Degradation of AlGaN/GaN HEMTs below the "critical voltage": a time-dependent analysis

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Despite the excellent performance of AlGaN/GaN HEMTs, the reliability of these devices is still a challenge. Joh et al. [1] indicated that there is a "critical gate-drain voltage" beyond which the gate diode can show a remarkable degradation, which was ascribed to the generation of lattice defects through converse piezoelectric effect. More recently, Marcon et al. [2] suggested that degradation may occur even below the critical voltage. The studies quoted above led to a significant advancement in the understanding of the physical mechanisms that limit the reliability of GaN-based HEMTs. **However, those reports did not analyze how degradation proceeds during stress time: to date, a model capable of explaining how device parameters vary during reverse-bias stress is missing.**

With this paper we present a detailed analysis of the degradation kinetics of AlGaN/GaN HEMTs, based on electrical and electroluminescence (EL) characterization. Experimental data provide evidence for the following, relevant, results: *(i)* **degradation** of GaN HEMTs may occur **even below the "critical voltage"**, for sufficiently long stress times. A "time-to-breakdown" (t_{bd}) can be defined, for each stress voltage level. *(ii)* **before permanent degradation, gate current becomes noisy**, indicating that damage is about to occur; *(iii)* degradation can be ascribed to a defect generation and percolation process. Permanent degradation is reached when a conductive path is generated between the gate and the channel. *(iv)* time-to-breakdown strongly depends on the initial defectiveness of the sample.

The study was carried out on GaN HEMTs, with a 22 nm AlGaN layer (barrier, 26% aluminum content). Drain and Source ohmic contacts are based on Ti/Al/Pt/Au. Gate Schottky contact is based on Ni/Au (40 nm and 300 nm for Ni and Au respectively). Devices were submitted to reverse-bias step stress, to extrapolate the "critical voltage" as described in [1]. As indicated in Fig. 1, devices analyzed within this work have a critical voltage of 35-40 V: a step-stress experiment induces a significant increase in the leakage current of the transistors, with no strong modification in the drain current.

To analyze the time-dependence of the degradation kinetics, we carried out constant voltage stress tests on a number of devices. Constant-voltage tests were carried out below the "critical voltage": typical results are summarized in Fig. 2, for a device stressed at V_G=-30 V, V_D=V_S=0 V. During the initial phase of a constant-voltage stress test (here for t<300 s), both gate current and threshold voltage show a recoverable (and exponential) decrease (Fig. 2). Permanent degradation occurs approximately 300 s after the beginning of the stress test, and consists in a sudden increase in gate leakage current. Before permanent degradation, gate current becomes noisy, indicating that degradation is about to occur (Fig. 2 and 3). After permanent degradation, the amplitude of gate current noise shows a further increase (Fig. 3). EL mapping indicates that permanent degradation consists in the generation of a number of leaky paths under the gate of the transistors (Fig. 4). **Analysis of the EL spectrum emitted by the luminescent spots** (Fig. 5) **indicates that luminescence originates from two different mechanisms**: *(i)* the deceleration of hot electrons injected from the gate, which results in a Maxwellian spectrum; *(ii)* defect-related recombination in the buffer, which results in a yellow emission band superimposed to the main Maxwellian spectrum. Finally, **results showed that permanent degradation may occur even at voltage levels significantly lower than the "critical voltage":** for instance, devices stressed at V_G=-15 V, V_D=V_S=0 V showed a permanent degradation approximately after 10^5 s (not shown here).

Based on the experimental evidence collected within this work, the following model was developed to explain the recoverable (Fig 6) and the permanent (Fig. 7) degradation of GaN-based HEMTs submitted to reverse-bias stress test. The model considers that in the buffer there exist the donor-acceptor pair responsible for yellow luminescence in GaN.

