P. Kurpas, I. Selvanathan, M. Schulz, J. Würfl

Performance Benchmarking of European GaN Epitaxial Wafer Suppliers in Comparison with Vendors from USA and Japan

Abstract

AlGaN/GaN HFETs have been fabricated on epitaxial wafers procured from 9 different vendors worldwide. In order to ensure proper comparability the epitaxial layer specification has been the same for all vendors. After extensive material characterizations all wafers from different vendors have been processed to GaN power HEMT devices using FBH's stable and reproducible GaN process line. Prior to this undertaking the stability of the process line has been verified independently. Results from non-destructive material characterization, on-wafer test structure evaluation and on-wafer DC and RF device measurements revealed remarkable differences in material qualities and allowed for reliable vendor benchmarking. Preliminary lifetime testing demonstrated high reliability of fabricated 1 and 2-mm GaN-HEMTs on epitaxial wafers from selected vendors achieving MTTF up to over 1x10^7 hours at channel temperatures in the range of 250...320°C and 30 or 50 V bias.

Index Terms **- AlGaN/GaN high electron mobility transistor, HEMT, HFET, benchmarking, epitaxy, processing, RF power, DC life test, satellite applications**

I. INTRODUCTION

AlGaN/GaN HFET transistors on SiC substrates are enabling devices for highly efficient RF power devices and are thus devoted to space applications. Remarkable progress was achieved in the last years regarding the epitaxial material supply chain as well as device fabrication.

This document summarises the work undertaken in the ESA funded project on benchmarking epitaxial qualities of GaN-HEMT wafers from different European vendors. FBH has been selected by ESA to perform this challenging project. In addition to the initial proposal, FBH and ESA decided to also include USA and Japanese wafer suppliers.

Thus, the final project goal was to compare GaN-HEMT technology levels achieved in Europe with the worldwide status in this field. For this purpose, FBH acquired wafers with a defined epi-structure from in total 9 vendors; 5 in Europe, 2 in the US and 2 in Japan. Commercial vendors and research institutions as well are represented in this comparison.

II. EXPERIMENTAL

The project was scheduled in following steps

- definition of common epitaxial GaN-HEMT structure and procurement of 3 wafers each from each vendor
- extensive non-destructive material characterizations
- AlGaN/GaN-HEMT device fabrication
- extensive DC and RF characterizations
- preliminary lifetime testing

Regarding the epitaxial structure an AlGaN barrier layer with a targeted thickness of 25 nm and composition of 25% Al and 75% Ga was set as the requirement to the vendors. Additionally, the growth had to be performed on high quality s.i. SiC substrates with 75 mm diameter. The specifications of all other epitaxial layers of the transistor structure, such as for example thickness and composition of the nucleation layer or the GaN buffer layer were left over to the vendors. These structures had been realized according to the vendor's own expertise and particular know-how.

III. RESULTS OF MATERIAL CHARACTERIZATIONS

Extensive non-destructive material characterization was performed on all delivered 36 epi-wafers prior processing. These measurements included:

1. Macroscopic substrate imaging by polarization orthoscopy
2. Double crystal x-ray diffraction (DCDM) mappings of substrate peak intensity and full-width-at-half-maximum (FWHM) values
3. Surface morphology imaging by optical microscope as well as by atomic-force-microscopy (AFM)

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P. Kurpas, I. Selvanathan, M. Schulz and J. Würfl are with Ferdinand Braun Leibniz-Institut für Höchstfrequenztechnik (FBH), Gustav-Kirchhoff-Str. 4, D-12489 Berlin, Germany.

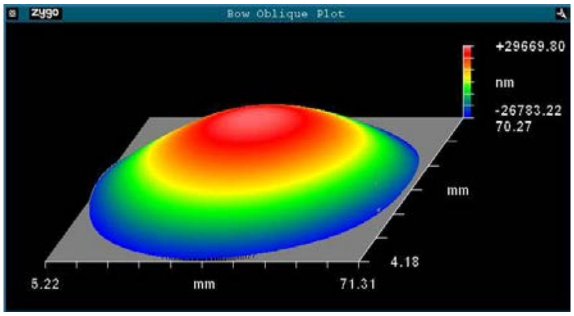

Fig. 1: Example for convex bowed GaN-HEMT wafer with very large total warp of 60 µm.

