Title: Physics of failure in near-terahertz III-nitride devices operating in extreme environments

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Problem Statement

Compared to legacy materials, III-nitride heterostructures provide the foundational capability to meet the power and frequency demands of the next-generation wireless communication and sensing systems operating under extreme environments. A major hurdle in the proliferation of III-nitrides in technology and future systems insertion is the lack of understanding of the time-dependent degradation mechanisms that negatively impact the functionality and reliability of these devices during their operational lifetime. To address this challenge, the proposed research will develop a <u>"computational tools" framework</u> that integrates the physics of reliability with carrier and thermal transport models. This integrated framework is necessary to predict and mitigate the fundamental root causes of device failure. The predictive capability of the computational tools will guide the experimental fabrication of highly reliable III-nitride devices, thus saving significant financial investment that is typically incurred during *reliability testing* of fabricated device structures. The computational tools framework will also lead to the development of new <u>reliability aware compact device models</u> that are specifically targeted toward studying the long-term dynamic response of near-THz transceivers and sensors. By unifying the physics of reliability and device scalability with compact models, this research will support the co-design of materials, devices, and circuits and eventually create a III-nitride ecosystem ready for deployment in 5G and 6G infrastructure.

Technical Approach

Reliability and time-dependent degradation of the underlying transistor technology has emerged as a major concern, as it reduces the operational lifetime of high-frequency (5G and 6G) communication and sensing infrastructure. The identification of the fundamental causes of device failure typically requires time-consuming and expensive testing and validation after test structures have been fabricated. Besides, the time and expenses incurred, results from reliability measurements are often fitted to empirical models which are unphysical and do not provide a link between materials science, physics, and time-dependent circuit failure.

In the proposed research, we will computationally study the impact of key <u>stressors</u>, such as l<u>arge gradients of electric field and temperature</u>, on device degradation during its operation under extreme environment. Temperature also influences the dynamics of trap occupancy, leading to undesirable DC-to-high-frequency dispersion effects. Toward gaining a better understanding of the system lifetime in extreme environments, we will examine the impact of stressors on the static and dynamic response of the device for a variety of material specifications and geometry. For example, the stressors will determine the change in fundamental material characteristics (i.e. mobility, thermal conductivity etc.), which in turn will impact the I-V characteristics. Additionally, the model will also be able to predict the time evolution of stressors and consequently its impact on the time evolution of device output (i.e. I-V characteristics). To alleviate the formation of hot spots, a diamond-based heat sink integrated on top of the stack will be designed, and its impact on thermal management and reducing the impact of stressors will be examined.

Given that the dimensions of these devices will be ultra-scaled (sub-100 nm) to achieve cut off frequencies exceeding several 100's of GHz, carrier transport will be modeled using the hydrodynamic formalism ((also known as energy balance) method) in which the subsystems corresponding to free carriers, traps, and the lattice are maintained at different temperatures, characterizing the global non-equilibrium of the system. The heat transport and carrier transport equations will be solved self-consistently yielding information on (i) temperature profile of the channel and (iii) temperature-dependent degradation in material parameters of the device. To solve the heat transport, an "effective" thermal resistance of the device structure will be computed based on technology and layout information. Traps in the device will be introduced under the gate and gate-drain access regions. Effects of traps on dispersion characteristics will be modeled as a function of (i) trap location and depth (into the barrier), (ii) energy level of the trap, (iii) capture/emission cross-section, and (iv) trap density. The modeling of the interaction between thermal and electric field gradients and trap characteristics is is essential toward realizing a reliability aware computational model.

Key Outcomes

At the fundamental level, GaN and its III-nitride counterparts are known to possess excellent material properties to implement near-THz transistors that ultimately enable wireless systems with high dynamic range, i.e. have high output power and efficiency to increase the signal strength or high linearity signal reception to minimize the spurs or noise in the spectrum. Yet, their deployment, particularly in harsh and demanding environments, is limited due to several time-dependent degradation mechanisms that evolve during the operational lifetime of the device. Key outcomes of this research are given below.

- This research will realize a computational framework to jointly model transport and heat conduction and trap dynamics that critically impact lifetime and device aging. By identifying and controlling key stressors (large excursions of temperature and field gradients), this research will enable the widespread deployment of III-nitride technology for key commercial and military applications.

- Results from this research will strengthen our understanding of degradation mechanisms and interpretation of experimental data. As such, our research will form the basis of fabrication of non-canonical III-nitride structures that are inherently more robust and can meet the power-frequency requirements of 5G and 6G systems over a broad range of operating conditions.

- Our results would also enable a circuit designer to make informed decisions on performance-reliability tradeoff based on their specific application.