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Materials and Strain Issues in AlGaN/GaN HEMT Degradation

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1. Introduction

Progresses in AlGaN/GaN high-electron-mobility transistors (HEMTs) have been really remarkable in the last decade. Power efficiency, breakdown voltage and frequency performance have been steadily improving. Device power densities larger than 40 W/mm at 4 GHz, power gain at frequencies beyond 200 GHz and single devices delivering more than 200 W have recently been reported. From the military microwave applications, the interest on GaN HEMT has spurred to the civil radiofrequency (RF) communications and the power electronics sectors [1,2].

Commercialization has brought the need for device failure and degradation studies, and for a better understanding of the physical mechanisms involved [3]. On the one hand, neither materials growth nor processing are mature yet. On the other hand, GaN presents novel physical concepts due to the symmetry of its wurtzite structure and the huge internal polarization fields. The question if the presence of large dislocation densities and specific trap levels, reported by various groups, may have a role in HEMT degradation, especially at high electric fields, may be posed. In nonintentionally doped GaN HEMTs, layer strain, polarization fields and surface properties are key factors in determining the final channel electron concentration. When facing AlGaN/GaN HEMT degradation and device failure, one would like to delineate those degradation mechanisms more intrinsic in the nitrides from those ones derived from general device processing.

In this presentation we would first consider the case of electric field-induced strain degradation via the converse piezoelectric effect, from both a theoretical and experimental point of view. The idea of strain relaxation through structural defect formation and subsequent effects on the channel electron concentration was originally proposed by *del Alamo's* group based on experimental findings in off-state reliability studies [4]. Next, we will address the point of strain changes that may be produced during certain processing steps or thermal storage tests. The experimental studies that have been conducted, mainly in relation to the rapid thermal annealing (RTA) step needed for ohmic contact formation, will be presented. Besides, considerations about the presence of H in AlGaN/GaN heterostructures (HJ), parasitics linked to traps and traps generated during thermal storage tests will be briefly discussed.

2. Experiments, Results and Discussion

These studies have been carried out under the KORRIGAN initiative (*K*ey *Or*ganization for *R*esearch in *I*ntegrated circuits in *GaN* technology), a large European Programme (29 partners from 7 countries) dedicated to the development of GaN technology for defense applications launched in 2005 [5]. Our laboratory has been involved in several research areas such as materials, processing and reliability. Experimental studies have been conducted using a full set of AlGaN/GaN-HJ wafers and HEMT devices with the same nominal layer structure, grown by several partners and processed by three different laboratories. The large data collection about HJ wafer physical analyses and transistor electrical parameters fostered present work.

Table 1 summarizes the main results derived from our theoretical analysis on electric-field-induced strain relaxation based on the minimization of the electric enthalpy functional. Namely, we found that the overall strain decreases as gate-source voltage (V_{GS}) becomes more negative, i.e. for V_{GS} decreasing in the off state, whereas the opposite behaviour takes place for positive values [6]. The strain variations are more pronounced in the later case due to channel carrier screening, as shown in Table 1. The calculated strain was used to determine the stored elastic energy (U_e), leading to the conclusion that the piezoelectrically-induced degradation is only expected under on-state operation. The data presented in Table 1 were estimated for a nominal transistor structure as that used in project KORRIGAN (i.e., 28% Al content in the barrier and 30-nm barrier thickness). Note that the maximum variation of strain for the source and drain sides is different if the drain-source voltage is not zero ($V_{DS} \neq 0$). This is especially important under on-state operation where the electric field strength can significantly increase in the drain side close to the gate. The on-state results presented in Table 1 are for the source side. In this case, additional tensile stress is generated by the converse piezoelectric effect, increasing the stored elastic energy. Instead, the stored electrostatic energy strongly increases in the drain side for off state operation.

The degradation of AlGaN/GaN passivated HEMTs, with different gate lengths and distances to drain and source, was experimentally studied by stressing independently V_{GS} from -10 to -35 V (hereafter test V_z) and V_{DS} from 0 to 45 V (hereafter test V_x), under off-state conditions in steps of 5 V. Gate (I_G) and drain (I_D) currents were monitored during all experiments in order to detect abrupt changes. Following

each test, *I–V* characteristics were recorded both in AC and DC to assess the impact of the electric field stress on the on-state HEMT operation. That $I_G > I_D$ was found throughout all tests, indicating that no signs of drain-source breakdown were detected. In Fig. 1, we show results for g_m before and after a representative electric-field stress. A significant recovery is produced after storage and UV illumination.

