Vertical Power Semiconductor Devices Based on Bulk GaN Substrates

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Power electronics serves as the necessary interface between an electrical source and a load that can differ in frequency, amplitude, number of phases, and where voltages and currents can be converted from one form to another [1]. The building blocks comprising a power electronics system include power semiconductor devices, gate drivers, controller circuits and the like. To date, the power semiconductor components of this system have been well served by silicon based diodes and transistors (MOSFETs, IGBTs). While the performance of silicon-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, these devices are rapidly approaching the fundamental material limits of silicon. This has resulted in a rapid expansion of efforts to develop wide-bandgap power semiconductor alternatives utilizing SiC [2] and GaN [3-8]. Desirable properties associated with GaN and related alloys and heterostructures include large bandgap energy which implies low intrinsic carrier concentrations useful for high temperature operation, favorable transport properties (large electron mobility and saturation velocity), a high breakdown field, and high thermal conductivity. SiC diodes have already been commercialized and they are increasing market share in applications that demand higher efficiency. There is great interest in developing GaN-based vertical power devices because the fundamental material based figure of merit (FOM) of GaN is significantly better than SiC. In this presentation vertical PN diodes, Schottky diodes, and vertical transistors fabricated on pseudo bulk GaN substrates are discussed. The measured PN devices demonstrate breakdown voltages as high as 3700V with a differential specific on-resistance of $3m\Omega\text{-cm}^2$. Furthermore, large area ($16mm^2$) PN diodes with pulsed current of 400A and breakdown voltage exceeding 700V are demonstrated indicating the recent advances in the bulk GaN substrate technology. To this end, early comparative studies of p-n junction fabricated using pseudo-bulk versus true bulk GaN (scalable ammonothermal, Na-flux ammonothermal) substrates will be presented. Contrary to common belief, GaN devices do possess avalanche capability. The temperature coefficient of the breakdown voltage is positive, indicating that the breakdown is indeed due to impact ionization and avalanche. Avalanche energy capability of 1000mJ is demonstrated for the 2600V diodes. This is an important property of the device for operation in inductive switching environments. Critical electric field, mobility, and hole minority carrier lifetime parameters for epitaxial GaN layers grown on bulk GaN are extracted from electrical measurements. The reverse recovery time of the vertical GaN PN diode measured by double pulse testing is not discernible. This is because the switching speed of the GaN diode is limited by capacitance rather than minority carrier storage and hence its switching performance exceeds that of the highest speed Si diode. Finally, fabricated vertical transistors with a breakdown voltage of 1500V and specific-on resistance of $2.2m\Omega\text{-cm}^2$ will be discussed.

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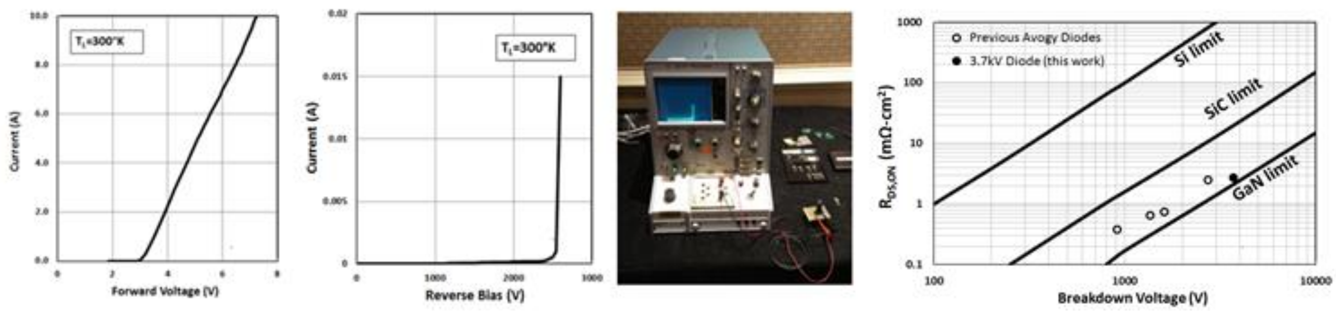

Fig. 1) Forward and reverse characteristics of PN GaN diodes and FOM summary of Avogy diodes.

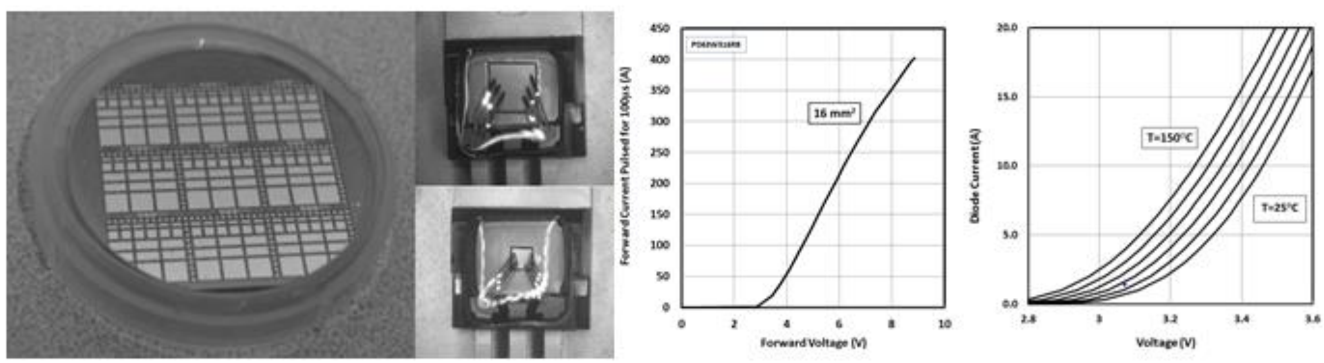

Fig. 2) Avogy fabricated 1-16mm2 GaN PN diodes with 400 A pulsed forward characteristics.

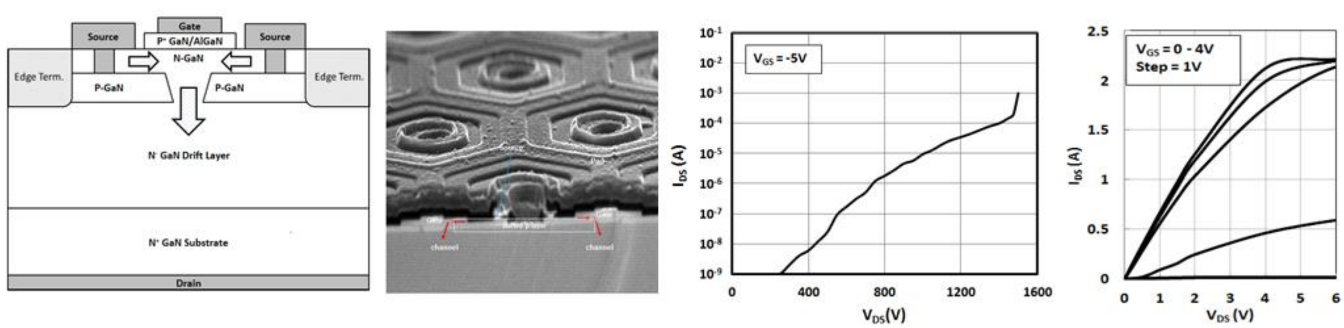

Fig. 3) Measured vertical GaN FETs with BV=1500V and 2.2mΩ-cm^2.