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HTRB Stress Effects on 0.15 μm AlGaIn/GaN HEMT Performance

P. Vigneshwara Raja¹, Jean-Christophe Nallatamby², Mohamed Bouslama³, Jean Claude Jacquet³, Raphael Sommet², Christophe Chang⁴, Benoit Lambert⁴

¹Department of Electrical Engineering, IIT Dharwad, Karnataka – 580011, India

²XLIM Laboratory, CNRS, UMR 7252, University of Limoges, F-19100 Brive, France

³III-V Lab, 91120 Palaiseau, France

⁴United Monolithic Semiconductors, 10 avenue du Québec, 91140 Villebon-sur-Yvette, France

Abstract — This paper describes the high temperature reverse bias (HTRB) stress effects on 0.15 μm AlGaIn/GaN high-electron mobility transistors (HEMTs) with Fe-doped buffer. The HEMTs were stressed to OFF-state bias ($V_{GS} = -7$ V, $V_{DS} = 25$ V) at 175 °C for 1000 hours of duration. The subsequent degradation in the drain current is analyzed. The changes in I_G - V_G at $V_{DS} = 0$ V (emulating gate Schottky diode leakage) are investigated before and after the stress to inspect the Schottky gate interface quality. The gate leakage current evolutions are further examined with the V_G and V_D sweeps. After ageing test, the deviation in the emission rate of Fe-related trap at $E_C - 0.5$ eV (located in buffer) is quantified by means of low-frequency (LF) output-admittance (Y_{22}) and drain current transient (DCT) spectroscopy. Moreover, the drift in the output power (P_{out}) during first interim measurement of stressed HEMT is evaluated, with the supporting TCAD simulations. These preliminary HTRB test results are useful to understand the fundamental failure mechanisms of the HEMT due to the ageing in actual operating conditions.

Index Terms — AlGaIn/GaN HEMT, trap, gate leakage, HTRB, power drift, reliability.

I. INTRODUCTION

The ultra-submicrometer AlGaIn/GaN HEMT technologies have proved effective for monolithic microwave integrated circuit (MMIC) and RF power amplifier (RPFA) applications. Nevertheless, the long-term reliability of the HEMT still needs further improvement for extending their operational lifetime. Before delivering the product to the market, the performance and reliability of the HEMT must be thoroughly checked to verify if the device will sustain the real-world environmental stresses and remain to meet the future demands [1]. The accelerated bias ageing test such as high temperature reverse bias (HTRB) encompasses elevated temperature storage and high gate-drain reverse bias to aggravate the various device failure modes with Arrhenius acceleration factor, thus mean-time-to-failure (MTTF) of the device may be anticipated [1], [2]. These reliability studies are useful to identify the root cause of the degradation mechanisms and some hidden failures modes, thereby allowing us to prevent those device failures. Moreover, certain application areas of the HEMT require high power and temperature operation. Therefore, this work is focused on HTRB stress effects on the state-of-the-art 0.15 μm AlGaIn/GaN HEMT characteristics.

The high gate leakage current of the gate Schottky contact is an important factor in affecting standby power dissipation, gate

voltage swing and device reliability [2], [3]. So, a special emphasis is devoted to investigate the HTRB induced changes in the gate current. Particularly, the gate leakage current is analyzed at $V_{DS} = 0$ V condition (imitating gate Schottky diode) to inspect the metal/GaN/AlGaIn/GaN Schottky interface properties, in relative to the pre-stress condition. The electron trapping in the HEMT due to the deep-level traps in the buffer layer reduces the maximum achievable performance during the dynamic operation [4]. The electrically active traps may also promote the gate-leakage current conduction through trap-assisted tunneling and Poole-Frenkel emission [3]. So, low-frequency (LF) output-admittance (Y_{22}) and drain current transient (DCT) characterizations are performed to evaluate the emission time constant evolutions of the Fe-related acceptor trap at $E_C - 0.5$ eV upon the ageing test. Moreover, the drop in the output power (P_{out}) during the first interim measurement of stressed HEMT is inspected by using supporting TCAD simulations. So, these preliminary HTRB test studies are expected to provide a fundamental understanding of the HEMT failure mechanisms due to aging in actual operating conditions.

II. EXPERIMENT

The studied AlGaIn/GaN HEMT structure incorporates Fe-doped GaN buffer layer grown on silicon carbide substrate, followed by AlGaIn barrier layer, and GaN cap layer. The HEMT features ultra-short gate length of 0.15 μm with a gate width of 4×50 μm , nitride passivation layer at ungated surface and source terminated field plate configuration.

