Robust and precise in-situ monitoring of plasma etching for GaAs laser diodes

In this application note, LayTec's TRIton® in-situ metrology system, based on reflectometry with three wavelengths, is applied for monitoring the plasma-etching of GaAs structures. Simultaneously, it enables real time analysis of etch rate and interface detection. Whilst interference fringes are used for high precision etch-rate deduction, short timescale changes in reflectance slope allows for interface detection. Here, various dry etch processes, such as reactive ion etching (RIE) and inductively coupled plasma (ICP) etching are monitored and analyzed by TRIton® and its related Software EtchNet, respectively.

In the fabrication of high-power laser diodes, particularly in the formation of ridge waveguides (RWGs), precise etch depth control is essential. For AlGaAs/GaAs lasers, the process involves two key etch steps: defining the RWG and etching deeper to form highly reflective distributed bragg reflectors (DBRs). Commercially available single-wavelength systems for etch-monitoring often struggle to simultaneously excel in both, etch depth deduction and interface detection.

LayTec's TRIton® system combines three wavelengths at 488 nm, 633 nm, and 950 nm, offering improved and uncompromised depth resolution and interface detection, even in thick layers by employing separate wavelengths for separate tasks and thus leveraging the advantages of both short and long wavelengths.

Etch depth deduction

The etch depth is determined based on the analysis of Fabry-Perot Oscillations (FPOs) arising from interferences within a layer stack due to the thicknesses of each layer and its optical properties for a particular wavelength. Whilst the refractive index n determines the number of oscillations within a given layer for a particular wavelengths, the extinction coefficient k characterizes to which extent the intensity is attenuated by absorption, e.g. light of 950 nm yields an oscillation length of ~ 150 nm per FPO with only negligible absorption in GaAs/AlGaAs. In contrast, shorter wavelengths of e.g. 633 nm yield an FPO period of ~100nm. Due to the smaller period the thickness can be determined with higher resolution. At the same time absorption is much stronger for 633nm limiting its capability to determine layer thickness to thicknesses <4 µm.

So, with just one wavelength compromises on the analysis quality, accuracy and precision are unavoidable. In this application note, we show the benefits of applying LayTec's TRIton® **(Fig. 1)** for in-situ monitoring based on a combination of three wavelengths for plasma etching of AlGaAs/GaAs laser structures. The short wavelength of 488 nm provides high depth resolution and precise interface assignment, while a long wavelength of 950 nm allows the etch rate to be monitored throughout the structure.

Fig. 1 LayTec's TRIton® in-situ metrology system for plasma etch monitoring installed on the top of an ICP chamber. In the lower part, TRIton's® optional camera for simplified measurement spot positioning can be seen.

Why three wavelengths?

The choice of wavelength is crucial for the high precision of LayTec's TRIton®. Fig. 2 briefly sketches the scientific background. It shows on the left Y-axis the absorption per unit length versus wavelength on the X-axis for GaAs and 50% AlGaAs thin film. The right Y-axis shows the penetration depth, which is the reciprocal of the absorption depth. The ideal combination of three wavelengths (visible, near infrared and infrared) is derived from the refractive index and absorption coefficients of the GaAs/Al0.5Ga0.5As material system. This results in the accuracy of LayTec's TRIton® that can't be achieved with a single wavelength.

Wavelengths near or above the GaAs bandgap have little or no absorption and therefore a high penetration depth. That allows the etch rate to be extracted using FPOs at 950 nm, where the reflection is characterized by a constant amplitude of its FPO **(right inset, Fig. 2)**.

A wavelength of 633 nm below the GaAs band gap shows a non-negligible absorption. The absorption remains low and several FPOs remain visible. This can be used to extract the etch rate and to detect an interface when the FPO is suddenly attenuated and disappears (reflection simulation, middle inset in Fig. 2). Reducing the wavelength even further below the bandgap shows high absorption resulting in strong FPO attenuation and reflectance contrast or step change in reflectance near an interface, allowing real-time detection of interfaces, e.g. AlGaAs/GaAs **(left inset in Fig. 2)**

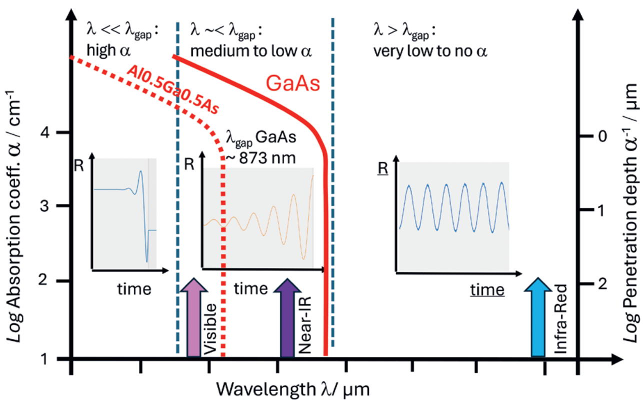

Fig. 2) Absorption spectrum and penetration depth versus wavelength of thin films based on GaAs and AlGaAs used to form the DH laser for high power applications

