Localization of Off-Stress-Induced Damage in AlGaN/GaN High Electron Mobility Transistors by Means of Low Frequency 1/f Noise measurements

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The location of the time dependent degradation in OFF-state stressed AlGaN/GaN high electron mobility transistors is studied using low frequency 1/f noise measurements, with additional electroluminescence analysis. The gate bias dependence of the 1/f noise is shown to be a powerful tool to illustrate that in addition to the gate edge breakdown, progressive time-dependent trap generation occurs underneath the gate area, possibly extending in the gate-drain access region due to the electric field peak associated with the gate field plate.

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AlGaN/GaN high electron mobility transistors (HEMTs) are considered to be of high potential for high power, high voltage applications. The ever-increasing power demand in radio frequency, industrial, and automotive fields is key for these devices that exhibit both high mobility and breakdown voltage.[1] Charge trapping, material defects, current collapse, and gate degradation are among the main challenges and sources of failure in GaN-based HEMTs.[3] Above all, the gate breakdown is still a limiting factor for achieving long-term reliability at high operative voltages. In this framework, the introduction of field plates and engineered gate shapes significantly mitigated current collapse and reduced gate breakdown occurence.[4] However, electroluminescence (EL) studies still show the appearance of degradation-related hot spots, under harsher stress conditions, at the drain side of the gate edge following OFF-state stress-tests.[5-7]

Low frequency 1/f noise was proven to be a useful tool for reliability studies of AlGaN/GaN HEMTs.[8] Early work revealed higher noise in GaN HEMTs than AlGaAs/GaAs devices due to the larger density of native defects.[9] The relatively high gate leakage current exhibited by Schottky-gate GaN HEMTs is also one of the main limiting factor which can contribute to the channel noise.[10] However, recent material advances and the reduction of surface and barrier defects have improved the noise performance of AlGaN/GaN HEMTs.[11] Electronic generation-recombination trap states close to the Fermi level can be effectively measured based on low frequency noise and used to extract trap characteristics, such as activation energy, capture cross section, and trap density, as well as monitor device degradation during reliability tests.[12,13] The gate voltage dependence of the normalized noise spectral density was reported by other authors to be applicable to GaAs and GaN devices, demonstrating the ability to isolate the effect of noise in different areas of the device channel. To date, this approach has not been used to benefit the understanding of device damage during reliability tests.

In this letter, the gate voltage and drain current dependences of the 1/f low frequency noise and EL signal are shown to be of great benefit to monitor and localize the damage in different parts of the GaN HEMT channel during OFF-state stress tests.

AlGaN/GaN HEMTs grown by metal organic vapor phase epitaxy on silicon carbide substrates were studied. The silicon nitride passivated devices had a 4 µm source-drain gap, a metal T-gate of 0.5-µm length, a channel width of 100 µm, and a 22-nm AlGaN layer thickness. Devices were stressed at room temperature in OFF-state condition at V_{gs} = -6V and V_{ds}= 35V for 30 hours, with inter-mediate noise and EL characterization. For the noise measurements, the devices were operated in the ohmic regime with V_{ds} = 50 mV and the source current measured with a wideband, low-noise current to voltage (*I*-*V*) converter. Electrical characterization was performed with an Agilent 4156A parameter analyzer. EL imaging in the visible spectral range was performed using an Opticstar charge-coupled device camera. The EL signal was recorded from the back side of the wafer via a retro-reflector system in order to probe the whole device area underneath the gate with micron resolution.

Figure 1(a) shows the I_d-V_{gs} characteristic before and after 30 hours of OFF stress in the linear regime V_{ds}= 50 mV, with the inset illustrating the degradation of the reverse gate current and figure 1(b) the evolution of the gate leakage at fixed stress bias. Initial degradation (soft-breakdown - SBD) is apparent as a first jump in the leakage current (figure 1(b)) followed by a wear-out phase that correlates with the increase, up to three orders of magnitude, of the reverse gate current as shown in the inset of figure 1(a). In agreement with other authors[5,7,14], the degradation is apparent in the emergence of a large gate leakage current while other device parameters, such as threshold voltage V_T, drain current I_d, and on-resistance R_{on}, were affected by OFF stress by less than 10%.

The low frequency spectral noise current density S_I is shown in figure 2 for V_G=V_{gs}-V_T = 0.1V, indicating a progressive increase by up to two orders of magnitude with stress time.

