# Reflectance-based optical multi-wavelength in-situ metrology for inductively coupled plasma etching of GaN-HFET

The fabrication of GaN-Heterojunction Field Effect Transistors (HFET) requires precise etching control down to about 1 nm. LayTec's TRIton® system enables highly precise endpointing based on reflectance measurements at three well-selected wavelengths. Thus, process control for HFET dry etching reaches a new level with respect to run-to-run precision. TRIton® can also detect etch rate drifts or variabilities in the chamber and thereby provides means to keep process yields at high levels for longer times.

The advent of e-mobility and regenerative energy solutions are driving the demand for efficient and reliable systems for electric energy conversion and processing. GaN as a power electronic material has revolutionized these applications due to its high breakdown voltage, and high electron mobility.

As of today, industrial-scale production of 'normally off' GaN HFETs requires etching with nm precision and typical etch rates within 1-5 nm/s [1].

Such extreme precision comes with a number of challenges: The etch rate can vary when etching a single wafer and within a batch of wafers. For example, process pressure, total impedance of the plasma chamber, concentration of plasma products, reflective properties of the wafer surface can all cause drift in the etch rate, affecting the yield and throughput of the manufacturing process. In addition, the actual thickness of the GaN cap varies from wafer to wafer or within a batch. Hence, time-based etch times become prohibitive for these processes and in-situ process control becomes mandatory for realizing residual film thickness variation within ±1 nm at high yield levels. Accordingly, a correct end point detection (EPD) for the etching process is of paramount importance.

For this Application Note, Dr. R.-S. Unger from Ferdinand-Braun-Institut FBH in Berlin applied LayTec's TRIton® in-situ metrology system for HFET dry etch monitoring. The etching group at FBH demonstrated how it enables robust EPD in the Inductively Coupled Plasma (ICP) etching process of GaN HFET. The remaining AlGaN layer was about 5 nm with an accuracy better than 1.5 nm. Typical ICP etch rates are about 1-10 nm/sec.

## LayTec's TRIton® in-situ metrology system

**Fig. 1** shows TRIton®, LayTec's tool for in-situ monitoring of dry etching processes on semiconductors. It has been integrated on a commercially available ICP etch chamber at FBH. To ensure fully automated EPD, tool-to-tool communication was established between TRIton® and the etcher. Trigger signals can be sent from the EtchNet control software to the etch chamber and vice versa, enabling the plasma to be switched on (etch recipe) and off when the target etch depth is reached (EPD algorithm).

TRIton® measures the reflectance intensity (transient) of three wavelengths at normal incidence over time during etching of the entire GaN HFET etch process. A camera with high-resolution (< 10 µm) allows convenient spot positioning and pattern recognition. In the following it will be shown, how TRIton® allows to develop a scheme for fully automated EPD for GaN HFET etching.

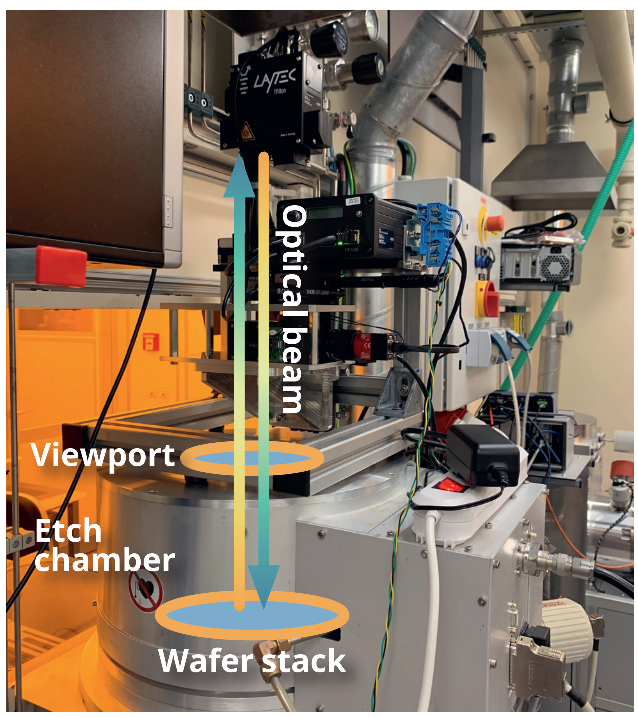


**Fig. 1** Photo and schematical sketch of the TRIton® metrology system installed on a ICP etch chamber at the FBH.

## Wavelength selection

The three wavelengths reveal in real time both the etch depth - based on Fabry-Perot oscillation (FPO) analysis - and the location of the layer interfaces, by analyzing and detecting sudden changes in reflectance slope for suitable wavelengths transients. This makes TRIton® a versatile in-situ metrology system for EPD as it can be customized to match any material system. The wavelengths should be selected according to the optical properties of the material system and related alloys to be etched (here an AlGaN/GaN stack grown by MOCVD) as well as to the specific layer stack.

