Understanding GaN Homoepitaxial Growth and Substrate-Dependent Effects for Vertical Power Devices

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Abstract

In order to enable device-quality epitaxial GaN layers, a deeper understanding of effects of the substrate and growth initiation on the material and electrical properties of the metal organic chemical vapor deposition (MOCVD) films is required. We investigate these effects on epi morphology, uniformity, and impurity incorporation at the interface and in the films using both non-destructive optical techniques as well as device fabrication and electrical testing. By studying these effects using wafers from several different vendors, with substrates from both hydride vapor phase epitaxy (HVPE) and ammonothermal techniques, an understanding of the requirements for device quality MOCVD homoepitaxy can be determined and appropriate techniques for rapid substrate screening can be identified.

INTRODUCTION

Vertical GaN power switch technology is expected to be utilized in next-generation medium to high voltage power converters due to the low ON-resistance and high breakdown voltage enabled by the improved critical electric field and mobility compared to Si and SiC-based devices. As large area substrates have become available by hydride vapor phase epitaxy (HVPE) and ammonothermal growth, the properties of nitrides are no longer dominated by defects introduced by heteroepitaxial growth, allowing recent realization of several fundamental vertical power devices, including diodes with edge termination, trench MOSFETs, and CAVETs [1-4]. However, additional materials challenges are coming to the forefront that need to be understood and surmounted in order to allow vertical GaN power devices to achieve their full potential, notably the realization of repeatable thick drift layers with low background doping. To enable this, a deeper understanding of substrate preparation and the effects of the substrate and growth initiation on the characteristics of the epitaxial layers is required for metal organic chemical vapor deposition (MOCVD) growth of homoepitaxial films [5]. We investigate these effects on epi morphology, uniformity, and impurity incorporation by growing simultaneously on wafers from different vendors. The goal of this work is to detect and identify defects in GaN substrates with a series of quick, non-destructive, inexpensive techniques with capabilities of mapping whole wafers.

EXPERIMENTAL PROCEDURE

Four different substrates - three grown by HVPE and the fourth by ammonothermal technique were obtained from different vendors. All had nominally similar as-received specifications (resistivity, thickness, off-cut angle, bow, surface finish). The substrates were evaluated with a variety of techniques including Raman spectroscopy, photoluminescence, white light interferometry, and Nomarski imaging, enabling to detection of different concentrations of grain boundaries, sample impurities, point defects, v-shaped pits, polishing defects, crystal stress damage, and non-uniform insulating and conducive regions. MOCVD GaN was deposited on all four wafers simultaneously to a thickness of 2 µm, using trimethylgallium and ammonia at 1030 °C, 200 Torr, and 3000 V/III ratio. After growth, the samples were characterized again with the prior techniques as well as secondary ion mass spectroscopy (SIMS), then vertical Schottky barrier diode (SBD) structures were fabricated on coupons of the epitaxial material to assess the electrical properties of the epitaxy. Circular diode structures from 50 to 500 µm in diameter were formed by lift-off of e-beam deposited Ni/Au (20/200 nm) on the top side and blanket Ti/Al/Ni/Au (20/120/40/80 nm) on the back side. The Ohmic contacts were annealed for 30 sec in nitrogen at 850 °C.

RESULTS AND DISCUSSION

Prior to growth, the substrates were characterized using multiple methods. In general, substrates A and D showed uniform characteristics across the wafer. They were nominally flat, and substrate A had regular step morphology across the wafer, as measured by white light interferometry. Both had consistent Raman maps and spectroscopy. However, out of all wafers, only substrate D had a Raman

spectra indicating high carrier concentration (>10^{18} cm^{-3}) as would be expected from n+ substrates. Further details of characterization on these relatively uniform substrates have been previously reported [6]. Substrates B and C were much more interesting from a characterization standpoint. Substrate B showed a wide variation in morphology with hillocks and divots on the surface by white light interferometry. Similarly shaped features were observed in Raman mapping of the A_1(LO) peak, as shown in Figure 1. Spectra taken from the different features show a change in peak position and width. This denotes a variation which can be contributed to changes in carrier concentration across the features [7]. In this case, the blue regions are more insulating ($n < 10^{17}$ cm^{-3}), and the large circular red region is more conducting ($n \sim 2 \times 10^{18}$ cm^{-3}). Photoluminescence imaging of this substrate showed a similar mottled appearance, further indicating changes in impurity incorporation across the wafer [6].

