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Reliability of GaN HEMTs: Electrical and Radiation-Induced Failure Mechanisms

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The GaN-based materials system is known to be advantageous for fabrication of RF power amplifiers, high power amplifiers, and high breakdown voltage diodes. A fundamental understanding of the reliability and failure mechanisms in these devices is critical to further technology development and commercialization. Device degradation has typically been attributed to the inverse piezoelectric effect and the hot electron effect however the specific point defects and activation energy for these processes have yet to be determined [1,2]. Furthermore, the chemical inertness and strong bonding of the GaN crystal is intrinsically robust to harsh environments. Given that the non-ionizing radiation hardness of a semiconductor material is inversely proportional to the lattice constant, GaN is predicted to have an activation energy for atomic displacement that is much higher than GaAs or Si. This makes GaN-based devices better candidates in for both displacement and ionizing radiation environments as well. In this work, we investigate the reliability of AlGaN/GaN HEMTs by employing atomic-resolution TEM to identify defects associated with radiation or electric field-induced device degradation, and understand the fundamental electrical stress and radiation-induced failure mechanisms.

The HEMT devices were fabricated on Si substrates using standard processing steps, with a Ni/Au or Pt/Au gate metal and SiN_X passivation. The devices were then cut into individual die and characterized by Hall, I-V, and C-V techniques to obtain the key metrics used to quantify device degradation: Hall mobility and 2DEG density, saturation current (I_{MAX}), off-state leakage (I_{MIN}), on-resistance (R_{ON}), gate leakage current (I_G), and threshold voltage (V_T). The devices were then subjected to either electrical stress or 2 MeV H^+ irradiation. After stressing, electroluminescence imaging was used to identify defective regions suitable for TEM analysis.

Electrical stressing was performed in a vacuum test station designed for high voltage electroluminescence (EL) measurements. The system employs a gate and drain SMU, both of which can be programmed to either hold a constant bias, perform a voltage step stress, or a step-recovery stress. A TE cooled CCD camera is mounted on the microscope and was used to capture EL images as the stress program was executed. A single bright spot was observed to appear at the gate edge relatively early in the stress program. While the intensity increased and more spots appeared during the stress, the location of the initial spot was always the failure point when catastrophic breakdown occurred. Therefore EL imaging can be used to identify the defective regions of the material for TEM analysis. Proton irradiation was performed at Auburn University using a repeated test/irradiation cycle until the devices failed. EL was only performed on a virgin device and a failed device.

After either electrical stressing or irradiation, samples were retested, and devices were identified for TEM analysis. At present only virgin devices have been imaged, however several features are already visible. Notably, there is a feature visible at the gate edge that is indicative of metal movement during the passivation process. A second feature is a step on the surface, which appears to be associated with an incomplete layer spatially restricted by grain boundaries. Analysis to identify the nature of these defects, their chemical environment, and local strain. Future imaging of the stressed and irradiated devices will indicate whether these defects contribute to device failure.

1. J.A. del Alamo, J. Joh. Microelectron. Reliab. 49, 1200-1206 (2009)
2. G. Meneghesso, G. Verzellesi, F. Danesin, F. Rampazzo, F. Zanon, A. Tazzoli, M. Meneghini, E. Zanoni. IEEE Trans. Device Mater. Reliab. 8, 332-343 (2008)

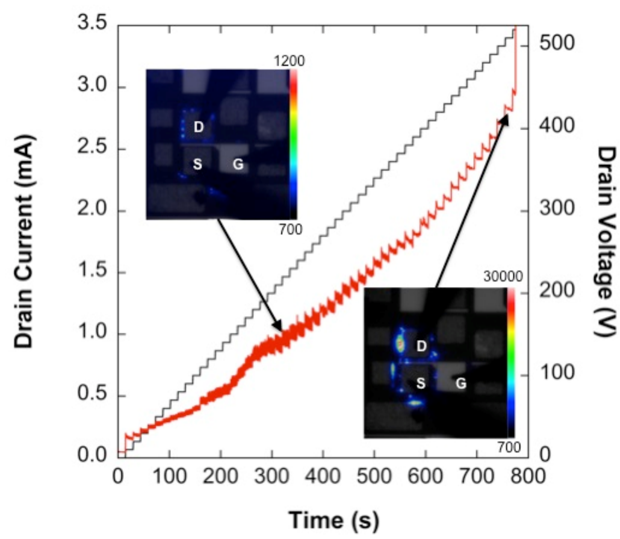

Figure 1. Current-voltage characteristics of the HEMT during the off-state step-stress program, and associated false-color electroluminescence images.

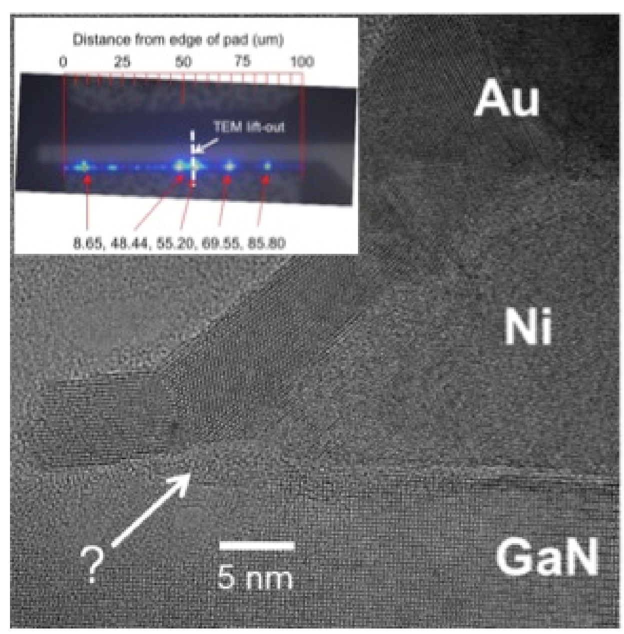

Figure 2.TEM image of process-induced defect at the gate edge of a HEMT. False-color EL image to identify defective region is shown as inset