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Vertical Power Electronic Devices based on Bulk Gallium Nitride Substrates

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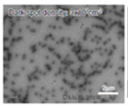
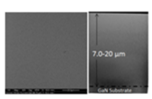
Abstract

In this paper power electronic devices based on bulk GaN substrates, in particular, high voltage (1.2-4.1kV) diodes and vertical transistors, will be discussed. Devices fabricated on pseudo-bulk GaN will be compared with those on ammonothermal as well as Na-flux GaN substrates. The cryogenic behavior of high-quality GaN p-n junctions are measured and reported for the first time. It is observed that the electrical properties of the p-n junctions are impacted by the freeze-out effect of the deep Mg-acceptor level, limiting the operation of these devices below 180K. Impact ionization based avalanche breakdown is measured and its positive temperature coefficient is charted between 77K- 450K. Inductive avalanche test results demonstrate that vertical GaN (area=0.36mm^2) p-n diodes can sustain single pulse and repetitive inductive avalanche currents as high as 10 A (at 1200V). Lastly, current status of vertical GaN transistors and most recent reliability studies of GaN diodes and transistors are presented.

1. Introduction

Most recently there is great interest in wide band-gap semiconductor devices and in particular vertical GaN structures for power electronics applications [1]. This is because currently used power electronic diodes and transistors are rapidly approaching the fundamental material limits of Si. This has resulted in an expansion of efforts to develop alternatives in the way of wide-bandgap power semiconductors including silicon carbide (SiC) and for gallium nitride (GaN) [2-7] as the material based fundamental figure of merit parameters for GaN and SiC are significantly better than Si. The desirable properties associated with GaN are high bandgap energy (and hence low intrinsic carrier concentration), large electron mobility, saturation velocity, a high critical breakdown electric field, and high thermal conductivity. While the superior material properties of GaN have been known for some time to be suitable for high power and high frequency devices, limitations to standard processing techniques such as selective area doping and the lack of a high quality native oxide which have been used in Si for decades, has hindered the development of products based on GaN. The necessity of growing GaN on mismatched substrates such as sapphire, silicon, and silicon carbide has also created difficulties for vertical device structures and resulted in high defect densities and poor material quality. In Table I the attributes of GaN grown on GaN is compared with GaN-on non-native substrates. Plan-view cathode-luminescence (CL) imaging reveals that the threading dislocation density in the films grown over bulk GaN substrates is limited by the defect density in the substrate and many orders of magnitude smaller compared with material grown on silicon, sapphire, or SiC substrates. Also, the ability to grow arbitrarily thick drift layers (up to 40μm) on native substrates allows the realization of high voltage (> 4kV) vertical diodes and transistors.

Table I. Materials Growth and Device Fabrication

Attributes	GaN on Si	GaN on SiC	GaN on Bulk-GaN
Defect Density (cm^{-2})	10^9	$5x10^8$	**10^3 to 10^6**
Lattice Mismatch, %	17	3.5	**0**
CTE Mismatch, %	54	25	**0**
Layer Thickness (μm)	< 5	< 10	**> 50**
Breakdown Voltage (V)	< 1000	< 2000	**> 5000**
Avalanche Capability	No	No	**Yes**
Device Types	Lateral	Lateral	**Vertical and Lateral**
Microscopy and Growth			

2. Experimental Results

Device layers are grown on bulk substrates by using MOCVD. Substrate orientation plays a significant role in the device performance and reliability. A nominal c-orientation (0001), with slight inclination toward the m-plane is preferred on bulk c-oriented-GaN substrates. For the case of on-axis growth, large hexagonal hillocks are naturally formed during growth. Hillocks formed by MOCVD epitaxial growth of GaN on an exact (0001)-oriented bulk GaN substrate are easily visible. Introducing a slight miscut of several tenths of a degree produces a smooth surface as shown in Fig. 1. Devices fabricated using Substrate B will consistently have lower reverse leakage currents and perform well under high temperature reliability bias (HTRB) conditions. The images cover about 1 mm^2 of GaN surface area. The white speckles are from back side reflection. Surface preparation and MOCVD epi growth initiation are also found to be critical. Reliability and yield models based on accurate spatial mapping of the surface morphology have been developed at Avogy and serve as an effective screen.