The HTRB stress tests were performed at IMS from University of Bordeaux and UMS by Florent Magnier [5]. The HEMTs were stressed to a higher reverse gate-drain bias voltage of $V_{GS} = -7$ V and $V_{DS} = 25$ V ($V_{GD} = -32$ V) at an elevated temperature of 175 °C for a longer time duration of 1000 hours. Subsequently, the HTRB induced changes in the HEMT properties are analyzed.

The drain current and gate leakage current of the HEMT were measured before and after the stress test by using Agilent B1500A Semiconductor device parameter analyzer. The experimental step for LF Y_{22} and DCT is given elsewhere [4]. After ageing test, the Y_{22} parameters were acquired at the same bias point of $V_{DSQ} = 10$ V and $I_{DSQ} = 50$ mA/mm in the frequency range of 100 Hz to 1 MHz for different temperatures 25 °C to 125 °C. In DCT spectroscopy, drain-lag pulsing

scheme (V_{DS} switched from 10V to 20 V for 100 ms pulse width) was employed to populate the traps in the HEMT. Then V_{DS} was reverted to its initial bias point ($V_{DM} = 10$ V) and the emission transient was measured over 1 μ s to 1 s for the temperatures ranging from 25 $^{\circ}$ C to 125 $^{\circ}$ C. The output power of stressed HEMT was measured at $V_{DS} = 20$ V and $I_{DS} = 200$ mA/mm at 5dB gain compression to evaluate the power drift.

III. RESULTS AND DISCUSSION

A. Drain Current Characteristics

Figures 1(a) and 1(b) show the output (I_{DS} - V_{DS}) and transfer (I_{DS} - V_{GS}) characteristics (at $T = 25$ $^{\circ}$ C) of the AlGaIn/GaN HEMT before and after the HTRB stress. The drain current (I_{DS}), magnitude of the threshold voltage $|V_{TH}|$ (positive shift in V_{TH}) and transconductance (g_m) are reduced after the HTRB test, due to the possible degradation in the 2DEG density (n_s) and mobility (μ_s) [6] caused by the thermally accelerated ageing (with Arrhenius rate) and the OFF-state electrical stress effects. As a result, the on-resistance (R_{ON}) of the HEMT increases after the stress experiment, as identified from the linear region of the I_{DS} - V_{DS} properties. Overall, the current driving capability of the HEMT is deteriorated upon the ageing test.

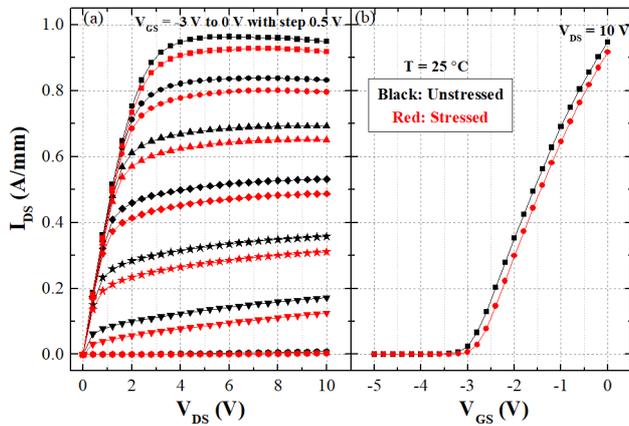


Fig. 1. (a) Output (I_{DS} - V_{DS}) and (b) transfer (I_{DS} - V_{GS}) characteristics of the AlGaIn/GaN HEMT before and after the HTRB stress test.

B. Gate Leakage Current

To analyze the gate Schottky diode interface properties, gate current (I_G) behavior is inspected at $V_{DS} = 0$ V bias condition. The unstressed HEMT characteristics are discussed first. The forward I_G - V_G at $V_{DS} = 0$ V obtained for various temperatures (25 $^{\circ}$ C to 125 $^{\circ}$ C) are shown in Fig. 2. Three different regions of current transport mechanisms are identified in the forward I_G - V_G . As the diode saturation current may only govern the current transport in Region-1, nearly constant and low current (< 10 pA) is observed. Beyond that, two linear regions (2 and 3) with different slopes are noticed in forward I_G - V_G , implying that the gate Schottky interface comprises of two diodes positioned in a back-to-back series arrangement [7]. Using thermionic emission model, Schottky barrier height (SBH) for the two-diode model (at 25 $^{\circ}$ C) is extracted as 1.15 eV (SBH-1) and 0.72 eV (SBH-2), respectively. The ideality factor (n) for the two-diodes is found to be 1.66 (n_1) and 4.36 (n_2) at 25 $^{\circ}$ C. The two-

diode model suggests [7] that the first diode is associated with the typical metal/GaN cap interface. While the second diode may be related with the AlGaIn/GaN interface. In this case, the Schottky barrier height (SBH-2) indicates the energy difference between the Fermi level of AlGaIn/GaN 2DEG and the GaN conduction band.

