An Overview of Gallium Nitride Substrate Materials Developments for Optoelectronic and Microelectronic Applications

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Keywords: GaN, bulk substrates, HVPE, FET, Schottky diode

Abstract

The hydride vapor phase epitaxy technique has been used to grow bulk GaN crystals for processing into free-standing substrates for optoelectronic and micro-electronic applications. Substrates up to 2 inches in diameter were fabricated and tested for materials properties and device applications. Defect densities as low as 5x10^4 cm^{-2} were measured via CL imaging. Semi-insulating electrical behavior was achieved through Fe doping with room temperature resistivity measurements as high as 2×10^9 Ω·cm measured using COREMA. Schottky diodes with >600V breakdown voltage and 20 ns reverse recovery time were fabricated. AlGaN/GaN HEMTs were fabricated and tested, resulting in an output power density of 5.0 W/mm at 2 GHz with a power- added efficiency of 35% and an associated gain of 14.5 dB. This constitutes the first report of significant power density from MBE-grown HEMTs on free-standing HVPE GaN substrates.

INTRODUCTION

Free-standing, bulk GaN substrates, two inches and greater in size, are considered critically important for realizing commercially viable GaN-based lasers, and evidence is increasingly suggesting their importance for other applications, such as LEDs and microelectronic devices. Of primary importance, bulk GaN substrates offer a way to achieve lower dislocation densities in GaN-based devices when compared to heteroepitaxial growth approaches. Dislocations in GaN have been shown to impact the light emission from LEDs [1] and the lifetime in laser diodes [2].

Among the techniques used for growing gallium nitride (GaN) single crystals, hydride vapor phase epitaxy (HVPE) has attracted the most attention and has been most successfully employed to manufacture bulk substrates for optoelectronic and microelectronic applications. In this work we report on recent materials development efforts in the fabrication of HVPE-grown GaN substrates for these types of applications, including materials characterization and device performance for Schottky diodes and HEMTs.

SUBSTRATE FABRICATION APPROACH

GaN substrates up to 2 inches in size were made via the HVPE technique using a boule growth approach. Using this process, three inch prototype substrates have also been demonstrated, showing the size capabilities of the crystal growth process. Thick crystals (>2mm and up to 1cm) were grown and processed into free-standing bulk substrates. The boule was shaped after growth to the desired size and substrates were cut from the boule using a fixed abrasive diamond wire saw. An epi ready surface was prepared using a chemical-mechanical polishing process.

MATERIALS CHARACTERIZATION

It was found that the GaN substrate crystal quality benefits from boule growth when contrasted against thin growth approaches due to a larger degree of defect interaction and subsequent dislocation annihilation. [3]. Defect densities as low as 5×10^4 cm^{-2} were measured for thick crystals (>2mm) via etch pit density measurements and room temperature panchromatic cathodoluminescence (CL) imaging, with typical defect densities <5×10^6 cm^{-2}, as shown in Figure 1. X-ray diffraction measurements showed narrow FWHM values for both symmetric and asymmetric reflections.

Conductivity control of the crystal was achieved through the controlled introduction of impurities: Si was used for N-type doping, and Fe was used to generate semi-insulating material. For the semi-insulating material, COREMA and high temperature Hall effect electrical measurements were performed. Resistivities as high as 2×10^9 Ω·cm at room temperature and 1.2×10^6 Ω·cm at 120ºC were measured. Epi-ready surfaces were created using a chemical-mechanical polishing step. RMS roughness values of 0.2 nm were measured via AFM on 5×5 μm areas. Cross-sectional TEM samples verified the removal of sub-surface polishing damage. Thermal conductivity measurements using the 3-ω method showed a room temperature thermal conductivity of 230 W/m·K for Fe-doped GaN.

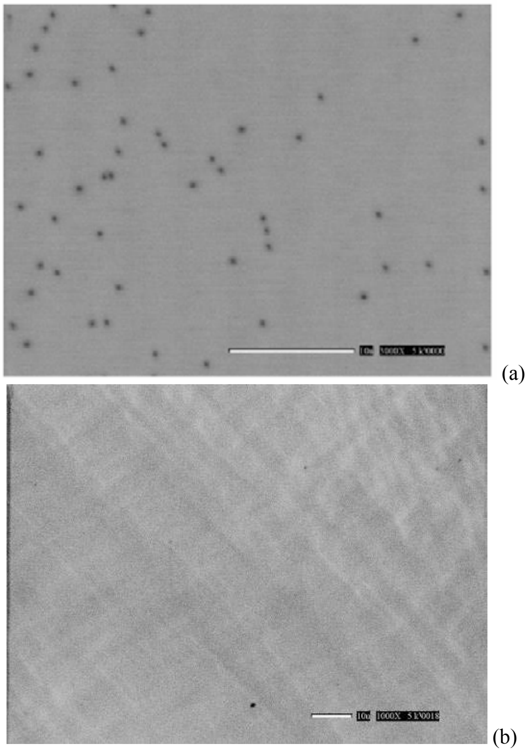

Figure 1: Panchromatic CL images of the surfaces of GaN substrates. The dislocation density is (a) $5x10^6$ cm^{-2} and (b) $5x10^4$ cm^{-2} (the scale is 10 µm in both images).

