Vertical Power Semiconductor Devices on Bulk GaN Substrates

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1. Introduction

Power electronics is the interface between an electrical source and a load that can differ in frequency, amplitude, number of phases, and where voltages and currents are converted from one form to another [1]. A power electronics system comprises power semiconductor devices, gate drivers, controller circuits and the like. The power semiconductor components of this system have been well served by silicon (Si) diodes and transistors (FETs, IGBTs). The performance of Si-based power semiconductor devices have improved over the past several decades resulting in tremendous improvements in efficiency, size, weight, and power density of power electronic systems for power supply, solar, wind, motor drive, ship propulsion, rail, and grid applications. However, these devices are approaching the material limits of Si. This has resulted in a rapid expansion of efforts to develop wide-bandgap semiconductor alternatives (SiC, GaN) [2-4].

2. Power Device Figure-of-Merit (FOM)

The power device figure of merit illustrates the trade-off between the device specific resistance (R_{sp}) versus the device breakdown voltage (BV). These conflicting requirements for a unipolar power device have been captured and formulated as $BV^2/R_{sp} \sim \mu_n E_C^3$, where μ_n is the mobility for electrons and E_C is the critical electric field at which breakdown occurs [5]. The clear advantage of wide band-gap semiconductor devices over Si devices arises from the cubed dependence of the FOM on E_C. While the critical electric field for Si is 0.3 MV/cm, a value > 3.5 MV/cm for bulk GaN has been extracted [5]. Table I summarizes material parameters assumed for evaluating semiconductor materials in power electronics.

Table I Material parameters for Si, SiC, and GaN

Material	μ_n (cm^2/V-s)	E_c (MV/cm)
Si	1350	0.25
4H-SiC	720-950	1.88-2.2
GaN	900	3.2
GaN-proposed	1150	3.5

The implications of the FOM are profound, in that to achieve the same on-resistance at a given blocking voltage a GaN device will take about 1/5th the area of a SiC or 1/30th of a Si device resulting in lowered capacitance, increased frequency of operation, and consequently system level shrinkage due to reduction in the size of inductors, transformers, capacitors.

3. MOCVD Growth of GaN on GaN Substrates

A better approach to realizing the true potential of GaN-based power electronics could start with growing GaN on low defect density GaN wafers.

Table II Physical attributes of GaN on bulk-GaN growth

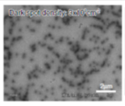
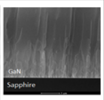
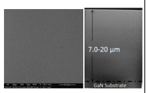
Attributes	GaN on Si	GaN on SiC	GaN on Bulk-GaN
Defect Density (cm^{-2})	10^9	$5x10^8$	10^3 to 10^6
Lattice Mismatch, %	17	3.5	0
CTE Mismatch, %	54	25	0
Layer Thickness (μm)	< 5	< 10	> 50
Breakdown Voltage (V)	< 1000	< 2000	> 5000
OFF State Leakage	High	High	Low
Device Types	Lateral	Lateral	Vertical and Lateral
Microscopy and Growth			

Table II compares the physical attributes that are critical for the epitaxial growth of GaN. Also shown in the table is a top-view comparison of defect densities of GaN-on-foreign substrate heteroepitaxial layers and on GaN-on-GaN homoepitaxial layers. Significant reduction in threading dislocation defect density (< 10^5 cm^{-2}) is observed in heteroepitaxy. Note that the cross section transmission electron microscopy (TEM) images demonstrate that the growth interface for the homoepitaxial GaN layer is not discernible. Low defect density is important in power devices because it affects the performance characteristics (breakdown voltage and off-state current), yield, and reliability.

4. Vertical Power Devices Based on Bulk GaN

Vertical architectures are preferred in bulk GaN devices for power electronics. There are multiple reasons for this such as ability to grow thick GaN drift layers allows breakdown voltages >>1200V, breakdown occurring in bulk and not surface, vertical current flow allowing the realization of high current devices (>20A) in smaller areas. The basic building block of any new semiconductor technology is the p-n junction. High performance vertical power devices have been achieved by MOCVD growth of GaN on GaN substrates and through the development of processing techniques applicable to the vertical p-n device and its edge termination as shown in Fig.1.

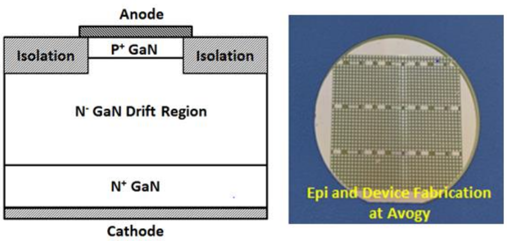


Fig. 1 Schematic cross section of the vertical GaN p-n diode and fabrication on 2 inch bulk GaN wafers by Avogy.

The edge termination scheme used in the diodes enables the devices to survive and operate in the avalanche region as shown in Fig. 2 [6]. The 10A rated diode blocking voltage reaches 2600V at T=300°K. Driven into avalanche by 30mS/15mA pulses equate to 1000mJ of avalanche energy. Figure 3 shows the 1200V/5A rated GaN p-n and SiC Schottky diodes in double pulse reverse recovery test comparison. Turn-off loss for the GaN diode is 10.3µJ versus 40.6µJ for SiC diode, indicative of the lower capacitance GaN device.

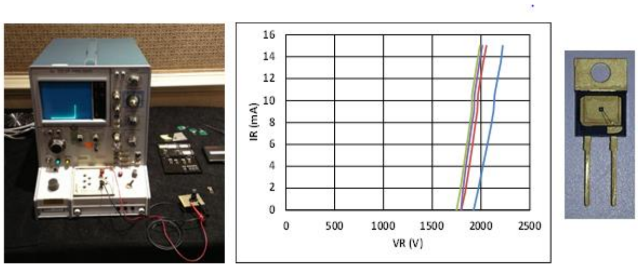


Fig. 2 Avalanche of vertical GaN diode housed in TO220.

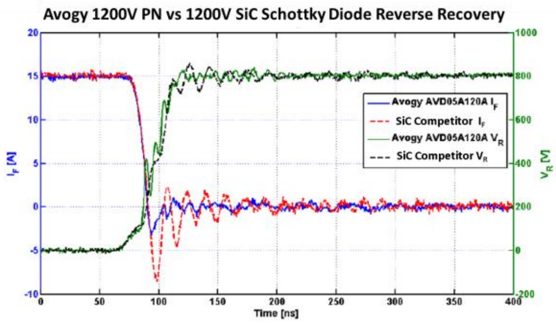


Fig. 3 15A/800V double pulse test of reverse recovery.

In Fig. 4 the progression of FOM for our vertical GaN diodes is shown culminating in avalanche breakdown of 3.7kV with R_{sp}=3mΩ-cm^2.

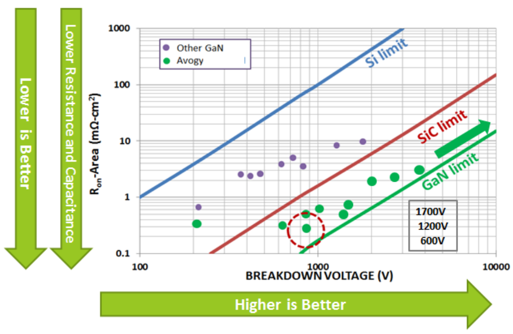


Fig. 4 Power device figure of merit for Si, SiC, and GaN.

In summary, GaN epitaxially grown on low defect density ($10^4$$cm^{-2}$) GaN substrates enable vertical devices that approach theoretical limits for GaN providing advantages in system level efficiency, size, and reliability for power electronics.

References

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