Contribution of varying accelerating voltage for S/TEM EELS and EDS analysis of AlGaN/GaN based semiconductors

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The integration of Scanning Transmission Electron Microscopy (STEM) with electron energy-loss spectroscopy (EELS) and Electron-Loss Near-Edge Structure (ELNES) has gained significant attention within the microelectronics sector. ELNES, in particular, offers enhanced insights into the local atomic and electronic structures of materials, surpassing the traditional X-ray Energy Dispersive Spectroscopy (XEDS) used for chemical analysis in that regard. This study aims to explore the properties of High-Electron Mobility Transistor (HEMT) devices constructed from $Al_xGa_{1-x}N$ semiconductors, which are designed for high-power and high-frequency applications [1], utilizing EELS. STEM analyses are conducted using a probe Cs-corrected JEOL Neo-ARM 200F, featuring a Cold-FEG and a GIF Continuum spectrometer.
The HEMT device under examination consists of a GaN channel and an AlGaN barrier structure, separated by a few-nanometre AlN spacer to enhance the performance of the 2-Dimensional Electron Gas (2DEG) formed at the interface [2]. Given the substantial lattice mismatch between GaN and Si, an AlN nucleation layer is initially grown on 300 mm Si wafers. Subsequently, $Al_xGa_{1-x}N$ buffer layers with progressively decreasing aluminum content are employed to manage the stress within the structure (Fig. 2 (a)). This buffer configuration facilitates the growth of a crack-free GaN channel, ensuring optimal electron mobility within the device.
In this study, the first objective will be to present the contribution of varying S/TEM accelerating voltage on the limitation of electron-beam damage at the active region interface. In fact, electron-beam irradiation is susceptible to induce sputtering and knock-on damage which are amplified by higher accelerating voltages and low sample thickness with aggravated surface contamination. As illustrated by Fig.1, a conventional high tension (HT) of 200 kV will favour carbon surface contamination as well as leading to the sample deterioration, in that case with the formation of nitrogen dimer at the periphery of a previously scanned area. In that regard, it was shown that the use of lower HT (i.e. 80 and 60 kV) greatly reduces damage and contamination, even at sensible areas as observed by experiments with intensive static-beam irradiations in AlN spacer.
Additionally, the probability of an incoming electron to interact with and ionize an atom is linked to the ionization cross-section of an atom inner shells. Thus, a larger ionization cross-section provided by lower HT [3] will lead to a greater probability of scattering events meaning an increased production of x-rays and increased EELS detections in theory. This phenomenon has been verified in this work on EDS signals of GaN, AlN and Si bulks for various thickness samples, t, (with $t \approx [30, 200]$ nm). Fig.2 shows that for each EDS peak (Al, Ga and N K peaks), we observe a significant increase of peak intensities for lower HT. It is also observed that the profile intensity of the heavier atoms (i.e) Al and Ga K peaks tends to follow the thickness profile where the N K peak intensity profiles in both materials seems to be constant or even slightly decrease for $t > 100$ nm. Furthermore, the contribution of the lower HT to the production of N K x-rays seems to be significantly less important in GaN compared to AlN most probably due to a higher material density of the GaN. This will eventually be confirmed by simulations of the interactions of electron in both AlN and GaN.
Finally, the contribution of lower HT to ELNES analysis of the N K edge (Fig. 3) will also be discussed in order to provide insight on the benefits of each HT in terms of signal intensities, energetical resolution and comparison of the fine structure to simulation, which are key factor for advanced EELS analysis.

References

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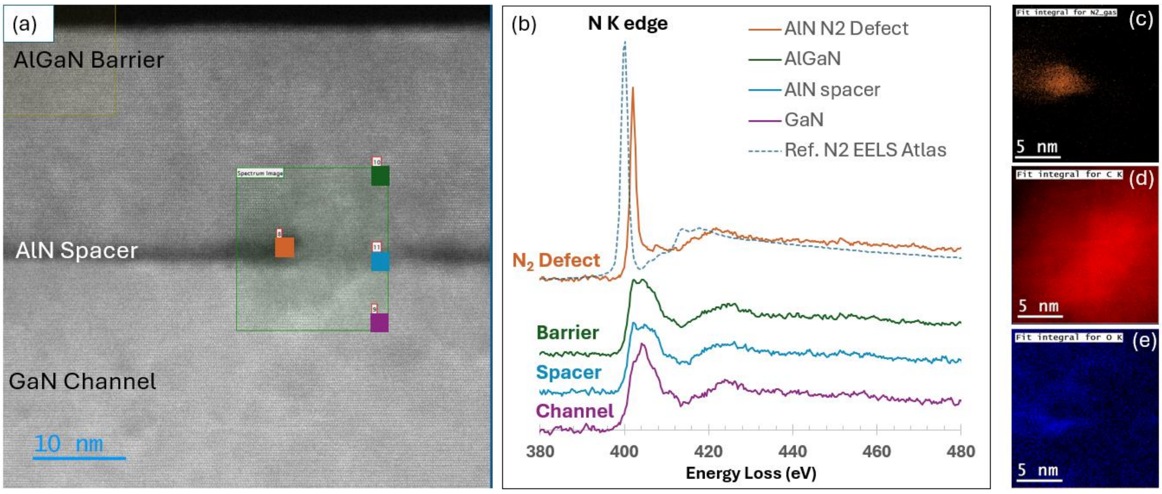