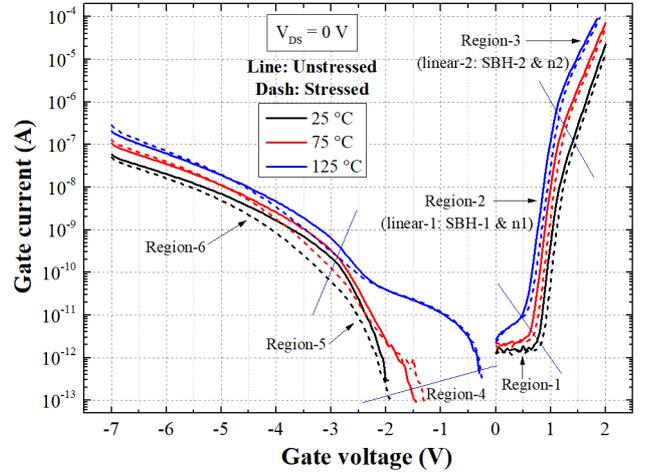


Fig. 2. Temperature dependent (25 $^{\circ}$ C to 125 $^{\circ}$ C) I_G - V_G properties at $V_{DS} = 0$ V of the unstressed and stressed HEMTs, show three different regions of current transport mechanisms on either direction.

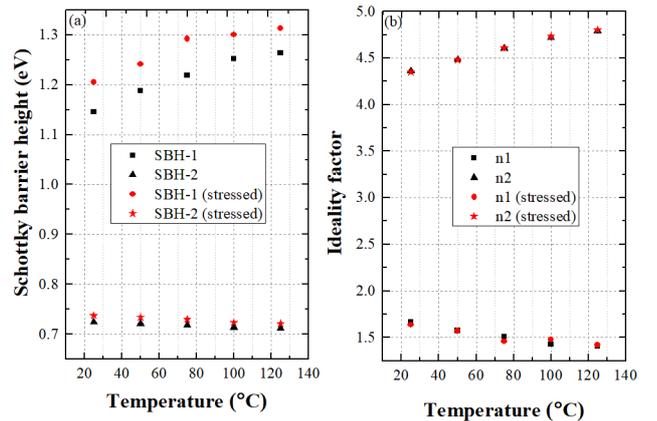


Fig. 3. Temperature dependence of Schottky barrier height (SBH) and ideality factor (n) extracted from thermionic emission theory for the two-diode model, before and after the stress.

The temperature dependence (25 $^{\circ}$ C to 125 $^{\circ}$ C) of SBH and n for the two-diode model is plotted in the Figs. 3 (a) and (b). It is perceived that the SBH-1 (1.15 eV to 1.26 eV) increases and n_1 (1.66 to 1.4) decreases with the increasing temperature (opposite to the expected variation); this behavior can be attributed to the inhomogeneous Schottky barrier at metal/semiconductor interface on the AlGaIn/GaN structure. On the other hand, the second-diode parameters such as SBH2 (0.72-0.71 eV) and n_2 (4.36-4.79) have shown a weak temperature dependency. After the ageing test, the forward I_G is decreased (see Fig. 2), due to the mobility degradation and the corresponding increase in the SBHs, as observed from Fig. 3(a).

The temperature dependent reverse I_G - V_G ($V_{DS} = 0$ V) properties demonstrate three different regions of operation, as represented in Fig. 2. In Region-4, only due to the reverse

saturation current conduction, the leakage current is found to be very low ($\leq 10^{-13}$ A). The possible current transport mechanism in Region-5 is the Poole-Frenkel emission model, viz. field-assisted emission of electrons from a trap near the metal/semiconductor interface to the continuum states corresponds to the conductive dislocations in the barrier layer [3]. In Region-6, the reverse gate current is governed through the Fowler-Nordheim tunneling as identified from the curve fitting of the experimental data. In many reports [3], [8], the electric field variation was considered to be constant beyond the threshold voltage ($< V_{TH}$) because of the depletion of 2DEG under the gate. In contrary, it is noticed from Fig. 2 that the leakage current increases rapidly beyond V_{TH} due to the increase in the surface potential, as similar to the observations of Ghosh *et al.* [9]. Therefore, the electric field profile computed from the TCAD simulation is used for the curve fitting analysis. The reverse I_G - V_G of the unstressed and stressed HEMT is also illustrated in Fig. 2; only a slight change in the gate leakage current at $V_{DS} = 0$ V is noted after the ageing test. Hence, the gate Schottky interface quality is not much affected after the HTRB test carried out for 1000 hours.