The wavelength selection is based on the analysis of the refractive index and absorption coefficients of the GaN/AlGaN material system. The near-UV wavelength (405 nm) was chosen because it only shows low absorption and therefore exhibits a higher penetration depth, resulting in the ability to extract the etch rate by analyzing the FPOs. In contrast, the two UV wavelengths (340 nm, 365 nm) show a strong absorption in GaN and are attenuated accordingly. This makes them particularly sensitive for interface detection as slight slope changes can easily be detected. This selection scheme is illustrated in **Fig. 2**.

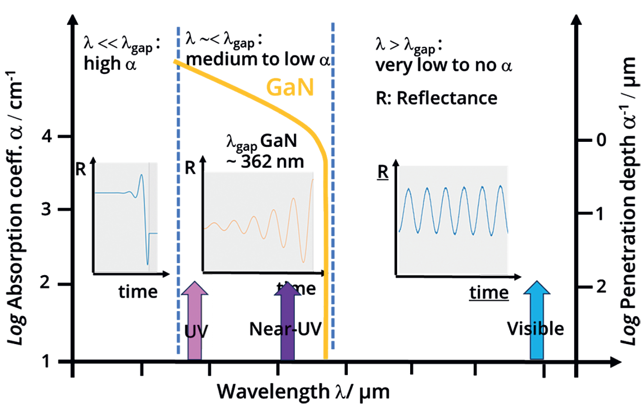


**Fig. 2)** Spectral absorption of GaN. Three wavelengths are selected to enable both etch rate extraction and interface detection.

## Reflectance calibration

The HFET structure consists of a AlN buffer layer grown on a sapphire substrate, then a 1.9 µm-thick nid- and p-GaN layer was grown. Subsequently, a 20 nm AlGaN layer was deposited and finally a 100 nm-thick p-GaN layer was grown. **Fig. 3.** shows the etch transient recorded when the entire structure grown on a sapphire substrate was etched through. The aim is to deduce a direct correlation between the in-situ reflectance intensity and the etch depth for all three wavelengths. Note that this correlation is completely independent of the etch rate and therefore provides an ideal mean for assessing the etch progress at any point in time during the etch process.

From **Fig. 3**, it clearly can be seen that the longest wavelength of 405 nm allows FPOs to be clearly identified even for GaN film thicknesses greater than a few µm.

By analyzing the time-dependent period of the FPOs the etch rate can be deduced during the process. Relying on this approach, the etch transients were used to investigate the influence of the wafer carrier on the etch rate in more detail. In **Fig. 4,** the recorded reflectance signals of an etch-through run with a fused silica carrier **(#2)** are shown. Compared to one with an aluminium/sapphire carrier **(#1, Fig. 3)** the rate for fused silica is much lower (compare number of periods per 100 sec as marked in **Fig. 3 and 4)**. In both cases, clearly visible FPO are obtained at all three wavelengths on the p-GaN and AlGaN barrier. Only the visible (405 nm) FPOs are retained through the entire thickness of the GaN buffer. A fast etch rate of ~ 220 nm/min is recorded for carrier **#1**. Although identical parameters are applied on carrier **#2**, the etch rate is much lower at about 51 nm/min. Obviously, time-based etching is not an option in this case. In contrast, the reflectance transients allow precise control of the etch depth over different carrier materials and different runs.

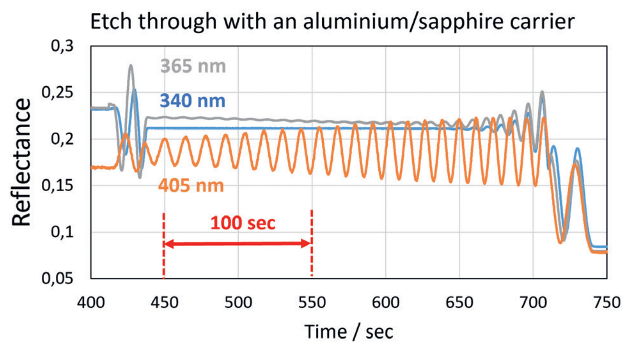


**Fig. 3)** Etch transient of an etch through run recorded by TRIton® during plasma etching of an GaN-HFET on a sapphire carrier. FPO are clearly visible for 405 nm (orange curve) throughout the entire structure, while FPO of the shorter wavelengths 340 nm and 365 nm are strongly damped near thin-film interfaces.

