Multi-technique characterization of GaN-based devices: a powerful tool to probe the in-depth chemistry

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Gallium Nitride (GaN) technology has proven to be a contender for power electronic applications and has shown its suitability for GaN-based devices such as High Electron Mobility Transistors (HEMT) for high-frequency applications. However, the miniaturization of the device dimensions, such as gate length, requires a thorough mastering of device fabrication process with the help of suitable analytical techniques. In particular, systematic electrical characterization has shown that the interface states have a significant impact on the electrical performance and long-term reliability of GaN HEMT devices. This work ambitions to develop a robust methodology to perform advanced chemical characterization of GaN transistors and better understand how the chemistry of the constitutive layers and interfaces properties impact the electrical response. In addition to STEM/EDX analysis on cross sections, conventionally used to access quantitative information and epitaxy quality, an innovative methodology combining X-ray photoemission spectroscopy (XPS) and Auger Electron Spectroscopy (AES) is developed. Indeed, these techniques not only provide access to elemental compositions but also to key information on chemical environments, especially modifications induced by each technological step during device fabrication. In particular, (nano)-Auger spectroscopy, with its high spatial resolution (12 nm), is a very promising tool to access buried interfaces directly on cross-section, bringing complementary information to STEM/EDX such as oxidation states or contaminant presence. If the added value of this multi-technique approach is obvious, the direct implementation and interpretation of XPS and Auger analyses is not straightforward. In fact, access to the ultimate composition of any GaN-based structure is conditioned by the fitting procedure to ensure a reliable nitrogen content determination. We propose here a reliable methodology to decompose gallium $L_2M_{4.5}M_{4.5}$ transition and nitrogen N 1s photopeak overlap for precise quantification. We will show how these preliminary results obtained by XPS and STEM/EDX analysis are crucial for an accurate interpretation of Auger spectrum acquired on the same materials with the nano-probe for chemical state identification and to refine the quantification. The correlation between structural observations, chemical information and electrical performances measured on a HEMT transistor will be illustrated on a concrete case.

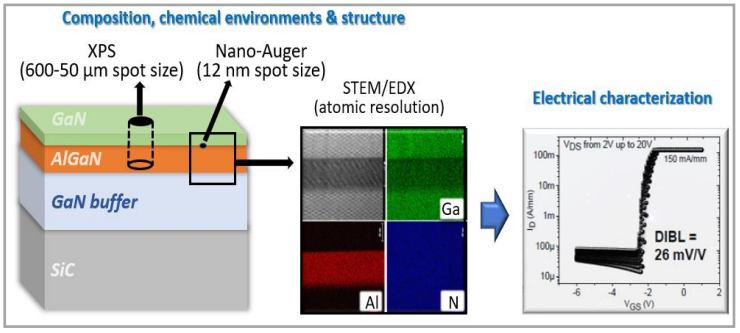

Figure 1: Overview of the multi-technique methodology employed for GaN devices characterization

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Supplementary Pages (Optional)

Gallium Nitride (GaN) technology has made drastic progress in the development of GaN-based HEMT devices over the past 10 years [1]. However, these electrical devices still require a thorough optimization of several phenomena such as high trapping effects which degrade the dynamic performance of GaN components. Although the understanding of these phenomena is not fully mastered, studies have shown that the interface states have a significant impact on the electrical characteristics of GaN HEMT devices [2]. To address this issue, we propose an innovative methodology combining STEM/EDX, XPS and nano-Auger to accurately characterize the composition at critical locations in the transistor structure, among them interfaces.

A first study combining the X-Auger electrons spectroscopy (X-AES) transitions simultaneously obtained with the X-ray photoemission spectroscopy (XPS) photopeaks using an Al-Kα source has been carried out. In HEMT transistor cases, several issues are identified: the depth probed by the XPS (≈ 10 nm) can be higher than the structures' multilayers thicknesses [3] and, in addition, Ga $L_2M_{4.5}M_{4.5}$ transition and nitrogen N 1s photopeak overlap. The use of a Mg source may not resolve the issue as another Auger line will be superimposed to the nitrogen photopeak. Thus, access to the ultimate composition of the HEMT structure may become a difficult process leading to erroneous information. The fitting method developed in this study for XPS data allows the modeling of Ga $L_2M_{4.5}M_{4.5}$ (~ 395 eV) and Ga $L_3M_{4.5}M_{4.5}$ (~ 420 eV) X-AES transitions including N 1s photopeak (~ 398 eV) using oxidized/deoxidized gallium-based references (III-V binary alloys) in order to determine the gallium and nitrogen contributions in GaN based-materials. This new and original approach consists of using the higher energy Auger line (Ga $L_3M_{4.5}M_{4.5}$) to help us find and fix the right fitting parameters on the lower energy transition where the overlap between nitrogen and gallium occurs. As experimental conditions during sample cleaning process could be limited while transferring them with possible exposure to air and results in oxidized surfaces, gallium oxide chemical environment has also been considered. With the aim of reaching buried interfaces, modifications induced by sputtering while depth profiling have been studied for developing a strong and universal methodology for processing XPS data of GaN components. The fitting parameters such as the background, peak positions, area ratio, Full Width at Half Maximum of gallium Auger transitions have been determined for each reference sample. The following figure (2) illustrates the methodology development: Ga_2O_3 sample is used to fix the gallium oxide envelope (a) to separate the oxide contribution from the Ga alloy environment (b), itself used as a base to model the GaN – surface spectra (c). While sputtered with an Ar+ monoatomic ion beam, both Auger transitions from the sputtered GaN sample present a new shape, different from the one on the surface requiring additional contributions (d). Once the sputtering effect is stabilized, the new shape parameters are determined and the fitting method is applied to an AlGaN sample (e) to control