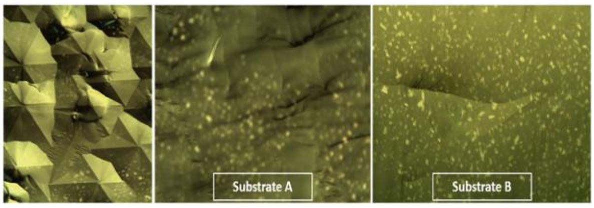


Fig. 1 Nomarski image of surface morphology

Homoepitaxial MOCVD growth of GaN on its properly specified native substrate and the ability to control the doping in the drift layers in GaN has allowed the realization of vertical device architectures with drift layer thicknesses of 6 to 40 µm and net carrier electron concentrations of $2x10^{15}$ to $2x10^{16}$ cm^{-3}. This parameter range is suitable for applications requiring breakdown voltages of 1200V to 5kV with a proper edge termination strategy. Measured devices (on substrate B) demonstrate power device figure of merit of differential specific on-resistance (R_{sp}) of 2.8 mΩ-cm^2 for a breakdown voltage of 4.1kV [8] and low leakage currents (<10nA). The improvement in the substrate quality over the last few years has resulted in the fabrication of diodes with areas as large as 16mm^2, with breakdown voltages exceeding 1200V, and pulsed (100µs) currents of 100-400A. Vertical transistors (Fig. 3) with impressive figures of merit (1.5 kV and 2.2 mΩ-cm^2) have also been reported [5,6]. Furthermore, impact ionization based avalanche breakdown has been demonstrated in GaN for the first time due to the high quality of the epitaxial layers grown on bulk GaN native substrates [4,7]. In Fig.2 the breakdown voltage of a 1400V p-n diode (at 300K) is measured between 77K and 423K. We note that the positive temperature coefficient persists to 100K. Below 180K the Mg-dopant freeze out effects come in to play.

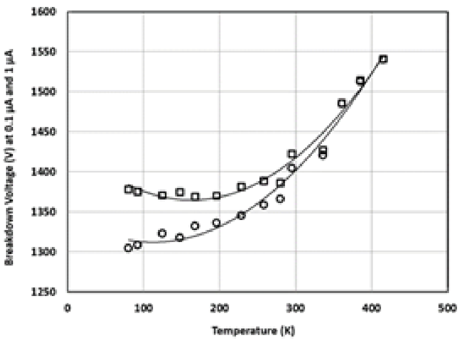


Fig. 2 Breakdown voltage versus temperature in a GaN p-n diode.

All the device results described above were fabricated on pseudo-bulk GaN substrates that are derived from thick crystalline films, grown by hydride vapor phase epitaxy (HVPE) on non-native substrates that are subsequently removed from the substrate. The TDD of these wafers is typically 10^6 - 10^7 cm^{-2}; and sophisticated dislocation-gettering techniques have been applied to reduce TDD to 10^4 cm^{-2} over a limited area (~mm^2). As bulk-GaN substrates are more widely adopted for large-area vertical devices, both electronic and optoelectronic, an improved structural quality will accrue from advances in bulk growth techniques such as ammonothermal or Na-flux.

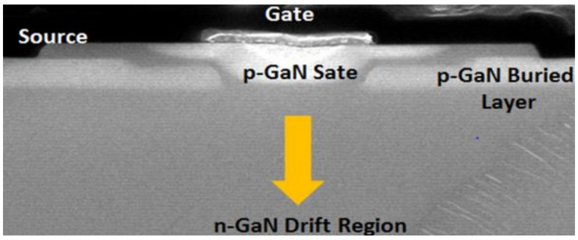


Fig. 3 Vertical GaN transistor

3. Conclusions

Vertical diode and transistor structures fabricated on bulk GaN substrates is emerging as a new frontier in power electronics. The material system certainly shows promise for applications requiring breakdown voltages larger than 900V to 5kV (and above). In this paper recent progress made in the area of substrate technology, vertical device architectures, temperature range of operation, and device reliability performance are discussed. Clearly much more work is needed in the development of the bulk GaN substrate technology, unique process integration techniques to realize vertical architectures, delineating the temperature range of operation, and elucidating all of the degradation mechanisms that can impact the long term reliability of GaN power electronic devices. The authors believe that the key problems will be resolved as the substrate technology matures (real bulk GaN wafers become readily available) and epitaxial growth (including selective epitaxial regrowth) processes are optimized.

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