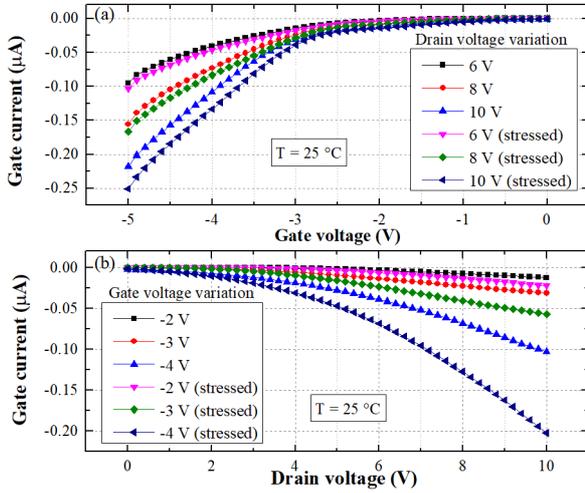


Fig. 4. (a) I_G - V_G for various drain voltages of 6 V, 8 V and 10 V and (b) gate current vs. drain voltage for different V_G (-2 V, -3 V, -4 V) for unstressed and stressed HEMTs at 25°C .

Figure 4(a) shows the HTRB stress induced changes in I_G - V_G characteristics for various drain voltages (6 V to 10 V) at 25°C . It is clear that I_G increases with respect to V_G for different V_{DS} upon on the ageing test. Particularly, the augmentation is more pronounced at higher V_{DS} values. The gate current versus drain voltage properties for different V_G (-2 V to -4 V) are considerably increased in the stressed HEMTs, as illustrated in Fig. 4(b). It is hypothesized that the HTRB stress may induce leakage current paths through the creation of defects in the barrier layer [2]. Thus, I_G is increased after HTRB stress, except for the case of I_G - V_G at $V_{DS} = 0$ V.

C. Y_{22} and DCT Spectroscopy

Figure 5 depicts the LF Y_{22} parameters of the Fe-doped AlGaIn/GaN HEMT measured before and after the ageing test for different temperatures (25°C to 125°C). Prior to the stress test, Arrhenius analysis of the Y_{22} frequency dispersion yields

the activation energy of 0.47 eV. The emission rate of the trap [4] is reduced at each temperature upon the stress, as shown in Fig. 5. Accordingly, small increase in the activation energy (0.49 eV) is obtained from the post-stress experiment. This suggests that the potential barrier for the electron emission from the trap level is bit increased upon the ageing, as a result slightly higher thermal activation energy is computed for the Fe-related acceptor trap in the buffer [4]. Fig. 6(a) shows the DCT spectroscopy of the unstressed and stressed Fe-doped AlGaIn/GaN HEMTs in the temperature range of 25°C to 125°C and their corresponding DCT derivative spectra are plotted in Fig. 6(b). From DCT spectroscopy, small increase in the emission time constant is noted after the stress experiments. However, almost the same activation energy is attained for both the unstressed (0.5 eV) and stressed (0.51 eV) HEMT. One point is evident that the emission time constant of the trap increases after the HTRB stress test.

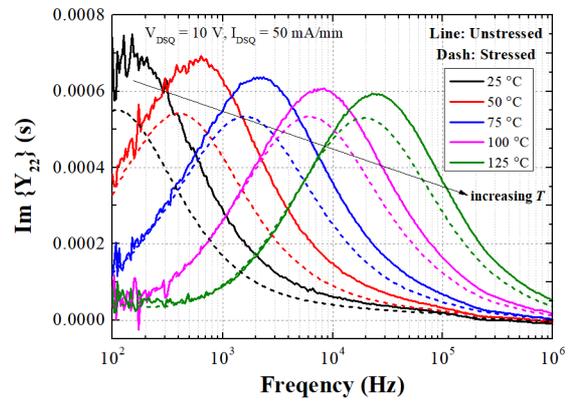


Fig. 5. LF Y_{22} parameters of the HEMT measured before and after the HTRB stress test at different temperatures (25°C to 125°C).