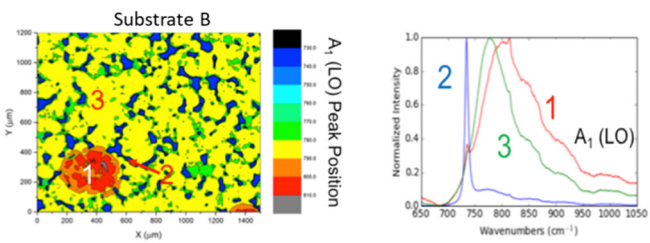

Figure 1. Raman map of A_1(LO) peak position (left) and spectra (right) illustrating non-uniformity in carrier concentration in substrate B. Area 1 shows high conductivity, while Raman areas labeled 2 are highly insulating.

Substrate C had a uniform Raman A_1(LO) peak position. However, the intensity of this peak varied across the wafer and peaks for forbidden modes in c-plane GaN were observed (Figure 2). This indicates a granular structure to the substrate.

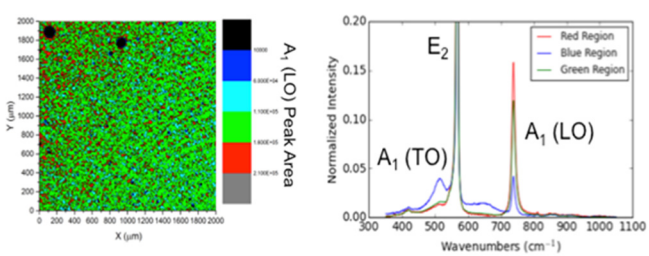

Figure 2. Raman map A_1(LO) peak area (left) and spectra (right) of the illustrating non-uniformity in crystallinity and poor carrier concentration in crystallinity substrate C. The red, blue, and green spectra correspond to Raman map colors.

The substrates were ordered as 'epi-ready,' and no further in situ or ex situ cleaning was performed prior to simultaneous growth on the substrates. Morphologically, the epitaxial films follow and slightly exaggerate that of the underlying substrate. This means substrate roughness of the substrates is an issue, as there is a direct correspondence between surface roughness and leakage current [8,9]. In general, the epitaxy on the substrates was similar in quality and impurity incorporation regardless of substrate, as observed in photoluminescence imaging and SIMS data (Figure 3). In accordance with the variation in carrier concentration in substrate B, some inhomogeneity broadening was observed in the near band emission peak of photoluminescence spectra, showing that the substrate variations do affect the epitaxial layer quality [10]. From SIMS, the only major difference in the impurity incorporation in the epitaxial films arises in C incorporation, which increases with wafer offcut (Fig. 4), which has been supported by theoretical calculations. The Si and O content in the films was near detection limits. Additionally, it can be observed that the growth on substrate A was slightly thinner than the other substrates, at 1.9 um and shows a tail of oxygen reaching into the first 0.7 µm of growth. This needs further review. The SIMS data shows varying impurity levels in the substrates and a large Si spike is observed at the HVPE-MOCVD interface, which needs to be further understood.

