# Isotropic Plasma ALE of Nitride Semiconductors

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*Primary CNF Tools Used: Takachi ALE*



## Abstract:

This study demonstrates the successful atomic layer etching of aluminum nitride and gallium nitride using sequential exposures to $SF_6$ plasma for surface fluorination, followed by $Cl_2/BCl_3$ plasma to remove the altered layer at 100 °C. We investigated the etch rates, the self-limiting behavior of the reactions, and their combined effect, aiming to better understand the underlying etching mechanism. A range of analytical tools was employed, including in-situ spectroscopic ellipsometry, X-ray photoelectron spectroscopy (XPS), and atomic force microscopy (AFM).

## Summary of Research:

Gallium nitride (GaN) and aluminum nitride (AlN), both belonging to the III–V semiconductor group, play a pivotal role in modern electronic and photonic technologies. Their wide bandgaps, strong thermal stability, and intrinsic piezoelectric properties make them particularly suitable for fabricating high electron mobility transistors (HEMTs), which are commonly used in radio-frequency (RF) and power electronics applications[1–3]. Additionally, due to their outstanding optical characteristics, GaN and AlN are also emerging as key materials for photonic integrated circuits and light-emitting diodes (LEDs)[4,5].

As device architectures continue to evolve in complexity and scale, there is a growing demand for more sophisticated processing techniques. One such advancement is the development of enhancement-mode (E-mode) HEMTs, which are especially desirable for applications such as power conversion and industrial power systems[6,7]. The fabrication of efficient and robust E-mode HEMTs often requires the formation of recess gate structures[8,9]. However, traditional dry etching methods have notable limitations, often inducing damage to the surface and the two-dimensional electron gas (2DEG), which negatively impacts device performance[10]. To address these challenges in next-generation devices, atomic layer etching (ALE) has emerged as a promising alternative to conventional etching techniques[11,12].

ALE operates on the principle of dividing the etching process into a series of self-limiting, sequential steps. This separation allows for precise control over the formation and transport of reactive species, enabling improved process uniformity and avoiding the surface damage typically associated with reactive ion etching. The ALE cycle generally comprises two distinct phases: a surface modification step that lowers the material's surface binding energy, followed by a removal step[13,14].

Utilizing SF6 plasma for surface modification and $Cl_2/BCl_3$ plasma for removal, we achieved etch rates of 4.4 Å/cycle and 5.7 Å/cycle for AlN and GaN respectively, which correspond approximately to one unit cell per cycle. Etch rates were monitored with in situ ellipsometry as seen in Figure 1. This approach displayed very controlled results, as well as self-limiting behavior when the duration of the removal step was changed, demonstrated in Figure 2. In order to prove that the ALE recipe obeys the fluorination and ligand exchange mechanism similar to thermal ALE, XPS spectra were utilized at different points of the cycle. During surface modification, a significant Al-F peak emerges, indicating the formation of AlF3. During removal, the peak reduces in intensity, indicating the formation of volatile AlCl3. The spectra are displayed in Figure 3. This ALE approach also achieves surface planarization, leading to a 21% roughness reduction as seen in Figure 4 for AlN.

## References:

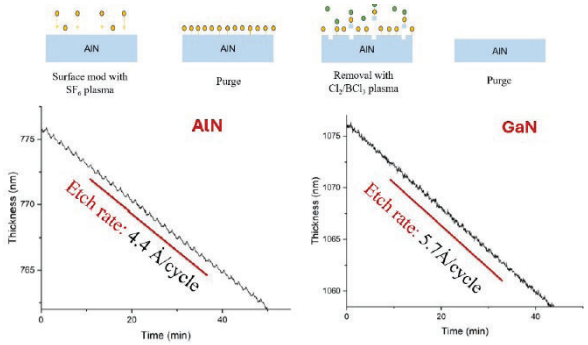


*Figure 1: ALE cycle and etch rates for AlN and GaN*

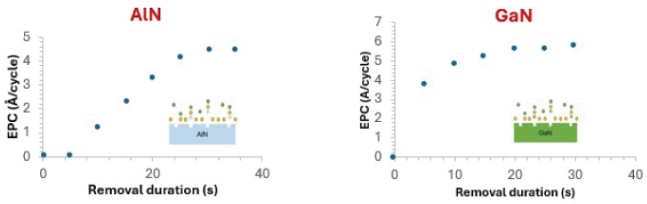


*Figure 2: Removal step saturation curves for AlN and GaN displaying self-limiting behavior*

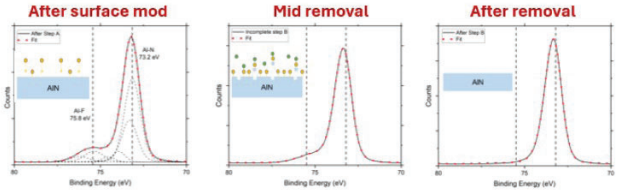


*Figure 3: XPS spectra demonstrating fluorination and ligand exchange mechanism*

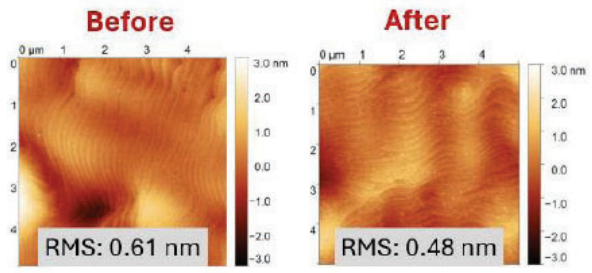


*Figure 4: Surface morphology before and after etching for AlN*


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