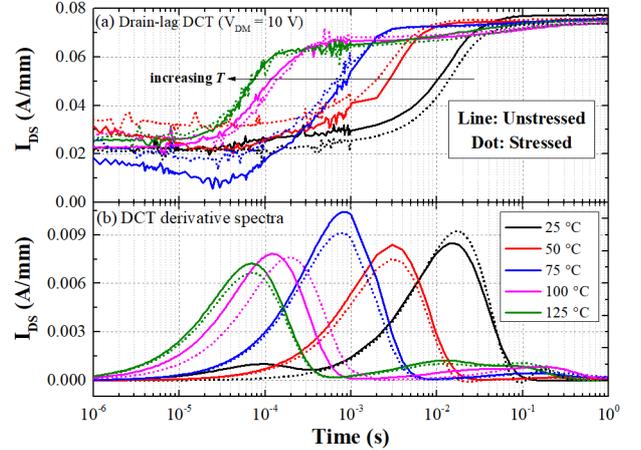


Fig. 6(a). DCT spectroscopy of the unstressed and stressed Fe-doped AlGaIn/GaN HEMTs in the temperature range of 25°C to 125°C and (b) their corresponding DCT derivative spectra.

D. Output Power Drift

Figure 7 shows the variation in the output power (P_{out}) during the first interim measurement for an unstressed HEMT and two stressed HEMT (A and B) devices. The output power is found to decline (power drift) with time in stressed HEMTs, which can degrade the RF and microwave performance of the HEMT.

There is no considerable change in P_{out} for the unstressed HEMT. To determine the possible physical mechanism behind the power drift, TCAD simulations are carried out by introducing acceptor trap at $E_C - 0.53$ eV / $E_C - 0.73$ eV / $E_C - 0.93$ eV in the barrier layer at different location (gate-source region / under gate / gate-drain region).

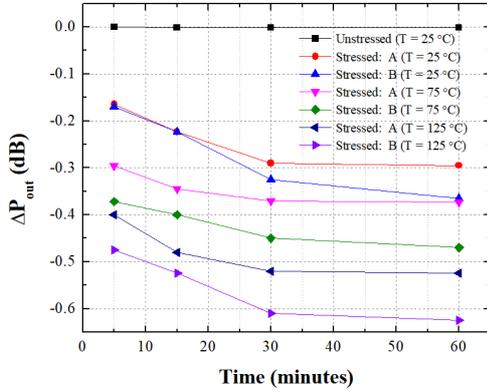


Fig. 7. Output power (at 5 dB gain compression) variation during first interim measurement of unstressed and two stressed HEMTs.

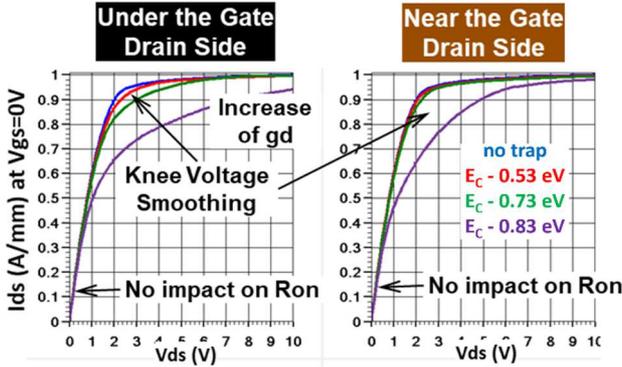


Fig. 8. Identification of knee-voltage smoothing in simulated output characteristics after including acceptor trap at $E_C - 0.53$ eV / $E_C - 0.73$ eV / $E_C - 0.93$ eV under gate and in gate-drain region of barrier layer.

Figure 8 demonstrates the knee-voltage smoothing in the simulated output characteristics after including acceptor trap under gate and in gate-drain region of the barrier layer. The knee-voltage smoothing is not observed by placing the trap in the following locations: (1) source-gate region of barrier layer and (2) any location in buffer region. These observations reveal that the OFF-state electrical and thermal stresses may create defects under gate and in gate-drain region of barrier layer [2], [5], thereby smoothing the I_{DS} during the transition between linear and saturation region of output characteristics. This phenomenon causes power drift in the stressed HEMTs.

IV. CONCLUSION

The HTRB stress effects on the Fe-doped AlGaIn/GaN HEMT are reported. The output and transfer drain current characteristics of the HEMT are degraded upon the ageing test. The forward I_G - V_G at $V_{DS} = 0$ shows that the gate Schottky interface comprises of two diodes positioned in a back-to-back arrangement. The I_G - V_G at $V_{DS} = 0$ is not affected much after the HTRB test, indicating that the quality of the gate Schottky interface is retained. However, I_G increases with further variation in the gate and drain voltages. The emission rate of the Fe-related acceptor trap at $E_C - 0.5$ eV is decreased after the stress experiment, as observed from the LF Y_{22} and DCT. The output power drift is observed during first interim experiment of stressed HEMTs may be due to the creation of defects under gate and in gate-drain region of the barrier layer.

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