Process-Reliability Relationships in GaN and GaAs Field Effect Transistors and HFETs

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Extended Abstract

Although accelerated life testing of low noise and power GaAs MESFETs under d.c. bias and RF operation has been conducted, some failure mechanisms remain to be of concern. We will address these concerns and will report on failure models of AlGaAs/GaAs HFETs. The set of reliability physics models then will form the starting point for development of physics based failure models for GaN HFETs devices. Processes in effect in GaN, but not in GaAs, owing to higher fields and much larger field, temperature, and strain coupling are included.

Failure Modes and Mechanisms of AlGaAs/GaAs HFETs

The AlGaAs/GaAs HFET degradation mechanisms, beyond those for GaAs MESFETs, include deep levels in the barrier and changes in the 2DEG concentration. The I-V collapse in the dark, and persistent photo-conductivity are more related to the material quality than to the long-term device stability. The decrease in 2DEG density is due to carrier de--confinement, enhanced by field-aided impurity diffusion at the heterointerface (would also occur in GaN HFETs). The defects, present or created by high field (temperature, strain) followed by hot electron capture, would reduce the available carriers. These anomalies also cause high levels of LF noise. Similar effects must undoubtedly take place in the GaN system. Extensive analyses coupled with test heterostructures have been undertaken to uncover the nature of these anomalies for the failure model development. Electromigration plays an important role in GaAs HFETs since GaAs,[2] being a binary compound, may have a wide variety of surface conditions (various native oxides and their clusters, surface states etc.). Further, electromigration is influenced by conductor-line material parameters and inhomogeneities, as well as structural features of the conductor layout, etc.

GaN FET physics of failure/degradation

The degradation mechanisms germane to GaN, in addition to those present in GaAs, are primarily related to surface traps, metal semiconductor and inter-metal diffusion, compound formation, interface and bulk defect states. However, local high fields (>> GaAs) coupled with strain and temperature as well as the increased hot phonon generation will alter the key GaN HFET degradation mechanisms. Clearly, the GaAs model is a starting point to be followed with its expansion to incorporate the GaN specific mechanisms. A variety of "trap" related device effects are reported which include transconductance frequency dispersion, current collapse, light sensitivity, gate- and drain-lag transients, and restricted microwave power output. The activity directed toward characterizing these effects parallels similar developments in the GaAs-based technology.

Electron capture-emission by surface and bulk traps affects the 2DEG density resulting in current collapse, and transconductance dispersion. Because the associated characteristic time is ~ $1\text{ns}<\tau<1$ s, the trapping limits device performance even at relatively low frequencies. In addition,

the thermally activated traps contribute significantly to LF noise. Understanding the origin of the traps in GaN-based transistors, their physical and energy location, and the physical mechanisms involved in the trapping is critical for not just the optimization of device performance, but for reliability modeling and reliability optimization for the GaN HFETs. Degradation caused by surface states and preexisting bulk and interface states are reversible. However, when new defects begin to be created and their density cascades due to the combined effects of high field, heat and strain, the resulting device degradation becomes catastrophic.

a Bulk buffer traps

Bulk traps in early GaN MESFETs and HFETs have been investigated. The fitted photoionization thresholds located the two dominant defects at ~ 1.80 and 2.85 eV below the conduction band edge, and after the 0.55 eV and 0.2 eV Franck-Condon correction, respectively. The DX centers plausibly associated with O have been observed in AlGaN may also be present. The enhancement of the optically induced drain-current recovery for photon energies at or above the band gap, E_g, of GaN has been measured and in contrast, no such increase for photon energies above E_g of AlGaN has been observed, hence, placing the traps to be within GaN buffer layer. However, it is obvious that further investigations are necessary. For instance, Trap 2 appears to be correlated with MOCVD growth pressure since trap 2 density increases at lower pressures.

b. **Bulk Barrier traps**

Bulk barrier defects results in the trapping of carriers injected from the gate and/or hot carriers injected from the channel and leads to current reduction by reducing 2DEG density. The lateral and vertical fields also enhance the charge emission from the barrier traps. The field effects, therefore, are particularly important and are taken into account. Localized trapping centers within the bandgap in the vicinity of the gate where the gate potential defines the energy position of the trap level with respect to the Fermi level have been investigated.

c. Surface traps

A strong correlation of gate lag with the surface treatment suggests that at least some trapping centers, besides the bulk GaN and AlGaN traps, are located at or near the surface. Surface trapping can be identified by measuring gate lag for a devices with different surfaces achieved by chemical treatment or dielectric passivation. The temporal character of charge emission from these traps is typically a stretched exponent with a characteristic time in the range of seconds. Kelvin probe microscopy showed that electrons migrate 0.5–1 μm along the surface away from the gate. An area of particular concern is the limiting effect of electronic traps on RF performance. Electrostatic force and Kelvin probe microscopes can measure both local surface charge and potential with high spatial resolution. Traps form quasi-static charge distributions, most notably on the wafer surface or in the buffer layers underlying the active channel, act to restrict the drain-current and voltage excursions.

Finally, our effort has culminated in the development of physics based failure models for GaAs and GaN based FETs. More important we report on the development of an integrated fundamental science approach encompassing degradation processes such as the material/heterostructures, bulk, surface and interface states, temperature, strain, and high field effects such as hot carriers and hot phonons generation as well the materials science of contacts and Schottky barriers.