The 1/f spectra represent the noise contribution from the channel and potentially from any leakage path through the AlGaN barrier. Gate leakage current fluctuations can in fact contribute to the measured noise.[10] However, since we measure the noise in the source current, and in the bias conditions used here most of the gate leakage current flows to the drain, any gate noise contribution is minimized. Any residual contribution is likely to be small, since according to Ref. 10 gate-leakage related noise in devices that exhibit Hooge parameters above 10^{-4} does not dominate the measured channel noise. In the devices reported here Hooge parameters[15] before stress in open channel and weak inversion were in the 10^{-3} and 10^{-2} range, respectively. Hence, in the following analysis it is assumed that only the channel noise contributed to the measurements. We note that although high values of Hooge parameters usually indicate a poor-contact technology in which the noise is basically controlled by the source and drain terminals,[13,15] this is not the case here, as shown later.

In order to locate the source of the noise in the channel area before and after stress, i.e. how the stress-induced damage is actually created, the gate voltage dependence of the normalized current spectral noise density S_I/I^2 was studied. The HEMT channel resistance can be considered as the sum of two independent parts $R_{CH}=R_G+R_U$, where R_G and R_U are the resistances of the gated and ungated channel, respectively. Three regions were observed when S_I/I^2 was plotted versus $V_G=V_{gs}-V_T$ for a given frequency (10 Hz in this work), where V_T is the threshold voltage extracted from the linear I_d-V_{gs} curve. When S_I/I^2 is proportional to V_G^{-1}, noise from the gate region ($S_{I,G}$) dominates and $R_G \gg R_U$. In the transition region, where $S_I/I^2 \propto V_G^{-3}$, the gated part of the channel contributes to the noise, but the drain-source resistance is already dominated by R_U, i.e., $R_G < R_U$. When noise is independent of V_G, only the ungated device channel noise ($S_{I,U}$) contributes and $R_G \ll R_U$.[15,16] This illustrates the potential of this method for distinguishing the evolution of the damage and to monitor the creation of the defects in the device channel during stress.

Figure 3 depicts the change of the normalized current spectral density noise S_I/I^2 versus the effective gate voltage V_G before and during OFF-state stress. Immediately after the onset of the SBD, no increase in channel noise, neither in the gated nor ungated part, was apparent, even after several EL spots emerged, as demonstrated in figure 3(a) and its inset, respectively. It is worth noting that EL spots were recorded neither in fresh devices nor in the gate-drain access regions. SBD-related hot spots located at the gate edge and the relative gate leakage current increase (figure 1) therefore appears to be independent of the channel noise. At longer times after the SBD event, i.e., during the subsequent device stress in the wear-out phase, S_I/I^2 increased only in the V_G^{-1} and V_G^{-3} regions as shown in figure 3(b) after 2 hours of stress. Hence, the increase of the stress-related defect density underneath the metal gate, possibly where the electric field peaks, led to the noise increase only in the $S_{I,G}$ region. However, subsequently, after 30 hours, S_I/I^2 increased also in the V_G^0 part of the characteristic reported in figure 3(b), i.e., the ungated portions of the channel. Not only was there an associated increased number of EL spots at the gate edge, but the changes in noise spectrum were characterized by defects possibly generated over an extended portion of the channel, in the gate-drain access region, perhaps associated with the additional electric field peaks at the T-gate corner field-plate edge.[17]

In order to model the measured channel noise, the normalized current spectral density S_I/I^2 taken at 10 Hz was plotted in figure 4 versus the drain current as a function of the stress. Good correlation with the $S_{VFB}(g_m/I_d)^2$ characteristics was found, where S_{VFB} as input-referred spectral noise density was adjusted here to achieve a good fit to the data, and g_m/I_d extracted from the measured characteristics during stress. This indicates that the channel noise can be modeled by the carrier number fluctuation model based on trapping and de-trapping of charge in defects close to the channel interface.[18] Assuming the defects were located in the AlGaN barrier, from the input-referred spectral noise density S_{VFB} extracted from the fitting of figure 3, it was possible to determine the density of near-interface traps N_{ot} with the following[19]:

$$S_{VFB} = \frac{q^2 kT\lambda N_{ot}}{WLfC_b{}^2} \;, \qquad (1)$$

where λ= 0.5 nm is a tunneling parameter, here corrected for the AlGaN/GaN conduction band alignment, W and L are the gate width and length, respectively, and C_b is the AlGaN barrier capacitance. From equation (1), N_{ot} resulted, before stress, after 2 hours, and after 30 hours of OFF stress about $2\text{x}10^{16}$ $\text{eV}^{-1}\text{cm}^{-3}$, $1\text{x}10^{18}$ $\text{eV}^{-1}\text{cm}^{-3}$, and $2\text{x}10^{19}$ $\text{eV}^{-1}\text{cm}^{-3}$, respectively. This model assumes a uniform generation of defects in area, depth, and energy in the AlGaN barrier underneath the gate and must be considered as an upper bound value. In fact, it is likely that defects were mostly generated in a narrower barrier region close to the gate edge where the electric field peaks. This assumption can work for short channel transistors, where the ratio between the damaged area at the edge and the rest of gate area is close to 1, but definitely breaks down in long channel devices, where the ratio is << 1. It is possible that these stress-induced traps are linked to the gate SBD, with gate leakage occurring by percolative transport through defects. This is in reasonable agreement with Ref. 20, where the gate leakage current random telegraph signal fluctuations through the AlGaN barrier were explained in terms of modulation of leakage paths in the AlGaN barrier by the generation of other percolative paths and single active traps[20] during OFF stress.

In conclusion, time-dependent damage in AlGaN/GaN HEMTs induced by the OFF stress-test was studied by means of gate bias dependence of low frequency noise. This approach was demonstrated to be useful not only to identify in which device area active defects were generated during device stress, but also to obtain quantitative defect generation estimates. 1/f noise behaviour suggests that stress-induced generation of defects occurs in the AlGaN barrier, in addition to those defects related to the gate-edge breakdown. These defects are primarily located underneath the gate, but extend into the high field gate-drain region, possibly associated with the field-plate edges.

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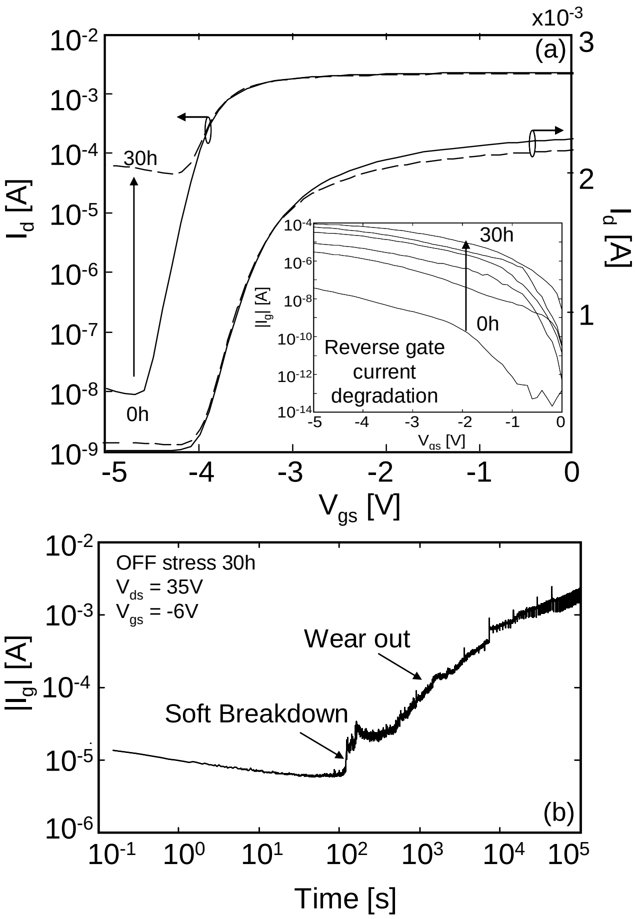

FIG. 1. (a) DC drain current (V_{ds}= 50 mV) in linear and logarithmic scale and reverse gate current degradation (inset) as function of the gate voltage before and after OFF-state stress; (b) gate leakage current as function of the stress time.

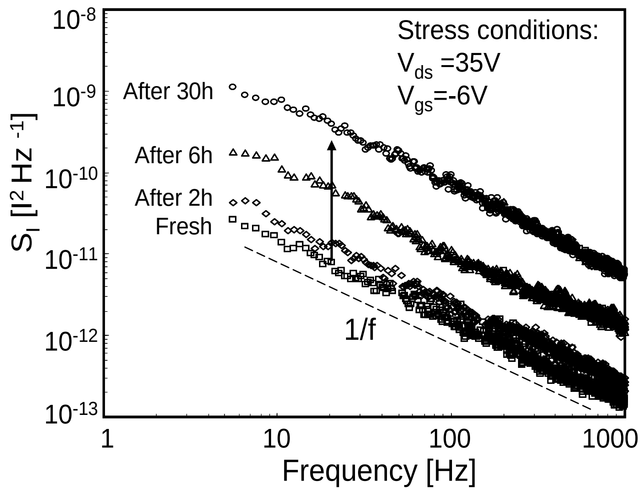

FIG. 2. Low frequency 1/f channel noise current spectral density in OFF stressed AlGaN/GaN HEMT for V_{gs}-V_T ~ 0.1V.

