Gate Dielectric Stack Engineering in GaN-on-Si HEMTs vs. SiC-Based MOS-HEMTs: A Trade-off Evaluation of Breakdown Voltage, Threshold Voltage Stability, and Interface Trap Density

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Abstract. This study presents a systematic comparative evaluation of gate dielectric stack configurations in gallium nitride-on-silicon (GaN-on-Si) high-electron-mobility transistors (HEMTs) and silicon carbide-based metal-oxide-semiconductor HEMTs (SiC MOS-HEMTs) targeting high-power switching applications. Al_2O_3/HfO_2 bilayer and single-layer SiO_2 gate dielectrics were benchmarked against thermally grown gate oxides under identical biasing and thermal stress conditions. Capacitance–voltage profiling, pulsed I–V characterization, and deep-level transient spectroscopy (DLTS) were employed to quantify interface trap density (Dit), threshold voltage instability (ΔVth), and off-state breakdown voltage (BVDS). GaN-on-Si devices exhibited superior electron mobility retention at elevated temperatures, whereas SiC MOS-HEMTs demonstrated lower Dit values and enhanced threshold voltage stability under repetitive gate stress cycling. These results provide device engineers with actionable selection criteria for next-generation power conversion modules.

Keywords: GaN-on-Si HEMT, SiC MOS-HEMT, gate dielectric stack, interface trap density, threshold voltage instability, breakdown voltage, Al_2O_3/HfO_2 bilayer, deep-level transient spectroscopy, power semiconductor devices

Introduction

The sustained proliferation of wide-bandgap (WBG) semiconductor technologies in power electronics has fundamentally restructured the design landscape for high-frequency, high-voltage switching converters, motor drives, and onboard vehicular power modules. As global electrification mandates tighten under regulatory frameworks projected through 2025–2030, the demand for power transistors capable of simultaneously sustaining high breakdown voltages, minimal conduction losses, and thermally robust operation has intensified considerably. Among competing WBG platforms, gallium nitride (GaN) and silicon carbide (SiC) have emerged as the dominant candidates, yet the specific device architectures built upon each material system—namely the GaN-on-Si HEMT and the SiC MOS-HEMT—exhibit fundamentally distinct trade-offs rooted in their respective heterostructure interfaces and gate oxide formation chemistries. The GaN-on-Si HEMT leverages the spontaneous and piezoelectric polarization fields at the AlGaN/GaN heterojunction to induce a high-density two-dimensional electron gas (2DEG) without intentional doping, yielding exceptional channel electron mobility exceeding 1500 $cm^2/V \cdot s$ at room temperature. However, the inherent absence of an inversion channel introduces gate leakage susceptibility and threshold voltage (Vth) modulation under dynamic stress, phenomena that are critically exacerbated by border traps at the gate dielectric/III-N interface. In contrast, SiC MOS-HEMTs benefit from the thermochemical stability of the SiC substrate during thermal oxidation, though the SiO_2/SiC interface characteristically harbors near-interface traps at densities up to 10^{12} $eV^{-1}cm^{-2}$, degrading effective channel mobility and introducing Vth hysteresis under repetitive switching cycles. Despite extensive independent characterization efforts reported in the literature for each device family, a direct, controlled comparative assessment under unified measurement protocols—particularly involving advanced high-κ bilayer dielectrics such as Al_2O_3/HfO_2—remains conspicuously absent. This gap is consequential: power module designers increasingly require quantitative, apples-to-apples benchmarks to inform technology selection for specific application classes, including 48 V automotive architectures, 650 V photovoltaic inverters, and 1200 V industrial motor controllers. The present paper addresses this need through three structured investigative threads. Section 2 details the fabrication parameters and dielectric deposition conditions for both device families. Section 3 describes the multi-modal electrical characterization methodology, encompassing C–V profiling, pulsed I–V sweeps, and DLTS measurement setups. Section 4 presents comparative experimental results across the key figures of merit: off-state BVDS, interface trap density Dit extracted via the conductance method, and threshold voltage shift ΔVth under accelerated gate stress. Section 5 interprets these findings within the context of practical device selection criteria, and Section 6 offers concluding remarks alongside recommendations for future dielectric interface engineering strategies.