DEVICE RESULTS

N-type and semi-insulating substrates were employed in Schottky diode and FET device studies, respectively. Schottky diodes with different device sizes (100µm, 300µm and 600µm) were fabricated directly on the Ga-face of several free-standing GaN substrates. A full area back-side ohmic contact was prepared on the N-face of the bulk GaN using Ti/Al. Without any edge-termination scheme, a reverse breakdown voltage of 630V was achieved, corresponding to a breakdown field of 13.7 kV/cm. The reverse breakdown voltage decreases as the device size increases. The forward turn-on voltage was as low as 1.6V at room temperature for 100µm diameter Schottky diodes. The best on-state resistance was 4.86 mΩ·cm^2 for diodes with V_B=630V, producing a figure-of-merit (V_B^2/R_{ON}) of 81.7 MW·cm^{-2}. The Schottky diode also showed an extremely short reverse recovery time (< 20 ns) switching from forward bias to reverse bias.

$Al_{0.3}Ga_{0.7}N$/GaN HEMT structures were grown by molecular beam epitaxy on Fe-doped semi-insulating GaN substrates. Details of a similar growth procedure appear elsewhere [4]. HEMTs and process monitors (e.g. Hall, circular transmission line, and inter-device isolation patterns) were fabricated and characterized. Dc and rf measurements were made before and after Si_xN_y passivation. Prior to passivation, electron Hall mobilities as high as 1800 cm^2/Vs at sheet densities of 1.0×10^{13} cm^{-2} were measured. Typical saturated drain current densities, threshold voltages, and gate leakage currents at V_{DS} = 10 V on 150-µm gate width and ~1-µm gate length devices were 750 mA/mm, -5.1 V, and 3 µA at V_{GS} = -7, respectively. On devices with source-to-drain spacings of 4 µm and nominal gate lengths of 1 µm, off-state breakdown voltages of up to 200 V were measured without field plates or similar device modifications, indicative of the high quality of the device layers. This is among the highest breakdown voltages reported for MBE-grown GaN HEMTs and better than our best results on SiC substrates for the growth process used. We believe these improvements in breakdown voltage and gate leakage result from growth on low-dislocation density substrates. After Si_xN_y passivation, dc measurements on devices with 0.5 µm gate lengths yielded I_{DSS} = 1140 mA/mm. We measured an output power density of 5.0 W/mm at 2 GHz with a power- added efficiency of 35% and an associated gain of 14.5 dB (Figure 2). This constitutes the first report of significant power density from MBE-grown HEMTs on free-standing HVPE GaN substrates.

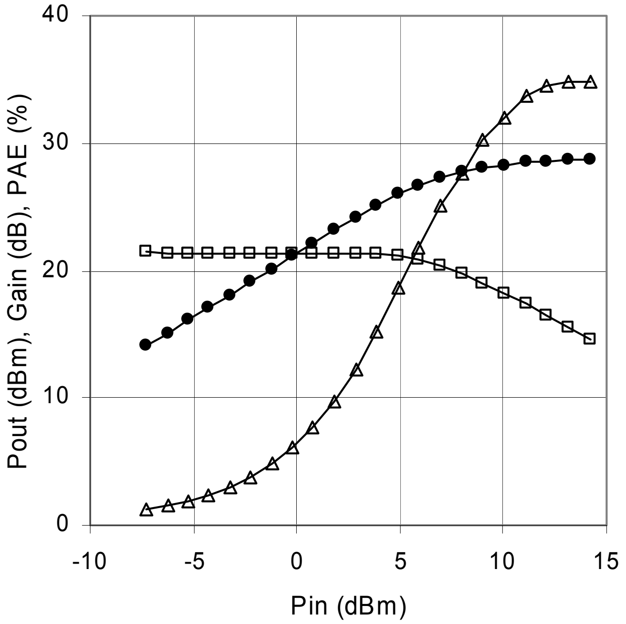

Figure 2. Output power (●), power added efficiency (Δ), and gain (□) of a 150-µm gate width, 0.5-µm gate length device.

CONCLUSIONS

Free-standing GaN substrates grown by the HVPE technique were grown and characterized. The dislocation density in the substrates benefited from the boule growth approach, which was four to six orders of magnitude lower than conventionally grown heteroepitaxial GaN material on substrates such as sapphire or SiC. The high breakdown voltages for the Schottky diode and HEMT devices, as well as the power density performance of the HEMT, are indicative of the benefits of the reduced defect density in the material.

ACKNOWLEDGEMENTS

This work was partially funded by ONR and by the Missile Defense Agency through Contract No. N00164-04-C-6066 monitored by Charles Pagel and Contract No. W9113M-04-C-0082 monitored by Fred Clarke. We would like to thank J. Muth for providing the thermal conductivity measurements and the CL images, and N. Green for the HEMT device processing and B. Bass for e-beam lithography.

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ACRONYMS

CL: Cathodoluminescence
FWHM: Full Width at Half Maximum
HEMT: High Electron Mobility Transistor
HVPE: Hydride Vapor Phase Epitaxy
MBE: Molecular Beam Epitaxy