material orientation and a lapping procedure for correction. Using this method, substrate orientation can be controlled to within ±0.25 degrees of the desired off cut. After the substrates undergo orientation correction, a polishing process is used that employs both mechanical polishing and chemical mechanical polishing. The final polish has been shown to produce surfaces with roughness values less than 1 nm which is suitable for epitaxial growth.

INTRODUCTION

The wide band gap semiconductor GaN is a very attractive material for use in short wavelength laser diodes, high-brightness blue, green, and white LEDs, and high-power and high-frequency electronic applications due to its wide bandgap, high breakdown voltage, and high temperature capabilities. Bulk, single crystalline GaN substrates offer advantages over heteroepitaxial approaches for GaN-based devices; however, production processes for bulk GaN substrates of high quality are still in the early stages of volume production. In one aspect of manufacturing, repeatedly obtaining uniform substrate off-cuts and orientations is important in achieving a reliable production process. Kyma Technologies has developed a hydride vapor phase epitaxy (HVPE) growth process for the production of bulk GaN substrates. This process has enabled the growth of crystals for the production of c-plane substrates up to 2 inches in diameter. Following crystal growth, epi-ready surface preparation and substrate orientation control has required development of new wafering processes, including crystalline alignment measurements using X-ray diffraction and chemical mechanical polishing. Using this wafering process, substrates can be made with a variety of orientations including both polar and non-polar GaN. In this paper, we will describe the production challenges for manufacturing bulk GaN substrates and the control of their physical and geometric properties, focusing on the mis-cut angle and direction of c-plane substrates.

BULK GaN BY HVPE

A commercially viable process has been developed for the production of bulk GaN substrates using the HVPE process [1]. The HVPE process used at Kyma is carried out on sapphire with an AlN nucleation layer. The AlN layer is deposited using a physical vapor deposition process. A sapphire substrate of the desired off-cut is first coated with the AlN layer. The morphology of the nucleation layer consists of highly oriented, epitaxial columnar grains. The off-cut angle and orientation of the sapphire has a significant impact on the stress, microstructural properties, and defect formation in the GaN crystal and must be optimized for bulk crystal growth. GaN crystals up to 11mm in thickness have been demonstrated using this process. For c-plane substrates, GaN layers 1.5 – 2mm thick are typically grown, which self-separate from the sapphire upon cooling, yielding large area crystals for substrate processing.

There are many inherent challenges that must be addressed when it comes to the growth of bulk single crystal GaN. These include controlling the formation of macro defects or inclusions in the crystal during growth, reducing growth stress that occurs as a result of the evolution of the microstructure in the GaN, thermal expansion stress generated by mismatch between the GaN and sapphire, and prevention of poly-crystalline growth at the edge of the growing crystal. Doping of the GaN crystal for different applications also requires specific growth recipe optimization for different dopant and crystal conductivities.

Once the GaN crystal is formed, there are also challenges associated with wafering the crystal and achieving an epi-ready substrate. These problems include orientation correction, dicing, grinding and polishing to achieve wafers with a low surface roughness value as well as being as close to on-axis as possible. This paper will outline the HVPE growth process used and discuss the approaches for orientation correction of bulk GaN single wafers and the polishing process used to achieve final surface roughness values of less than 1nm.

ORIENTATION CORRECTION

When preparing substrates for epitaxial growth, it is desirable to control the surface off-cut angle, which is defined as the angle between the surface normal and the substrate basal plane lattice vector (in this case the c-plane), and the off-cut direction in order to obtain surfaces with the preferred properties for epitaxial growth. For GaN, there are several factors that can lead to the need to correct the orientation of the crystal. It is well known that stresses can develop during the growth of one crystal on a lattice mismatched seed crystal [2]. It is also known that there is a high amount of stress that develops during the growth of both AlN and GaN on sapphire [3]. Stress during the growth of the GaN layer can lead to bow of the underlying sapphire substrate and tilt of the crystal as it grows. Additionally, the free-standing GaN substrate requires planarization of the top and bottom surfaces. All these factors can result in the need to correct the orientation of the substrate surface relative to the crystal lattice. This is done using x-ray diffraction and a lapping procedure that can correct to within ±0.25 degrees of a desired orientation, usually measured relative to the (0001) axis for c-plane substrates.

