Vertical GaN Power Devices

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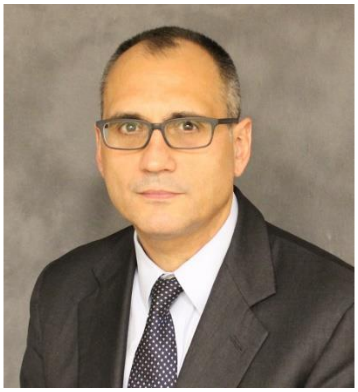
Abstract

Silicon (Si) has been the semiconductor material of choice for power devices for quite some time due to cost, ease of processing, and the vast amount of information available about its material properties. Si devices are, however, reaching their operational limits in blocking voltage capability, operation temperature, and switching frequency due to the intrinsic material properties of Si. Wide bandgap (WBG) power semiconductors, such as gallium nitride (GaN) and silicon carbide (SiC), are an attractive emerging alternative to Si in many applications. Power converters based on WBG devices can achieve both higher efficiency and higher gravimetric and volumetric power conversion densities than the equivalent Si based converters. The power figure of merit (PFOM), which captures the trade-off between the device specific resistance (Rsp) versus the device BV clearly illustrates the advantage of GaN over Si and SiC devices. This arises from the cubed dependence of the figure-of-merit on the critical electric field where the critical electric field for GaN is 10 times that of Si and 1.6 times that of SiC. To date, the majority of GaN power device development has been directed toward lateral architectures, such as high-electron mobility transistors (HEMTs), fabricated in thin layers of GaN grown on foreign substrates (including Si or SiC). Such lateral devices suffer from well-known issues such as current-collapse, dynamic on-resistance, inability to support avalanche breakdown, and inefficient thermal management. Many of these shortcomings arise from defects originating in the very large lattice and coefficient of thermal expansion (CTE) mismatch between GaN and the substrate. Furthermore, most power electronics semiconductor and diodes are vertical architectures. Fabricating vertical semiconductor device structures on lattice and CTE matched bulk GaN substrates possible to realize the material-limited potential of GaN including true avalanche-limited breakdown and more efficient thermal management, leading to large device currents (> 100A) without resorting to device parallelization, high breakdown voltages (1.2 to 5kV), and increased number of die on a wafer. Recent availability of both 2- and 4-inch bulk GaN substrates is enabling breakthroughs in GaN device performance with vertical diode structures. In this tutorial recent advances in bulk GaN substrates and vertical architecture GaN power electronic devices (diodes, transistors, and application circuits) is surveyed with emphasis on the ARPA-E (Department of Energy) funded projects in the SWITCHES and PNDIODES Programs along with recent significant advances made in Japan. The SWITCHES Program (launched 2013) aimed to catalyze the development of vertical GaN devices using innovations in materials and/or device architectures that drive the costs of the devices. The goal was to enable the development of high voltage (>1200V), high current (100A) single die power semiconductor devices that, upon ultimately reaching scale, would have the potential to reach functional cost parity with Si power transistors while also offering breakthrough relative circuit performance (low losses, high switching frequencies, and high temperature operation). The PNDIODES (Power Nitride Doping Innovation Offers Devices Enabling SWITCHES, launched 2017) Program funds transformational advances and mechanistic understanding in the process of selective area doping in the III-Nitride wide band gap (WBG) semiconductor material system and the demonstration of arbitrarily placed, reliable, contactable, and generally useable p-n junction regions that addresses a major obstacle, enables high-performance and reliable GaN vertical power electronic semiconductor devices.

Biography



Dr. Isik C. Kizilyalli currently serves as a Program Director at the Advanced Research Projects Agency – Energy (ARPA-E), Department of Energy. Kizilyalli's focus at ARPA-E includes high efficiency power conversion, power electronics, grid reliability, reliable semiconductors for extreme environments, instrumentation for intrinsically safe nuclear energy, and enhanced geothermal systems. Prior to joining ARPA-E, Kizilyalli served as founder, Chief Executive Officer, and Chief Technical Officer of Avogy Inc., a venture backed start-up focused on GaN power electronics, energy efficiency, and power systems. Previously, he was with Bell Laboratories, followed by Nitronex Corporation, and solar PV startup Alta Devices where his team holds the world record for single junction solar cell conversion efficiency. Kizilyalli was elected a Fellow of the Institute of Electrical and Electronics Engineers (IEEE) in 2007 for his contributions to Integrated Circuit Technology. He also received the Bell Laboratories' Distinguished Member of Technical Staff award and the Best Paper Award at the International Symposium on Power Semiconductors and Integrated Circuits in 2013. Kizilyalli holds his B.S. in Electrical Engineering, M.S. in Metallurgy, and Ph.D. in Electrical Engineering from the University of Illinois Urbana-Champaign. He has published more than 100 papers and holds 119 U.S. patents.