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Evaluating Epitaxy Quality in Compound Semiconductors Using AC-STEM/EDS

Assessing epitaxial growth uniformity for AlGaN based UV laser diodes and GaAs based vertical cavity surface emitting lasers.

Introduction

Fine control over structural and compositional uniformity during epitaxial growth of compound semiconductors is critical for developing reliable and efficient devices. III-V materials offer a platform for a wide range of devices that can be tailored to specific electro-optical needs by alloying to the appropriate composition. However, many different types of defects and nonuniformities can occur during growth that severely hinder final device performance especially at interfaces and compositionally graded layers. Thus, it is important to evaluate epitaxy quality before device fabrication steps.

In this application note, we will discuss the importance of assessing epitaxial growth uniformity for AlGaN based UV laser diodes and GaAs based vertical cavity surface emitting lasers. By employing aberration-corrected scanning transmission electron microscopy (AC-STEM) we show that we can clearly observe differences in epitaxial layer roughness and composition with atomic level precision.

Nitride Based Epitaxy

AlGaN is commonly employed for high power and UV applications. However, high quality growth is non-trivial and can often result in many undesired features. During growth, step flow growth is the preferred behavior for uniform layers, as step bunching or island growth can result in varied layer thicknesses and compositional segregation. Not only will these affect a single layer, they can translate through the entire structure causing severe non-uniformities in thickness and composition. Here we provide several examples of how AC-STEM with EDS can be utilized to understand epitaxial variations that span from the nanoscale to the atomic scale during growth.

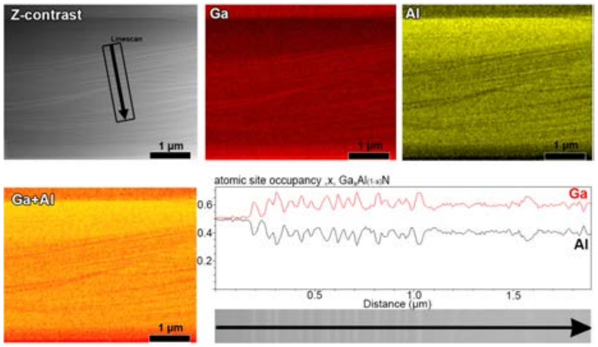

Figure 1 : STEM imaging and EDS analysis in a thick AlGaN epitaxial layer grown on a GaN substrate.

Figure 1 shows a thick AlGaN layer grown on a GaN substrate via MOCVD for laser use. Although the gas flow inputs were unchanged through growth, we observe streaks of bright contrast in the HAADF (Z-contrast) image through the AlGaN layer. The HAADF Z-contrast image intensity scales with the total atomic weight in each column (average atomic number x density). Thus, local changes in intensity are tied to compositional variation. By supplementing Z-contrast imaging with energy dispersive X-ray spectroscopy (EDS), we show supportive evidence that the bright streaks are comprised with higher Ga composition. Further, by extracting a linescan shown by the black arrow in the Z-contrast image, we place the compositional fluctuation on a quantitative scale. As shown in this linescan, the compositional difference between a Ga rich band and the neighboring matrix can exhibit atomic site fraction changes by up to 20 percent. These results can be explained through work by Kataoka et. al., where step edges formed during growth lead to Ga enrichment due to the higher Ga incorporation efficiency at facets than Al [1]. Although this case shows the compositional fluctuation through a single layer, this effect propagates through the epitaxy into the sites responsible for emission. Therefore, it is important to minimize locations for preferential Ga incorporation through controlling the sample topology during growth.

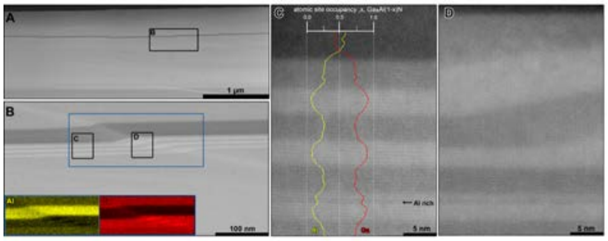

Figure 2: STEM analysis showing non uniformities across various AlGaN epilayers in the active region. (A) low magnification image of the active region. (B) higher magnification image acquired from the black box inset in (A) with EDS mapping performed from the blue box. (C&D) Atomically resolved images from the insets in (B) with a corresponding EDS linescan overlay.