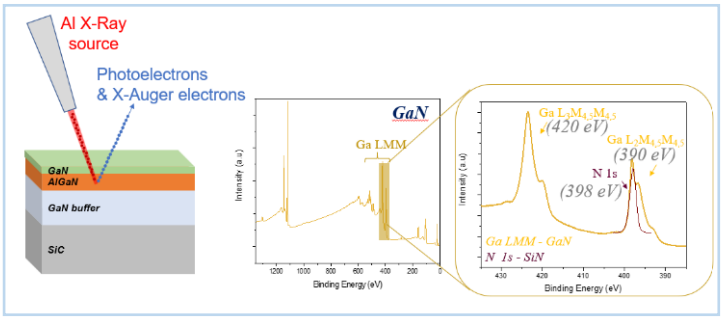

Figure 1: Overlap of N1s/Ga $L_3M_{4.5}M_{4.5}$ region using XPS Al K source

the consistency and reliability of the method. The resulting quantification has been verified by tracking representative ratios for each sample and comparison with complementary STEM/EDX analysis on cross-section.

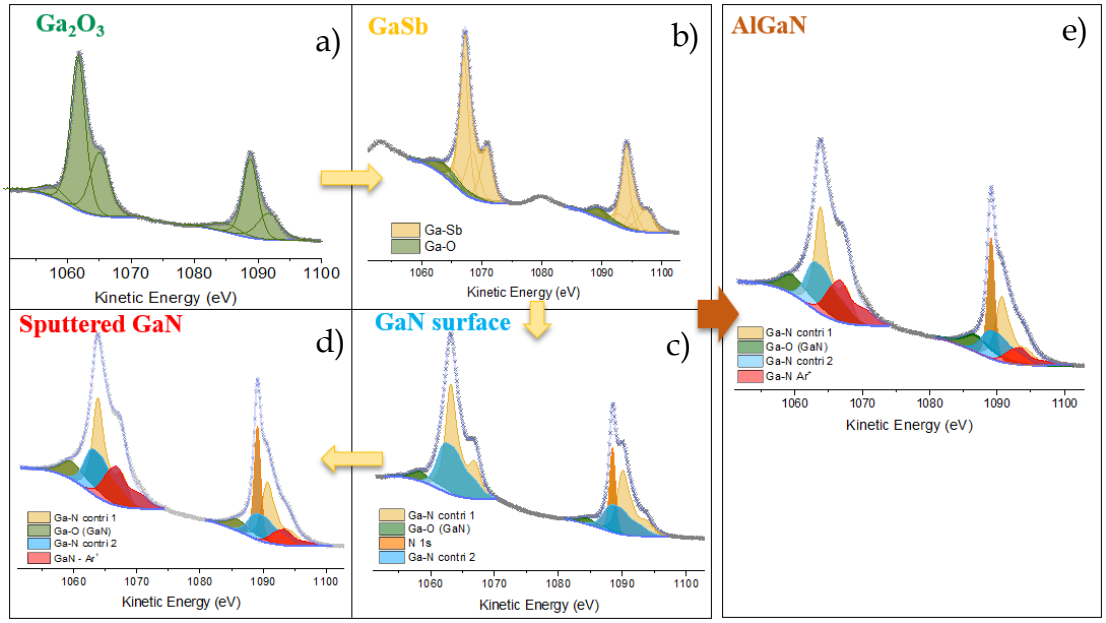

Figure 2: XPS methodology development using a), b), c) Ga-based reference including d) modifications while depth profiling and applied on an e) AlGaN sample

Thanks to the combination of these reference spectra, this innovative analysis method leads to the complete decomposition of an N 1s – Ga $L_3M_{4.5}M_{4.5}$ spectrum and will be a real asset for the analysis at the interfaces of GaN-based HEMT devices. However, the transposition on (nano)-Auger implies the adaptation of the XPS fitting method on Auger spectra, as the generated spectra from the electron source will differ from the one acquired with an X-ray source in many aspects. Moreover, quantification in Auger spectroscopy is usually realized on differentiated spectra. The upstream determination of the different layers composition by XPS and STEM/EDX is mandatory to determine Relative Sensibility Factors (RSFs) for Ga-based materials as these RSF condition the quantification accuracy.

In further studies, HEMT devices' poor electrical performances such as current collapsing or low Drain-Induced Barrier Lowering (DIBL) will be correlated with the device's chemical and structural properties improving the understanding of transistor's behavior based on the multi-technique characterization of GaN-based devices.

[1] L. F. Eastman *et al.*, "Progress in high-power, high frequency AlGaN/GaN HEMTs"

[2] P. Vigneshwara Raja *et al.* "Trapping effects on AlGaN/GaN HEMT characteristics"

[3] Y. Bourlier *et al.*, "In-depth analysis of InAlN/GaN HEMT heterostructure after annealing using angle-resolved X-ray photoelectron spectroscopy"