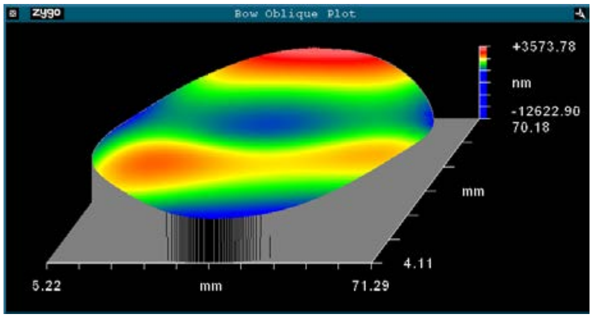

Fig. 2: Example for a comparably flat grown GaN-HEMT wafer with total warp in the range of 1.2 to 2.8 µm.

Fig. 3: Example of a GaN-HEMT epitaxial wafer exhibiting quite high surface roughness (rms=9.2 nm) and moderate GaN buffer layer uniformity (thickness standard deviation of 3.2 % and total thickness variation of 9 %) visualized by Candela^{TM} inspection. An extended defect line in the substrate is detected here, too.

Fig. 4: Result of Candela^{TM} inspection on a wafer, which verified the smoothest surface (rms=1.0 nm) and one of the best GaN buffer layer uniformity (thickness standard deviation of 0.5 % and total thickness variation of 1.3 %) in the benchmarking wafer pool.

4. Wafer warp and surface roughness mappings by surface reflectometry using New View^{TM} optical system
5. Surface defect and roughness mappings by Candela^{TM} optical system
6. GaN buffer thickness uniformity mappings by optical white-light interferometry
7. Assessment of defect density in GaN buffer layer by high-resolution x-ray diffraction (HR-XRD) for (0002) and (30-32) rocking curves
8. AlGaN barrier thickness and composition in wafer centre by high-resolution x-ray diffraction (HR-XRD)
9. Sheet resistance mappings by MRES-2000M system from SWS-Tec/KITEC.

Figures 1 and 2 show two extreme results from wafer warp inspection. Despite of the high warp value of ~60 µm for the wafer shown in fig. 1 it was possible at FBH to fabricate devices on it. On the other hand, fig.2 confirms the possibility to grow quite flat GaN-HEMT wafers. Figures 3 and 4 give results from Candela inspections showing the wide range of surface roughness and GaN buffer uniformity found on the delivered wafers. The obtained results from epitaxial material characterizations were presented at ESA workshops and were partly published [1, 2].

IV. DEVICE FABRICATION AND DC AND RF CHARACTERIZATION

In order to obtain a real meaningful qualification of an epi-wafer the manufacturing of active devices and performing small signal and large signal testing under is indispensible. Thus, a stable and reproducible fabrication process had to be established. Furthermore, the processing should be as invariant as possible toward the observed differences in wafer qualities as described in previous chapter.

For this purpose a mature GaN-HEMT processing has been established on the base of a 0.25 µm T-gate approach with subsequent nitride passivation [3]. Fig 5 confirms the processing stability by showing dc transconductance values of devices from wafers processed in two subsequent fabrication runs as an example. The data points are forming unique pairs being representative for the respective epitaxial wafer suppliers.

