

Semiconductor power devices have been the key to growth of power electronics market, and cover application areas ranging from mobile stations (commercial) to missile seekers (military). Continuously increasing demand for improving the power handling capacities and need for higher bandwidth capable devices has impelled the need for search of novel device structures and materials other than Silicon. High electron mobility transistors (HEMT) based on Gallium Nitride (GaN) have emerged out as one of the most promising candidates to replace Si based power semiconductor devices. GaN HEMTs offer several advantages to their Si counterpart, such as high electron mobility ($\sim 2000 \text{ cm}^2/\text{V-s}$), high sheet carrier density ($\sim 1 \times 10^{13} \text{ cm}^{-2}$), and higher critical electric field ($\sim 3 \times 10^6 \text{ V/cm}$), etc. The theoretical material limits for GaN shows promising applications in power as well as RF domain. These application areas combined with the widespread LED market is expected to bring down the cost of development of GaN based devices to be competitive to that of Silicon based devices. However, despite of very high-power density and operational frequency figures already demonstrated for GaN HEMTs, their application is limited by various reliability challenges, such as current collapse, ambient light dependent behavior, hot electron induced degradation, etc., which are attributed to presence of dislocations/impurity induced traps in these devices. For performance optimization and improved reliability, Si based power devices have largely benefited from TCAD based analysis. On the other hand, lack of a reliable computational framework for GaN HEMT devices has restricted engineers to rely on experimental analysis leading to increase in time and cost of technology development. In this work, physical models are comprehensively studied to establish a computational framework for AlGaN/GaN HEMT devices to accurately predict DC behavior of the device. Advantages of computational modeling are then utilized to understand the behavior of C-Doping in GaN buffer which leads to improvement in breakdown voltage in AlGaN/GaN HEMT devices. The physical insight thus gained into behavior of C-Doping in GaN buffer is then utilized to propose a modified buffer doping scheme to overcome the limitations of C-Doping, by optimizing the acceptor trap concentration in GaN buffer, while maintaining the breakdown voltage of the device.

Firstly, in order to estimate the device performance in terms of DC characteristics, physical parameters affecting the device performance are exhaustively studied and a strategy is thereby developed to define an adaptive framework to estimate device performance irrespective of the epitaxial stack arrangement. The material dependent physical parameters such as polarization, quantum effects and mobility are taken into account along with the growth-related parameters like traps in the GaN buffer and on the device surface. In addition to this, device geometry related parameters like, AlGaN barrier thickness, Schottky gate metal/semiconductor interface, Source/Drain contact-channel interface, and formation of side diode by contact of gate electrode with GaN in the MESA region are also taken into account. The parameters related to device operation including device heating and carrier heating are also considered while estimating the device performance. The computational framework thus developed reasonably predicts the output characteristics as well as transfer characteristics of the device along with Schottky gate leakage characteristics. This framework works as the foundation for the GaN buffer designing discussed in this work.

Facilitated by the physics based computational framework, behavior of carbon atoms in the GaN buffer is then analyzed to explain the origin of delayed avalanche action in AlGaN/GaN HEMT devices by carbon doping of GaN buffer. The carbon doping is modeled as traps in the GaN buffer and is analyzed in terms of its impact on electric field distribution within the device. Presence of C as acceptor traps as well as donor traps is studied in terms of its influence of buffer resistivity and voltage handling capacity of the device. Based on the physical understanding and

agreement with experimental trends it is conclusively established that C behaves as self-compensating dopant in GaN buffer and hence results in electric field relaxation thereby improving the breakdown voltage. Moreover, it is established that the presence of C as donor traps is the primary contributing factor in relaxing the vertical field in GaN buffer, thereby increasing the voltage handling capacity of the GaN buffer. On the other hand, C behaving as acceptor trap in GaN buffer controls the buffer resistivity.

Enabled by the understanding of the field relaxation with C-Doping of GaN buffer, a novel doping strategy for GaN buffer is proposed to achieve ultra-high breakdown voltages while maintaining DC performance of the device. Motivated by the understanding of impact of donor traps introduced by C-Doping on avalanche breakdown, Si & C co-doping in GaN buffer is proposed to improve the breakdown voltage while minimizing the C-Doping requirement. The minimized C-Doping requirement is expected to bring down the acceptor trap concentration in GaN buffer, thereby improving device performance as well as reliability. Simulation based analysis is carried out to establish the relevance of proposed technique in obtaining ultra-high breakdown voltage in AlGaIn/GaN HEMTs backed by physical explanation. In addition to this, a modified buffer doping profile is proposed to maximize the device performance while maintaining the breakdown voltage.

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