Above the thick AlGaN resides the active region which includes multi-quantum wells (MQWs) responsible for emission, shown in Figure 2A. By looking more closely at the MQWs in Figure 2B, we observe a step running through the layers which alters the thickness and composition as shown from the Al and Ga EDS elemental maps which come from the blue box. Further increasing the magnification at locations C and D show the MQWs away from a step and at a step, respectively. Although the MQW layer thickness is significantly altered at a step, there is also a region in the first QW that is locally Al rich that runs continuously through the epitaxy. Unintentional atomic scale details such as this localized Al rich region can be easily overlooked using other characterization methods alone.

Arsenide Based Epitaxy

Vertical cavity surface emitting lasers (VCSELs) are a critical optoelectronic technology enabling a wide variety of communication and sensing applications. Figure 3A shows an overview image of the active area and the DBR on the n and p sides with the growth direction oriented from right to left. Within this image we can observe roughness in the p-DBR layers while the n-DBRs exhibit less significant roughness, although they still contain smaller scale steps. It is worth noting that the roughness observed in the p-DBRs occurs when switching from Al rich to Ga rich while the Ga rich to Al rich interfaces are much smoother. The observed roughness can be observed more easily in Figure 3B with arrows indicating regions of alloy ordering. Energy dispersive X-ray spectroscopy (EDS) maps are shown to corroborate the roughness is related to composition. Figure 3D shows EDS maps over a similar area across the n-DBRs. Here, we observe no alloy ordering similar to the p-DBRs but we do observe the presence of a growth step in the epitaxy indicated by the red arrows. Similar to the growth step observed at the top of the n-DBRs, we observed steps in the MQWs, as indicated in Figure 3C from the red lines. Finally, we also perform EDS across these MQWs to check for elemental distribution. For this example, the MQW stoichiometry is roughly GaAs while the barriers are $Al_{0.15}Ga_{0.35}As$. The resolution in high resolution EDS line scans is approximately 1 nm.

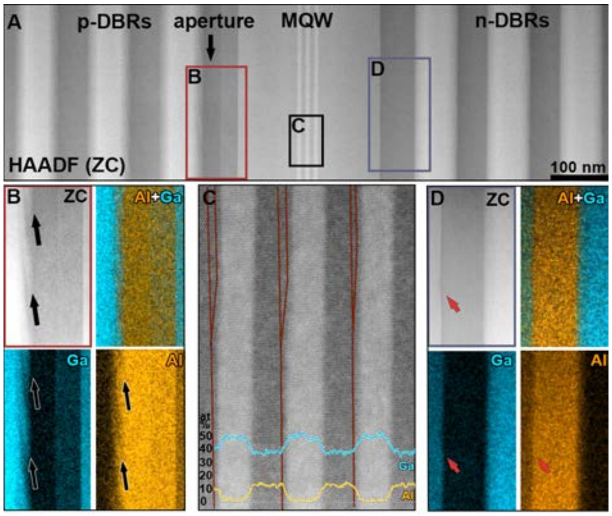

Figure 3: STEM analysis of AlGaAs based VCSEL epitaxy with the growth orientation from right to left. (A) shows the active region with several DBR both n and p sides. (B&D) show the ZC image and EDS maps from the insets in (A) with arrows pointing to locations containing layer roughness. (C) shows the MQWs with lines indicating steps and the EDS linescan overlay.

Conclusion

Each of the highlighted features in this application note is unintentional characteristic of the sample that was grown-in but can prove detrimental to device performance. Further, AC-STEM imaging is essential towards studying these types of fine sample features because bulk techniques lack the necessary spatial resolution. Additionally, this type of analysis can also be performed after device fabrication; however, It is often advisable to evaluate the epitaxial quality prior to device integration. By combining the analysis showcased in this note with other Eurofins EAG services such as SIMS, it is possible to gain a clear understanding of the epitaxy structure and composition with atomic scale resolution and dopant level composition sensitivity. Contact us today to learn how AC-STEM/EDS can help with your next project.

References: *Kataoka, Keita, et al. “Formation mechanism and suppression of Ga-rich streaks at macro-step edges in the growth of AlGaN on an AlN/sapphire-template.” Journal of Crystal Growth 534 (2020): 125475.*