Careful device analyses revealed large, vendor dependent differences of transistor performances for both, DC and RF testing:

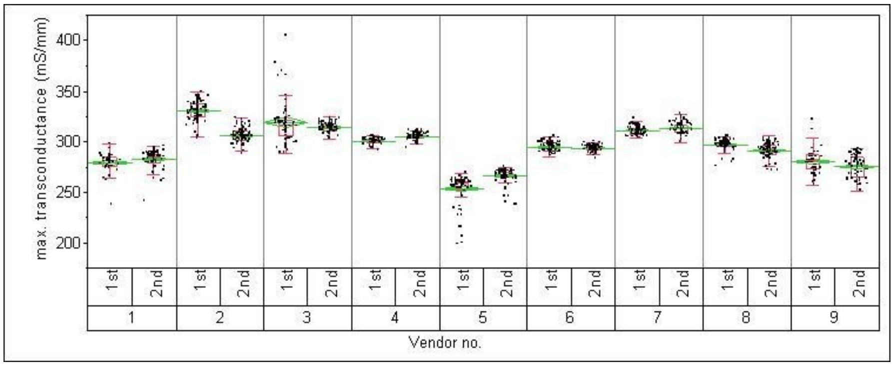

Fig. 5: Maximum transconductance of 2x50 µm AlGaN/GaN-HFET measured on pairs of wafers (1st and 2nd wafer) from 9 different vendors (vendors 1...9) processed in two subsequent runs (mappings of 148 transistors each per wafer).

- breakdown voltage ranging from 30 up to 200 V for a gate-drain-distance of 4 µm,
- gate and sub-threshold leakage current levels from few µA/mm to several 100 µA/mm,
- drain-lag factor between 10 and 38%,
- RF output power levels in the range of 4...6 W/mm at 28 V operation at 2 GHz (2x125-µm device),
- corresponding power-added efficiencies PAE between 45 and 62%,
- linear gain in the range of 21...27 dB.

V. ESTABLISHMENT OF CORRELATIONS BETWEEN MATERIAL AND DEVICE PROPERTIES

In this project a large data base was established from material characterizations prior to processing and the parameters obtained from processed test structures and GaN HEMT devices. Thus, correlations between device performance and epitaxial layer qualities could be established. Figures 6 and 7 show an example for a non-uniform distribution of breakdown voltage on a GaN-HEMT wafer from a particular vendor. This distribution could be correlated with instabilities of growth rate in this epitaxial reactor which indicate a non-uniform distribution of defects in the GaN buffer layer.

VI. PRELIMINARY RELIABILITY ASSESSMENTS

In the limited scope of this project only preliminary lifetime testing could be performed. For this purpose accelerated aging of 6 packaged GaN-HEMT transistors each from 5 selected vendors was done at base-plate temperatures of 150 and 175°C. The bias points were set at a drain voltage levels of 30 or 50 V and dissipated power levels of 4.5 or 7.5 W/mm respectively. The lifetime tests have been performed at three different channel temperatures (250, 280 and 320°C). In accordance with the GREAT^2 project funded by ESA, the device failure criterion was defined as a 10% decrease in drain current measured at V_{gate}=1 V after cool-down to room temperature. Fig. 8 gives an example of obtained results confirming different stability of devices processed on wafers from different vendors. Some of the devices biased at 30 V did not yet (after 6500 hours) reach the failure criterion. Similar high stability of ~4000 hours has even been achieved at 50 V and $T_{channel}$=320°C for devices fabricated on wafers from particular vendors [4]. Fig. 9 shows the mean-time-to-failure (MTTF) evaluation for devices processed on wafers from 3 different vendors. Large differences in activation energy ranging from 0.25 to 1.15 eV were determined indicating different degradation mechanisms. Best MTTF values of ~1x10^7 hrs for operation at $T_{channel}$=125°C were obtained. They are verifying the high reliability level obtained for GaN-HEMTs processed on optimum balanced epitaxial material.

VII. HARDWARE DELIVERIES

After demonstrating its stable and reproducible GaN-HEMT process, FBH was offered the opportunity to provide devices for a payload experiment testing device sensitivity to cosmic radiation on board of the Alphasat communication satellite [5]. In this connection, FBH fabricated GaN devices especially optimized for the payload experiment designed by the University of Aveiro and EFACEC, both based in Portugal. The devices are incorporated in a 2 GHz oscillator experiment which enables remote sensing of its own parameters (e.g. output power, DC-currents etc.) once being space-borne in the geostationary orbit [6]. The Alphasat launch is scheduled for mid 2012, thus these devices will be one of the first European GaN-HEMT transistors in space.