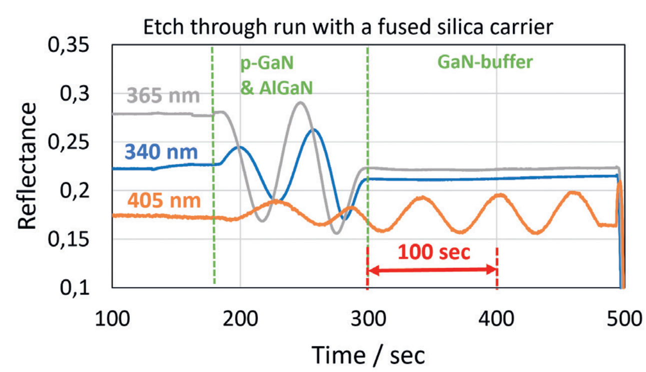


**Fig. 4)** Etch transients recorded during etch through run with a fused silica wafer carrier. Reflectance in the visible at 405 nm exhibits FPO throughout the entire structure, while step changes are observed at shorter wavelengths (340 and 365 nm), enabling the detection of layer interfaces.

## Endpoint detection for GaN HFET dry etching

TRIton® is developed particularly for controlling processes with highest requirements for precision and specifically for EPD applications. In the following, its capability for high-precision endpointing is demonstrated by etching an AlGaN layer with the EPD requirement for a within-layer stop with a remaining AlGaN thickness of 4 nm. Based on a proprietary algorithm and the knowledge gained from the calibration run, the end point was calculated from the 340 nm and 405 nm reflectance signals. Then, several EPD runs were performed on GaN HFET samples. Using the calibration acquired during the etch-through run, both the remaining AlGaN thickness and the etch rate were extracted. Both metrics are shown in **Fig. 5** for a series of seven non-identical runs. These results demonstrate how LayTec's TRIton® EPD algorithm successfully enabled meeting the requirement of a residual AlGaN thickness of about 4 nm with a variation better than 1.5 nm in a reproducible way.

Analysis of residual AlGaN thickness and run-to-run etch rate variability provides a powerful means of identifying process shifts (i.e. statistical process control). This allows throughput to be maximized by avoiding yield-losses and by using process time most efficiently, while still meeting the target depth of the recess specifications.

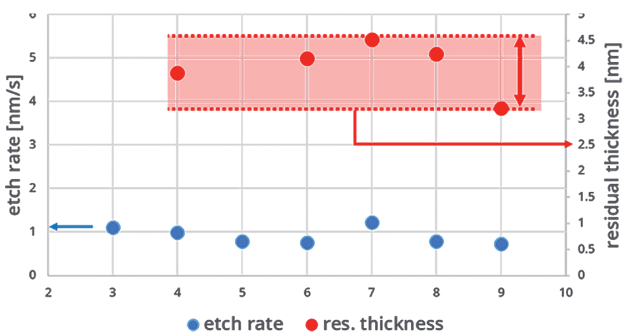


**Fig. 5)** Process variation as observed by TRIton® over a series of identical runs. The etch run number is given on the x-axis. For each run, the etch rate is extracted (blue). The remaining AlGaN thickness (red) has been calculated based on values of reflectance at 405 nm at EPD time or etch termination time, if the run was stopped based on TRIton® endpointing.

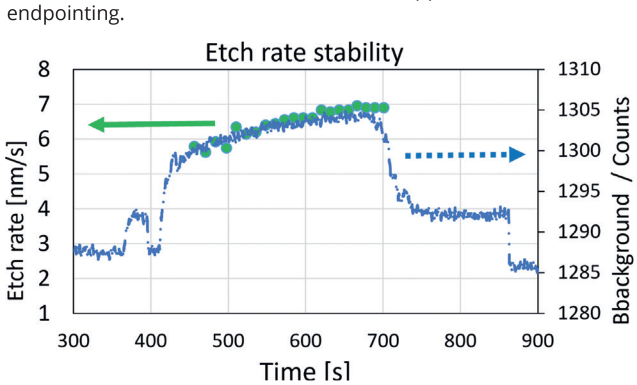


**Fig. 6)** In-situ plasma background signal from TRIton® data. The green points show real-time etch rate (left Y-axis) versus time as extracted from the lengths of consecutive FPO's at 405 nm. The blue data points show the background in counts over time of the signal at 405 nm.

## System health monitoring

TRIton® can be used to perform in-situ diagnostic and statistical system health monitoring supporting preventive maintenance schemes by monitoring the etch rate in real time for every single run. Besides the reflectance, TRIton® also measures simultaneously the plasma emission as background signal which correlates also to the etch rate as will be shown in the following. Based on the data shown in Fig. 3, the etch rate was determined (Fig. 6) by simulating and fitting the change in periodicity of the FPO's at 405 nm and found to increase to 6 to 7 nm/s in the GaN buffer. This was attributed to a chamber warm-up effect, as plasma generates heat and as processes are run, the chamber warms up and reaches a steady temperature. From **Fig. 6** it can be seen that the increase of the plasma background signal is directly correlated to the etch rate.