Integration of LayTec's in-situ metrology system

Fig. 1 shows LayTec's TRIton® metrology system mounted on a typical ICP etcher at the Ferdinand-Braun-Institut (FBH) in Berlin. The field of view of a wafer being etched can be scanned with an xy-motorized stage across the view port. TRIton® offers an optional camera for imaging of the pattern for positioning the light spot on the desired part of the pattern. The in-situ metrology tool is equipped with three LEDs (488 nm, 633 nm, 950 nm) and LayTec's proprietary EtchNet software **(Fig. 3)**. Direct communication between the etch chamber and the TRIton® is implemented. This allows the recipe sequence to be started and stopped when process completion is detected.

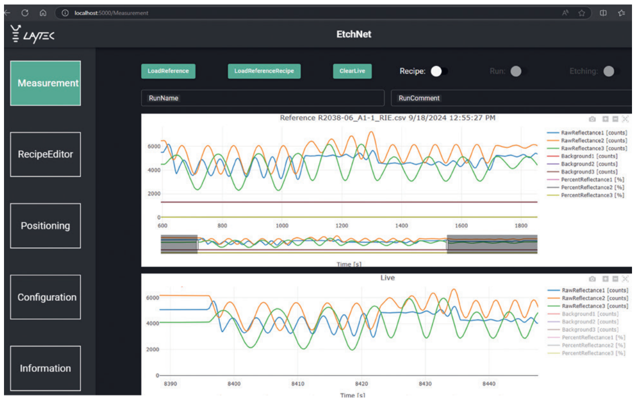

Fig. 3) Upper graph shows recorded transients at three wavelengths of a vertical cavity based on GaAs/AlGaAs DBRs during an etch through run. Lower graph shows live data during etch process.

Monitoring of GRINSCH structures

In the following, TRItons® capabilities are demonstrated on GaAs structures being etched by RIE and ICP. Conventional double heterostructure (DH) GaAs laser structures usually based on a graded index separate confinement heterostructure (GRINSCH), i.e. a layer with a gradient in Al content. For this purpose, specific stack structures have been grown by MOVPE on 3" GaAs wafers. The stack structure is listed in **Tab. 1** containing three layers of different Al contents: a lower and a higher Al content to form relatively low and high index contrasts between each layer. As they are found at the boundaries of a GRINSCH structure. GaAs layers were grown acting as substrate layers. It needs to be noted that the use of epitaxial growth data acquired with the LayTec in-situ epitaxy monitoring system EpiCurve® TT offers a significant advantage within LayTec's Connected Metrology® ecosystem, also for interpreting etch data as it provides accurate knowledge about the layer thicknesses.

Layer #	Targeted structure			x	d (nm) target	Cumul. Sum d (nm)
1	cap	GaAs	GaAs		40	40
2	AlGaAs 85	Al[0.85]Ga[0.15]As	Al[x]Ga[1-x]As	0,85	500	540
3	spacer 2	GaAs	GaAs		300	840
4	AlGaAs 55	Al[0.55]Ga[0.45]As	Al[x]Ga[1-x]As	0,55	500	1340
5	spacer 1	GaAs	GaAs		200	1540
6	AlGaAs 25	Al[0.25]Ga[0.75]As	Al[x]Ga[1-x]As	0,25	500	2040
7	buffer	GaAs	GaAs		200	2240

Tab. 1) Typical stack of ternary alloys. These alloys define the upper and lower boundaries of the graded index separate confinement heterostructure of a laser. The metrology system allows to extract optical thin film properties, refractive index and absorption coefficient of each layer.

In-situ monitoring of various dry etch processes

At the Ferdinand-Braun-Institut (FBH) LayTec's TRIton® has been used for the analysis of GaAs/AlGaAs the beforementioned layer stacks. Therefore, etch transients (i.e. reflectance intensity at a given wavelength vs. process time) were obtained during both reactive ion etching (RIE) (chlorine gas and Ar; Al carrier indirect) and inductively coupled plasma (ICP) etching, occurring at substantially different etch rates on pieces diced from the 3" GaAs wafers described in Tab. 1. On those, the transients were gathered on dedicated test pads of 300 µm x 300 µm and are compared in the following.