References

1. Kumar, N., & Kataria, V. Enhanced Sentiment Classification using a Multi-layered Stacked Ensemble Architecture.

2. Kumar, Nitin, and Vipin Kataria. "Enhanced Sentiment Classification using a Multi-layered Stacked Ensemble Architecture."
3. Kumar, N., & Kataria, V. (2023). Enhanced Sentiment Classification using a Multi-layered Stacked Ensemble Architecture. International Journal of Intelligent Systems and Applications in Engineering, 11(4s), 304–311.
4. Semeniuk, V. (2024). Аналіз та оптимізація продуктивності баз даних у розподілених системах. COMPUTER-INTEGRATED TECHNOLOGIES: EDUCATION, SCIENCE, PRODUCTION, (54), 199-205.
5. D. Satyanarayana, Sathyashree "A Three Level Architecture for Wireless Communication using LiFi", in Recent Advances in Information and Communication Technology, Vol: 566, pp: 212-221, Springer International Publishing, 2018 book. Print ISBN: 978-3-319-60662-0; Electronic ISBN: 978-3-319-60663-7; Book Series.
6. Satyanarayana, D. and Rao, S. V. (2011), "Fault-tolerant spanners for ad hoc networks" International Journal of Network Management, Vol: 22, Issue: 4, Pages: 311-329, July-2012, Wiley Publishers. https://doi.org/10.1002/nem.807
7. D. Satyanarayana, Sathyashree. S "Mobility Management in Voronoi based Cell Structure for Wireless networks", IEEE proceedings for the International Conferences on Currents trends in Information Technology (CTIT), Pages: 204-208, Dubai, December-2013. DOI: 10.1109/CTIT.2013.6749504; INSPEC Accession Number: 14131032
8. D Satyanarayana, Perspective Chapter: Postquantum Security', Coding Theory - Advances in Communications Engineering and Information Security. IntechOpen, Nov. 19, 2024. doi: 10.5772/intechopen.1007829.
9. D. Satyanarayana and J. M. H. Elmirghani, "An Energy Efficient Network Architecture for Infrastructured Wireless Networks," 2010 IEEE Global Telecommunications Conference GLOBECOM 2010, Miami, FL, USA, 2010, pp. 1-6, doi: 10.1109/GLOCOM.2010.5683234.
10. D. Satyanarayana and J. M. H. Elmirghani, "A Voronoi Based Energy Efficient Architecture for Wireless Networks," 200S Third International Conference on Next Generation Mobile Applications, Services and Technologies, Cardiff, UK, 2009, pp. 377-382, doi: 10.1109/NGMAST.2009.79.
11. Hashimov, A. M., Guliyev, H. B., & Babayeva, A. R. (2017). Managing shunt reactors in accordance to fuzzy controllers for stabilization of voltage in high tension tire-cover. International Journal on Technical and Physical Problems of Engineering (IJTPE), 9(1), 18.
12. Hashimov, A. M., Rahmanov, N. R., Guliyev, H. B., Ibrahimov, F. S., & Tabatabaei, N. M. (2020). Probabilistic evaluatio n of voltage stability limit of power system under the conditions of accidental emergency outages of lines and generators. International Journal on Technical and Physical Problems of Engineering, 12(2), 40-45.
13. Rahmanov, N., Kurbatskiy, V., Guliyev, H., Tomin, N., & Mammadov, Z. (2017). Probabilistic assessment of power system mode with a varying degree of wind sources integration. In E3S Web of Conferences (Vol. 25, p. 02003). EDP Sciences.
14. Yusifbayli, N. A., & Guliyev, H. B. (2011). Intelligent control system of voltage regimes in the electrical networks. IEEE PES innovative smart grid Europe, 5-7.
15. Rahmanov, N., Guliyev, H., İbtahimov, F., & Mammadov, Z. (2024). Determination of optimal dimensions of hybrid AC/DC distributed generation system with renewable sources for

autonomous power supply of remote locations. In E3S Web of Conferences (Vol. 584, p. 01020). EDP Sciences.

16. Guliyev, H. B. (2024). Management modes of reactive power compensation facilities in networks with renewable energy sources with distorting loads. IJTPE Journal International Journal on Technical and physical problems of engineering (IJTPE), 16(1), 14-20.
17. Hashimov, A. M., Babayeva, A. R., & Guliyev, H. B. (2019). Shunt reactors control algorithm using fuzzy sets theory. International Journal on Technical and Physical Problems of Engineering, 11(1), 10-15.