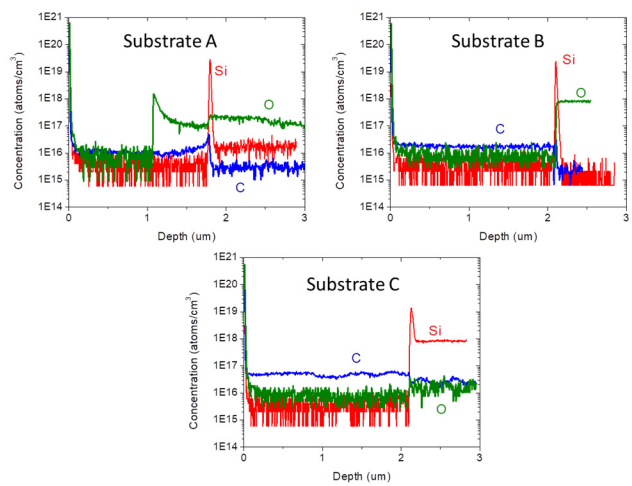

Figure 3. SIMS data of impurity incorporation for substrates A-C. A large Si peak marks the boundary between the 2 µm MOCVD films and the HVPE substrates.

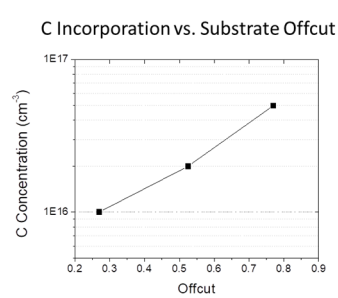

Figure 4. Graph of C incorporation in the MOCVD epitaxial layers vs. substrate offcut.

Examining electrical characteristics from the SBDs fabricated from the samples, all samples show rectifying behavior from I-V sweeps, and diodes from all samples can be found to breakdown above 200V. This corresponds to a critical field of greater than 1MV/cm, which is encouraging, as it is achieved from a basic structure without field engineering. However, the uniformity of this breakdown differed with substrate, with B and C showing the highest variability. This means that although the epitaxy quality was similar, the inhomogeneity in the substrates causes issues with device uniformity. Figure 5 shows the breakdown measurements for different sized diodes at several points across each substrate. For all samples the breakdown voltage decreased with increasing diameter. This is likely due to the statistical sampling of more catastrophic defects induced by either substrate non-uniformity or processing.

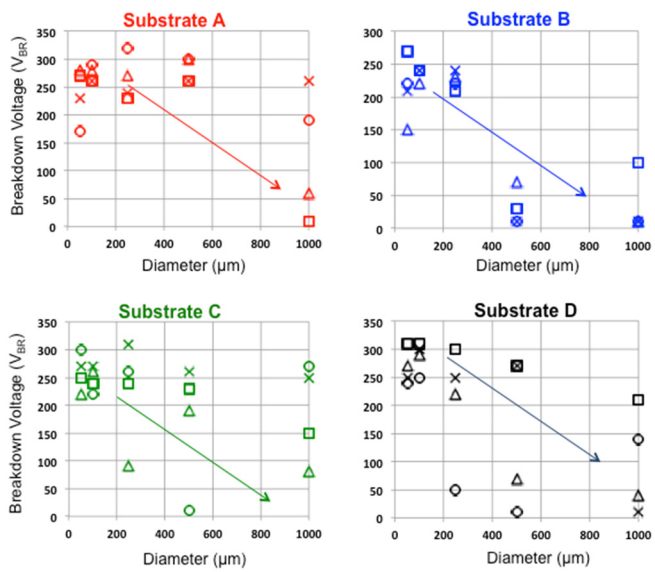

Figure 5. Breakdown voltage as a function of diode diameter and location on wafer (denoted by different symbols).

CONCLUSIONS

While most of the films showed the ability to withstand high electric fields, those with more uniform properties in the substrate also showed more uniform electrical properties. These results show that the bulk substrates enable the path to high voltage vertical devices, but also show the significant influence that substrates can play in device performance.

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ACRONYMS

HVPE: Hydride Vapor Phase Epitaxy
MOCVD: Metal Organic Chemical Vapor Deposition
MOSFET: Metal Oxide Semiconductor Field Effect Transistor
CAVET: Current Aperture Vertical Electron Transistor
SIMS: Secondary Ion Mass Spectroscopy
SBD: Schottky Barrier Diode