Figure 1. (a) HR-STEM micrograph with spectrum image in active region. (b) N K edges EELS spectrum in barrier, spacer and channel region with N_2 defect formation on AlN spacer at the periphery of the degraded spacer area shown by the loss of contrast observed in (a). (c, d, e) respectively the Mean Least-Squares (MLS) fitting maps of the characteristic N_2 defect observed, as well as the C and O K EELS edges illustrating surface contaminations.

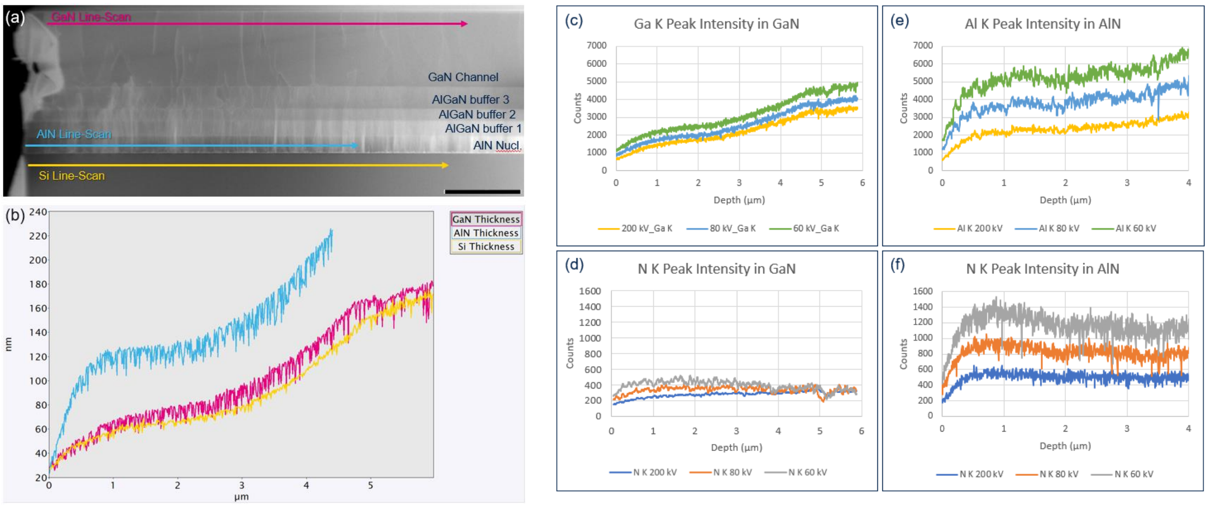

Figure 2. (a) HA-ADF micrograph of the stacking-fault with line scan location for bulk GaN, AlN and Si with their respective thickness profiles calculated from EELS Low-Loss (LL) spectra (b). (c, d) Ga and N K in GaN and (e, f) Al and N K in AlN EDS peak intensities respectively at 200, 80 and 60 kV.

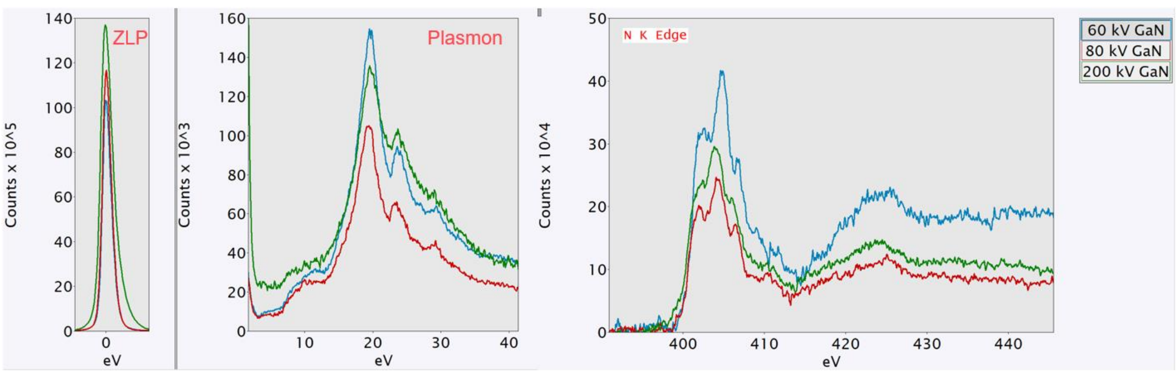

Figure 3. Contribution of lower HT for ELNES analysis in GaN with Zero-Loss Peak (ZLP), plasmon peaks and N K edge ELNES signal at 200, 80 and 60 kV. Slight differences of fine structures of the N K edge can be observed depending on HT with slight shifts in energy and intensities.

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