Recoverable degradation When a reverse-bias is applied to the devices, electrons are injected from the gate, and can accumulate in the AlGaN layer, thus determining a decrease in the leakage current (see Fig. 2). When accelerated electrons reach the buffer, they lose excess energy, and this can result in the emission of Bremsstrahlung radiation, with Maxwellian spectrum (Fig. 5, phase 2 in Fig. 6). Energy released by injected electrons can also *(i)* ionize the deep acceptor in the buffer, thus generating the measured yellow luminescence signal (Fig. 5, phase 3-4 in Fig. 6), or *(ii)* induce the transfer of an electron from the valence band to the deep acceptor (phase 5 in Fig. 6). This may result in the generation of a free hole, which is attracted by the negative gate voltage towards the AlGaN/GaN interface (phase 6 in Fig. 6), resulting in a decrease in the threshold voltage (see Fig. 2). This model was verified by 2D simulation, which showed good agreement with the experimental data (not shown here for sake of brevity).

Permanent Degradation For sufficiently long stress times, **defects may be randomly generated into the AlGaN layer**, due to the high applied field, or to converse piezoelectric effect [1]. Increasing trap concentration can result *(i)* in an higher gate current noise (since traps may randomly overlap, see Fig. 2 and 3), even before the occurrence of permanent degradation (Fig. 7 (a)), and *(ii)* in a stronger current collapse (Fig. 7 (b)). The generation of a conductive (defect-related) path between gate and buffer results in the permanent degradation of the gate diode. **Based on this model, permanent degradation is ascribed to a defect generation and percolation process.** Stress tests carried out on a number of identical devices indicated that **time-to-breakdown strongly depends on the initial leakage current level**, i.e. on the initial defectiveness of the devices (see representative data in Fig. 8). The analysis of a large number of samples indicated that **t_{BD} has a power-law dependence on the initial leakage current level** (related to initial defectiveness), for identical devices (with different initial leakage levels) aged under the same conditions.

In summary, with this paper we presented an extensive analysis of the degradation of GaN HEMTs submitted to reverse-bias stress. Results indicate that degradation may occur even below the critical voltage of the devices, for sufficiently long stress times. A model, capable of explaining the recoverable and permanent changes of the electrical parameter of the devices was presented, based on the experimental data.

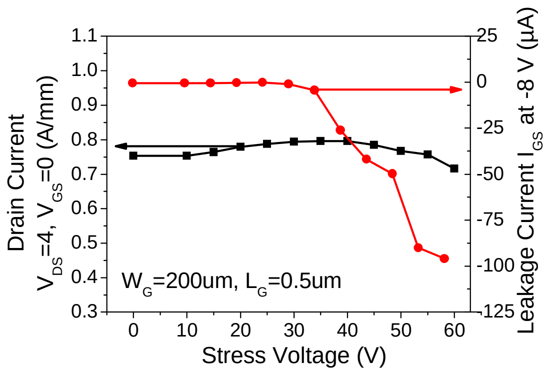

Fig. 1: variation of gate leakage and drain current for a HEMT submitted to a reverse-bias step stress experiment

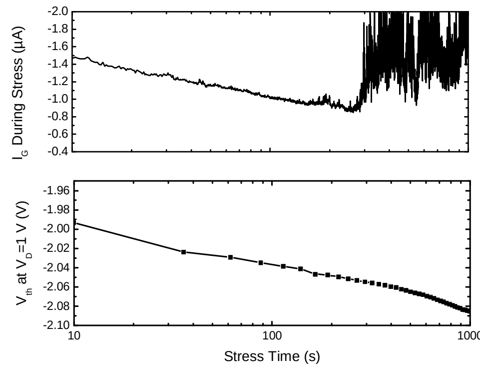

Fig. 2: variation of the (top) gate current and (bottom) threshold voltage for a HEMT submitted to constant voltage stress (V_G=-30 V, V_D=V_S=0 V)

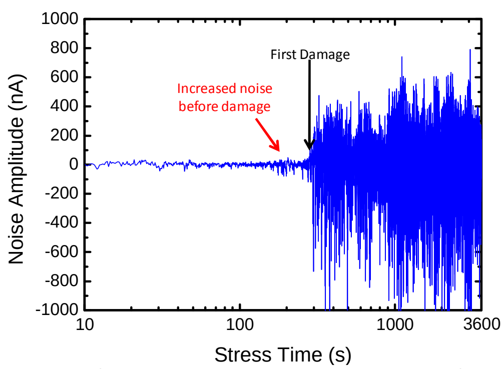

Fig. 3: variation of the noise superimposed to gate current, for a HEMT submitted to constant voltage stress (V_G=-30 V, V_D=V_S=0 V, same device as in Fig. 2)