CONCLUSIONS

On the base of extensive epitaxial material characterizations and taking advantage of optimized GaN-HEMT technology the goal of the benchmarking project was successfully achieved. The collected data provide a baseline technology reference for future fully space-approved GaN HEMT devices.

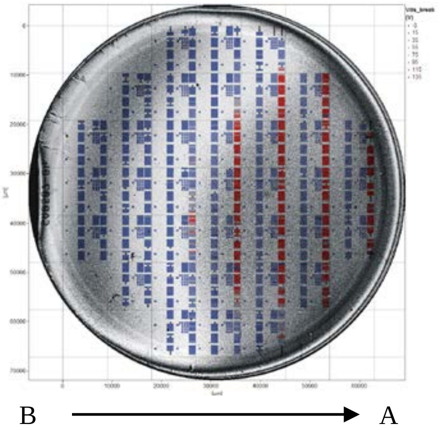

Fig. 6: Breakdown voltage device mapping superimposed with optical Candela wafer inspection prior processing. The dark blue symbols are representing weak devices with low breakdown voltage, whereas the light blue and the red symbols are characterizing high performance devices.

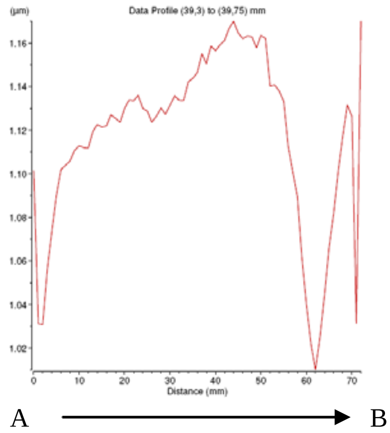

Fig. 7: GaN buffer thickness profile along the diameter of wafer shown in fig. 6 exhibiting the unusual non-rotational thickness distribution on this particular GaN-HEMT wafers.

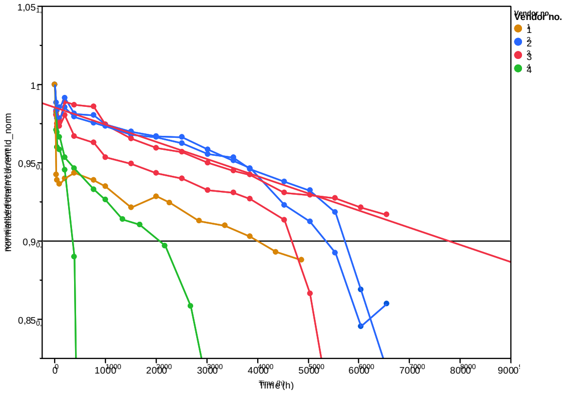

Fig. 8: Evolution of normalized drain currents with time of stress testing at V_{ds}=30 V, P_{diss}=4.5 W/mm, $T_{baseplate}$=150°C giving a channel temperature of $T_{channel}$~250°C (8x250-µm GaN-HEMT).

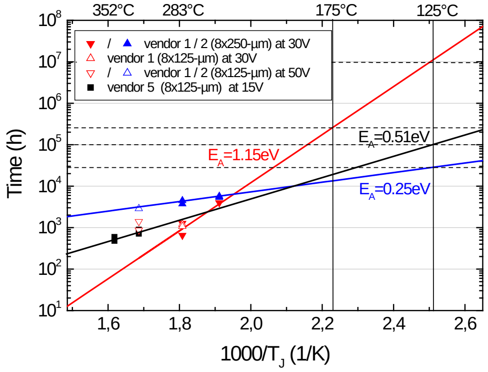

Fig. 9: Arrhenius plot of lifetime results at channel temperatures of 250, 280, 320 and 345°C and at V_{ds}=15 / 30 / 50 V on 1 and 2-mm devices processed on epitaxial wafers from 3 different vendors.

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