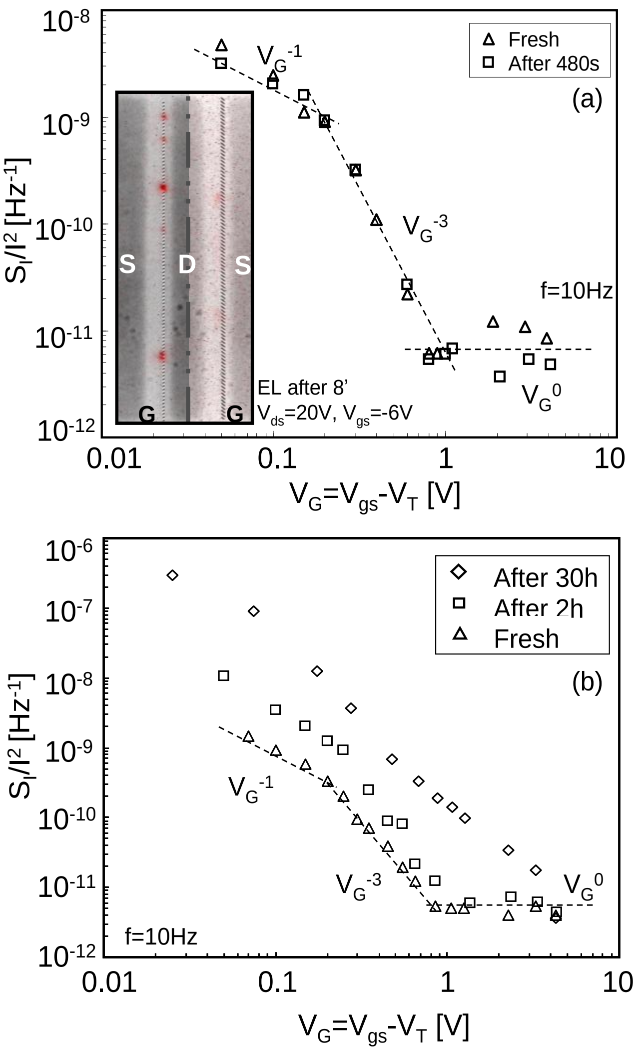

FIG. 3. Gate voltage dependence of the normalized current spectral noise density S_I/I^2 at 10 Hz: (a) Before stress and immediately after the SBD with the corresponding EL image in the inset; no hot-spots were recorded in fresh devices. (b) Before stress and after 2h and 30h of OFF-state stress.

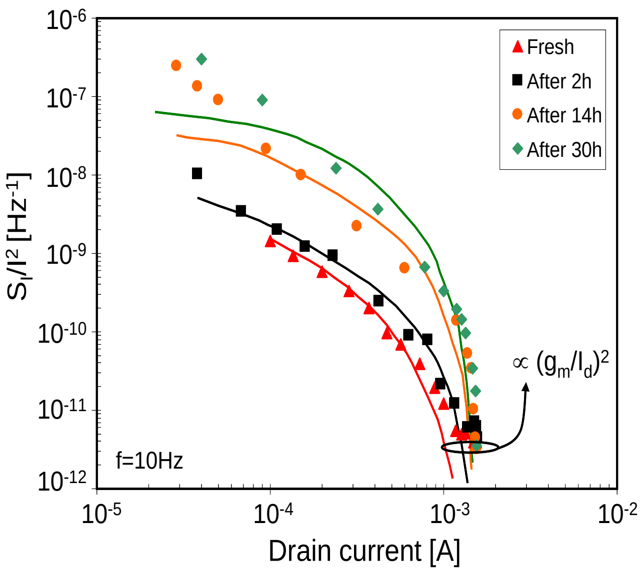

FIG. 4. Normalized current spectral noise density S_I/I^2 at 10Hz as function of the drain current during OFF-state stress. Data follow the $S_{VFB}(g_m/I_d)^2$ characteristic (solid lines).