In conclusion, TRIton® has enabled FBH not only to overcome the limitations caused by short-term process drifts, but also to document long-term changes in the plasma chamber, i.e. chamber conditioning.

Multiple etch runs were performed using the same etch recipe and same wafer (i.e. several pieces of the same wafer) in two different etcher conditions, while TRIton® was always used under the same operating conditions. In a conditioning run, a dummy GaN sample is etched to remove possible contaminations of the chamber and passivate residuals from previous runs with the actual etching material. Conditioning is done once, before starting the actual measurement campaign.

The conditioning of the chamber has a positive impact on the stability of the plasma etch process as the etch rate variability over the series of runs shows a smaller variation and standard deviation, as can be seen in the distribution of the blue data points related to a 'conditioned chamber' in **Fig. 7**. For the non-conditioned chamber (red data points), the variability of the etch rate is larger. Again, these statistical deviation would have hardly been measurable without TRIton®. Thus, it directly contributes to reducing unwanted deviation, meeting requirements and thereby increasing yield and productivity. It can also help identifying early issues and reduce disruption in the GaN device manufacturing process.

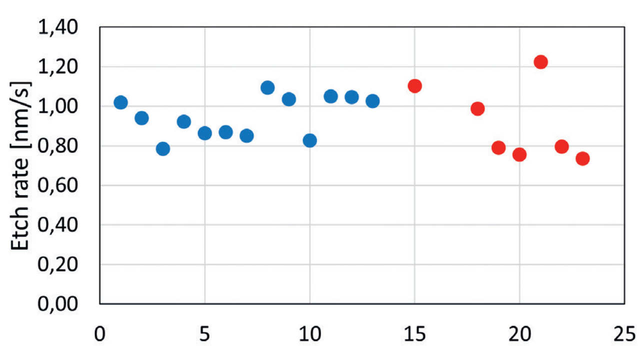


**Fig. 7)** EPD runs done with different pieces diced from the same wafer. The etch rate is extracted from the FPO period at 405 nm. TRIton® uncovered two regimes related to different chamber conditions (blue and red dots). This illustrates how TRIton® enables etch metrology that monitors the effects of etch chamber conditioning.

In summary, LayTec's TRIton® metrology system for in-situ dry etch monitoring based on three wavelengths enables the control of the remaining thickness in recess formation for GaN HFET with an accuracy better than 1.5 nm for a remaining thickness of, e.g. ~ 4 nm during ICP. At the same time the etch rate was also determined in-situ as ~6 nm/sec. Furthermore, careful wavelength selection allows simultaneous detection of layer interfaces. Finally, it was also demonstrated how TRIton® can be used for system health monitoring by keeping track of run-to-run variations and drifts in etch rate.

## The "Connected Metrology" approach

The LayTec Connected Metrology® ecosystem enables improved process control characterizing complex layer stacks along the manufacturing chain. In a typical frontend production line, wafers are typically measured multiple times. Using LayTec systems in all of these process steps bears the potential to forward and share the respective analysis data from each step to the subsequent ones, thereby unfolding the full potential of the Connected Metrology® approach. During epitaxy, EpiCurve® TT can determine the thicknesses and composition of many individual layers as well as their in-situ. In the ex-situ wafer mapping with EpiX® C2C by white light reflectance and photoluminescence, full 2D wafer maps are acquired characterizing the 2D uniformity of critical layer thickness, layer composition and other sample properties. During sub-sequent plasma-etching processes, the thickness monitoring and endpoint detection is again performed in-situ by LayTec's TRIton®. As the wafer is advancing through the frontend production line, the amount of information on the particular wafer increases and is combined for improved analysis in downstream processes. By connecting in-situ and ex-situ metrology, we can determine the critical layer parameters of increasingly complex layer structures at die-level.

Connected
Metrology®

## About us

LayTec, founded 1999 in Berlin, is a major provider of in-situ and in-line optical metrology for thin-film processes.

These metrology tools are used in a broad range of thin-film applications such as LED & laser production, power devices and transistors, thin-film photovoltaics, oxide and organic deposition as well as other large area deposition processes. LayTec's integrated metrology provides access to all key thin-film parameters in real-time – either in-situ, during the deposition process, or in-line. Also, in-situ metrology tools for dry etching have been added expanding LayTec's portfolio along the production chain.

Beyond these integrated methods, LayTec also offers mapping solutions which ideally complement in-situ measurements by providing uniformity analysis of the deposited layers. The implementation of LayTec metrology systems in production processes significantly shortens development cycles and enables an efficient quality control that helps to considerably reduce production and development costs.