The transients measured for all three wavelengths during both processes are depicted in **Fig. 4a** (RIE) and b (ICP). From these results, it becomes clear that despite the significantly different etching rates, i.e. ~ 80 nm/min for RIE and ~ 1200 nm/min for ICP, very almost the same reflectance patterns can be observed in the etching process, differing only by minute differences in the intensity of single fringes. This clearly demonstrates TRIton's® capability of resolving the precise stack layer structure indenpendently from the etching rate und thereby, its suitability for a wide range of etch processes

At longer wavelengths, due to the very low absorption at 950 nm, FPOs are clearly visible throughout the stack **(blue curves in Fig. 4a and b)**, with the number of FPOs being exactly the same for RIE and ICP. At the 'medium' wavelength of 633 nm, the amplitude of the FPO is reduced (due to absorption), while a step change is visible much clearer than in the 950 nm transient at each AlGaAs/GaAs interface. These step changes are ideally suited for endpointing particularly, if they exhibit a sudden kink-like change of slope.

At the shorter wavelength, strong damping of FPO and distinct reflectance step changes are observed at each interface. The main difference between the two processes is the duration: ~1700 seconds for RIE and ~110 seconds for ICP. Nevertheless, real-time extraction of etch rates and interface detection is still possible with ICP. It can also be seen that, generally, the intensity of the short wavelength transients is significantly reduced for ICP indicating a much rougher surface caused by the much faster etching.

Both processes clearly identify individual layers through sudden reflectance changes at 488 nm, with greater step changes when the index contrast between thin films is high. Reflectance contrast is most pronounced at GaAs/$Al_{0.85}Ga_{0.15}As$ interfaces and decreases as the Al content drops from 85% to 25% at interfaces 5/6 and 6/7.

Besides the index contrast, the suitability of a transient for interface identification also depends on the phase of the specific FPO of the transient. Also, here the simultaneous use of three wavelengths is a strong advantage.

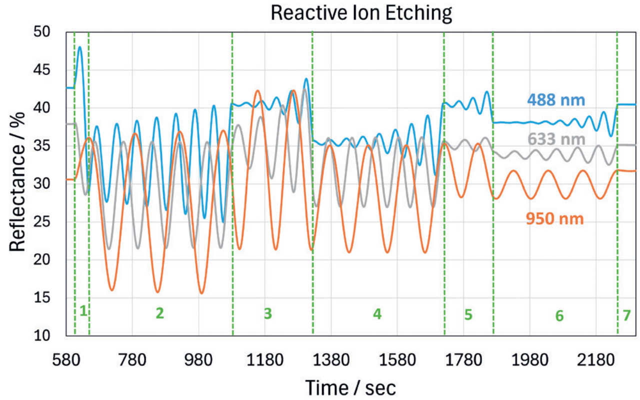

Fig. 4a) Etch transient recorded during the etch through of the layer stack from Tab. 1 using an RIE process. The reflectance changes at 488 nm indicates the presence of layer interfaces. Each of the layers distinguishable. Typical average etch rate is about 80 nm/min over the ~ 1700 s etch process duration.

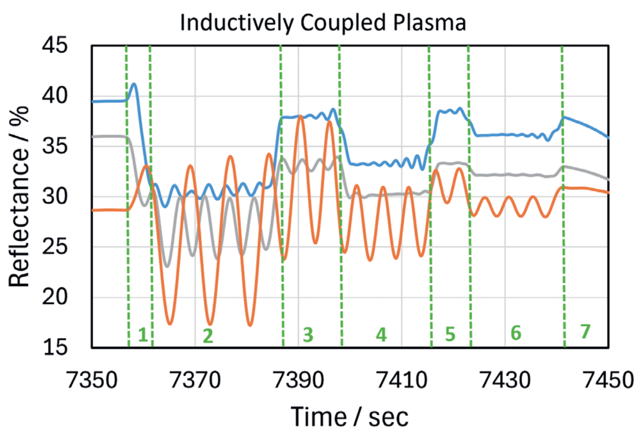

Fig. 4b) Etch transient from an ICP etching process. The same pattern as for RIE process (Tab. 1 and Fig. 4a) is seen, except that it occurs on a shorter time scale due to the much higher etch rate. Sudden steps in the reflectance at 488 nm enable to identify interfaces and distinguishing the layers. Typical etch rate measured with TRIton is about 1200 nm/min over the ~ 120 s etch process.

In conclusion, LayTec's TRIton® system, using three wavelengths, enables real-time extraction of etch rates and interface assignment in AlGaAs/GaAs structures for high-power GaAs laser diodes. The consistent patterns observed in both RIE and ICP processes highlight TRIton's® applicability and suitability across a wide range of etch conditions, making it ideal for statistical process control both in academic and industrial applications.

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.

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.

LayTec AG Seesener Str. 10-13 | 10709 Berlin, Germany | Tel.: +49 (0)30 89 00 55-0 | Fax: +49 (0)30 89 00 55-180 | Email: info@laytec.de | Web: laytec.de