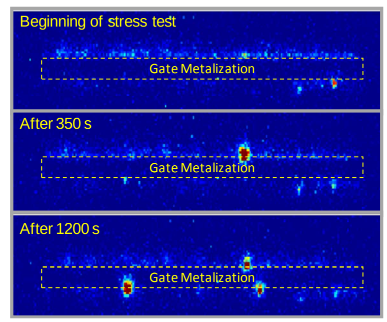

Fig. 4: spatially-resolved EL pattern recorded at increasing stress times on a HEMT submitted to constant voltage stress (V_G=-30 V, V_D=V_S=0 V, same device as in Fig. 2)

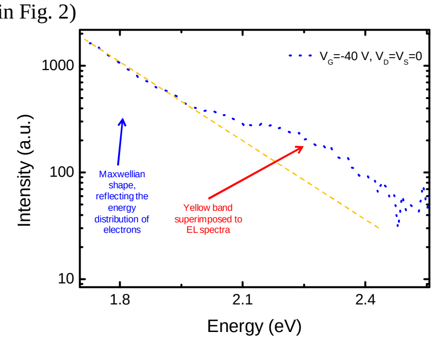

Fig. 5: EL spectrum of a reverse-biased HEMT, collected at V_G=-40 V, V_D=V_S=0 V

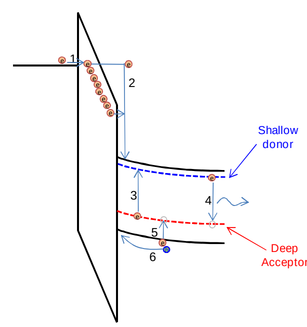

Fig. 6: schematic description of the model used to explain the recoverable degradation of AlGaN/GaN HEMTs submitted to constant-voltage reverse-bias stress

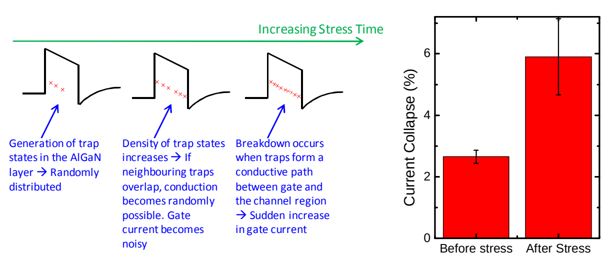

Fig. 7: (left) schematic description of the model used to explain permanent degradation of AlGaN/GaN HEMTs submitted to constant-voltage reverse-bias stress. (right) results of current collapse measurements carried out before/after reverse-bias stress on AlGaN/GaN HEMTs

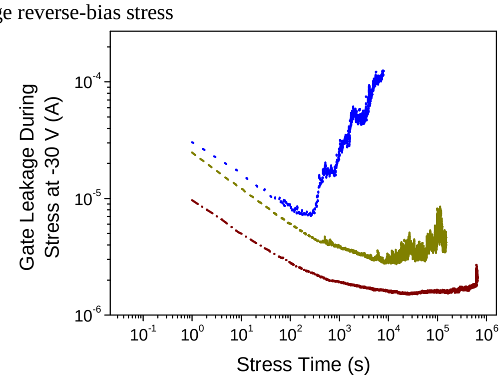

Fig. 8: variation of gate current for three HEMTs submitted to constant voltage stress (V_G=-30 V, V_D=V_S=0 V). The three HEMTs (located on the same wafer) have identical structures, and different initial leakage current levels (due to different initial defectiveness levels). Time to breakdown significantly depends on initial leakage level (this was verified on a larger set of samples, as reported in the text)

References

[1] J. Joh, J. A. del Alamo, Electron Device Letters, IEEE , vol.29, no.4, pp.287-289, April 2008
[2] D. Marcon et al., Electron Devices Meeting (IEDM), 2010 IEEE International , vol., no., pp.20.3.1-20.3.4, 6-8 Dec. 2010