Bias Conditions		**ΔE_z (MV/cm)**	**$\Delta\varepsilon_{zz}$ (%)**	**$\Delta\varepsilon_{xx}$ (%)**	**$\Delta\,\lvert\varepsilon_{zx}\rvert$(%)**	**ΔU_e (MJ/m^3)**
V_{GS}	**V_{DS}**	**$E_{z,0}$=0.51**	**$\varepsilon_{zz,0}$= –0.35**	**$\varepsilon_{xx,0,GaN}$ ~ 0**		**U_e=32.3**
1 V	**20 V**	–0.33	–0.010	~0	1.2×10^{-4}	0.3
–2 V	**20 V**	0.66	0.020	~0	4.0×10^{-4}	–0.6
–8 V	**0 V**	2.63	0.095	-8.4×10^{-4}	0.005	–2.5
–30 V	**0 V**	3.44	0.120	–0.012	0.013	–3.2
–30 V	**15 V**	3.72	0.130	–0.016	0.017	–3.4

Table 1. Maximum variation of electric field, strain and stored elastic energy with respect to V_{GS}=0 and V_{DS}=0 bias conditions (the 0 in the subscripts refers to the values determined under these conditions). E_z, ε_{zz}, ε_{xx} and ε_{zx} denote the vertical electric field (*z* here is the [0001] direction), and the out-of-plane, in-plane and shear strains, respectively.

To determine if some basic processing steps or thermal storage tests may induce strain changes, high-resolution x-ray diffraction (HRXRD) measurements were performed in as-grown HJ samples, just after RTA for ohmic contact processing, and in processed HEMT samples. As an example, Fig. 2 shows that a change in the GaN and AlGaN diffraction peak angle, i.e. the state of deformation, is produced after the processing. In the inset, a zoom around the AlGaN diffraction peak is presented, where the position clearly shifts after processing. In this figure, the grey line represents the simulation results of the as-grown measured sample. Electrical characterization data along each of these steps and their correlation with structural characterization results will be presented.

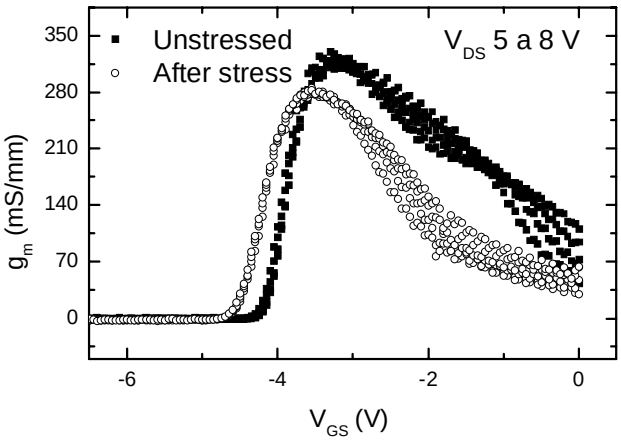

Figure 1. g_m as a function of V_{GS} at different values of V_{DS} before and after step-stress experiments under off-state operation.

The incorporation of H in AlGaN/GaN HJ grown by H-free and H-containing precursors was determined by nuclear reaction analysis (NRA). It was shown that the presence of H is independent of the growth technique and its profile decreases from the surface to become negligible at the GaN layer. Its origin seems to be related to post-growth incorporation and it was found that H surface concentration depends on sample topography [7].

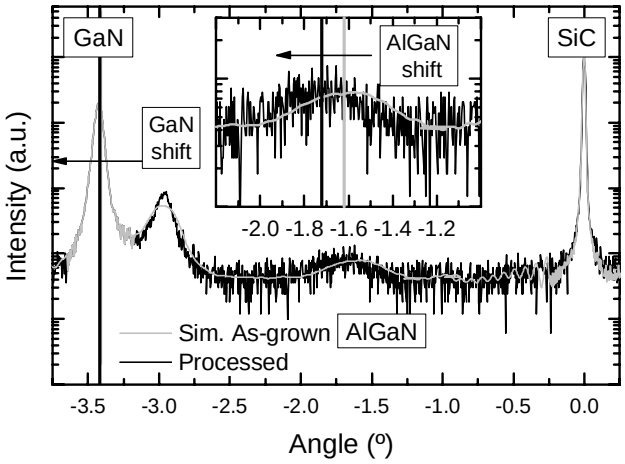

Figure 2. 00.6 XRD for standard as-grown (black line) and processed (grey line) wafers.

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