Challenges in the Automotive Application of GaN Power Switching Devices

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Abstract

High-voltage GaN power device research has gained momentum in recent years due to the superior material properties of GaN. Several critical advancements make its application prospect increasingly realistic, including the progress in native and GaN-on-Si substrates, development of normally-off gate structures, suppression of current collapse phenomenon, as well as demonstration of high voltage blocking capability. A highly attractive application for GaN power technology is the traction inverter system used in hybrid electric vehicles. However, the stringent cost and reliability requirements of automotive components, together with a highly competitive silicon IGBT industry create barriers for the transition from silicon power electronics to a GaN-based one. In this study, we review the state-of-the-art technologies of GaN power transistors, and evaluate them against the automotive requirements on power devices.

First, we discuss the choice of substrate materials. Native GaN substrate and GaN-on-Si are two candidates competing for power electronics applications. It was previously suggested that power switches in automotive DC-DC converters and traction inverters are better implemented by vertical GaN devices. Nevertheless, a very challenging manufacturing economy of GaN substrates limits the feasibility of vertical device technologies, even though such structures are advantageous for high-voltage and high-current operation. On the other hand, GaN-on-Si offers a potentially low-cost substrate for GaN power devices, but the difficulty in the growth of thick GaN layer on large silicon wafers needs to be resolved for the application in high-voltage electric drive systems.

Next, the characteristics of several transistor structures, such as GaN MOSFET, HEMT and hybrid MIS-HFET are reviewed and compared against each other. Key challenges for automotive application are identified that require further investigation by the GaN industry.

Normally-off operation of GaN HFET has been demonstrated by several teams. However, the gate threshold voltages reported are still too low for the noise margin requirements in vehicle systems. Common techniques, such as gate recess etching and fluorine ion treatment are shown to increase the threshold voltage, but these methods in turn introduce manufacturing control issues and device stability concerns.

The current collapse phenomenon and techniques to suppress it are frequently discussed in scientific literature. However, in many reports claiming successful control of the dynamic R_{ds_on} problem, only a portion of the maximal drain voltage was applied during the switching tests. It is clear that continued work in this area is needed to eliminate this issue up to the full rated voltages appropriate for the automotive traction inverters, and over long-term device operation.

Finally, based on the lateral transistor structures and realistic fabrication technology, we expect additional issues of GaN power switches that are critical for automotive systems but not frequently discussed. These include short-circuit withstand capability and the scaling barrier to high current ratings.

In summary, this paper presents a vision of Ford Motor Company on the potential application of GaN in our electrified vehicles. We recognize GaN power device as a very competitive candidate to displace silicon IGBTs in next-generation electric drive systems. However, major challenges exist that limit its near-term implementation. It is anticipated that GaN researchers and manufacturers make breakthroughs in these aspects in the next few years, and thereby prepare GaN switching devices for the stringent qualification process of automotive components.