The first step in the process is to lap the nitrogen face (backside) of the substrate to ensure a flat mounting surface for X-ray diffraction. Next, a series of X-ray measurements are performed using a Panalytical X'Pert X-ray diffractometer (XRD). Substrates are mounted in the diffractometer and a substrate alignment measurement program is run. Using omega and omega-two theta scans, the (0002) peak alignment is optimized. A phi scan is then performed and from this measurement, the maximum off-cut angle is determined. This off-cut angle is measured relative to the plane of the backside of the substrate. The off-cut orientation is measured relative to the <1$\underline{1}$00> direction of the substrate. Figure 1 shows an example of an XRD measurement where the maximum off-cut angle is determined.

Figure 1 shows omega peak values for the <0002> direction measured at various Phi angles. The off-cut of the wafer is then one half of the difference between the highest and lowest value along the sinusoidal curve. For example, the wafer from which the data in figure 1 was collected had an off cut of 0.45 degrees as grown and an off cut of 0.25 degrees after correction.

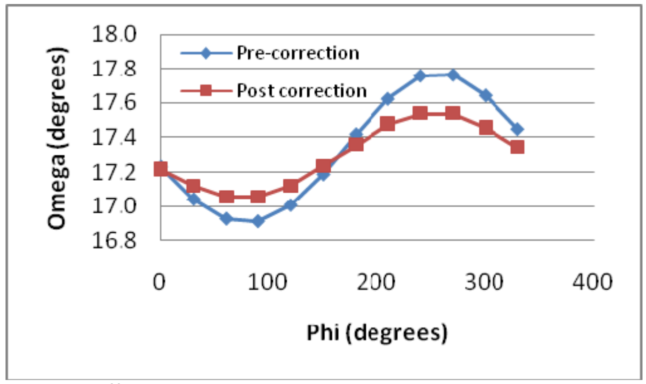

Figure 1: Off-cut calculation using XRD measurement

Once the orientation has been determined, the substrates are mounted on an adjustable fixture and lapped to on the gallium face (frontside) of the substrate. The lapping fixture is adjusted such that the substrate is lapped at a fixed angle to introduce or recover the specified angle for the frontside of the substrate, based on the XRD measurement. The substrate is then flipped over and the backside is lapped again to make it planar with the frontside. With the orientation corrected and the proper geometry achieved, the wafer is now ready for polishing. The current manufacturing practice requires individual measurement and correction of each substrate. Because of this, the process has been optimized to minimize the amount of time for each process step.

EPI-READY SURFACE PREPARATION

The surface of the wafer after lapping and orientation correction then undergoes a mechanical polish and finally a Chemical Mechanical Polish (CMP) to achieve an epi-ready surface. While the mechanical polish using a diamond slurry has the capability of producing a surface with a very low roughness value, a CMP step is required to achieve a sub nm surface roughness value [4]. The mechanical polish also leaves a layer of sub-surface damage that must be removed as well.

A CMP process has been optimized with respect to the polishing slurry's composition and size distribution as well as the chemical reactivity of the polishing environment that allows for good material removal rates without imparting unwanted damage or high lighting defects. Figure 1 shows an atomic force microscopy (AFM) image of a c-plane material after the CMP polishing process. The final RMS roughness as measured by AFM was 0.063nm on a 20µm x 20µm image.

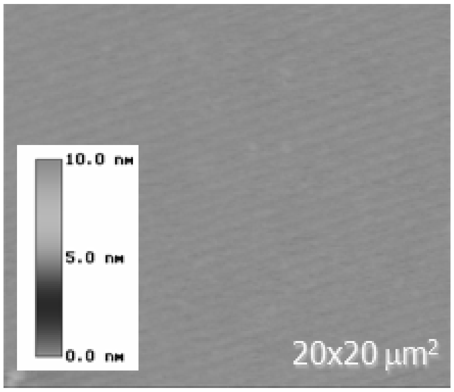

Figure 2. An AFM image of a c-plane wafer after chemical mechanical polishing. The RMS roughness is 0.063nm.

CONCLUSION

A stable and consistent process has been developed that allows for the production of epi ready GaN wafers. The hydride vapor phase epitaxial growth process has shown the ability to produce bulk GaN wafers up to 2 inches in diameter. A characterization process has been developed that can identify the off-cut orientation of every wafer produced with a very high degree of accuracy. With the off-cut data, a preparation procedure has been developed that can correct off-cut orientation to within 0.25 degrees of on-axis while at the same time producing the desired geometry and surface morphology.

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ACRONYMS

AFM: Atomic Force Microscopy
CMP: Chemical Mechanical Polish
HVPE: Hydride Vapor Phase Epitaxy
LED: Light Emitting Diode
XRD: X-ray Diffraction, X-ray Diffractometer