Plasma-Etch End-Pointing in InP-Based Laser Device Structures

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We developed real-time reflectance-based layer thickness measurements during plasma-etching of InP-based laser device structures with precision in the ±1nm range. We demonstrate that this real-time thickness precision enables high-precision end-pointing in ternary and quaternary layers on InP during plasma-etching for laser device manufacturing. The results have been achieved by forwarding *in-situ* thickness data measured during MOCVD to the subsequent plasma-etching process tool in combination with newly developed real-time analysis algorithms for *in-situ* reflectance data measured during etching on 200µmx200µm test pad in the mask.

INTRODUCTION

The process yield for solid state laser device production depends on the accuracy of both the epitaxy and etching processes. For industrial processes, the epitaxy technique of choice is mainly Metal Organic Chemical Vapor Deposition (MOCVD/MOVPE), where state of the art, real-time measurement of growth rates and layer thicknesses with precision in the ±1nm range are routinely possible, enabling the achievement of the required accuracy.

These results are obtained using both information acquired during MOCVD processes like:

- exact interface timings
- precise wafer temperature
- precise absolute reflectance scale

and high accuracy temperature-dependent complex refractive index N(T) based on *in-situ/ex-situ* XRD referencing [1]. $N(T) = n(T)+i*k(T)$, with $n(T)$ being the refractive index and $k(T)$ being the extinction coefficient, both depending on temperature T.

The knowledge of these parameters is far less accurate during plasma-etch processes, thereby limiting the possible end-pointing precision typically to ±10nm. In this paper we present a strategy to overcome such limitations and bring the overall device production accuracy within the ±1nm range.

MOVPE PRECISION

Fig. 1a shows reflectance data measured *in-situ* during growth of a laser stack on InP for emission at 1550nm (blue: 633nm and grey: 950nm), in an Aixtron 6x2" showerhead MOCVD system equipped with a LayTec EpiTT *in-situ* metrology tool. The stack is a typical laser vertical PIN structure, with a thick p-type Zn doped InP/GaInAs upper cladding, a central active zone based on strain compensated AlGaInAs multiple quantum wells and a Si doped AlInAs/InP lower n-type cladding [2]. The high-precision

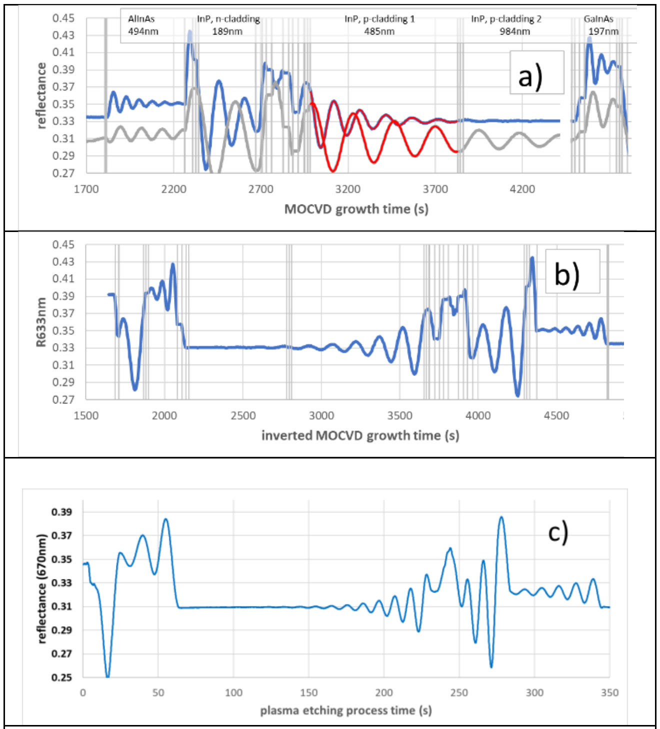

Fig. 1. Reflectance *in-situ* data of a laser structure on InP: a) as measured in MOCVD (some purge segments removed) for 2 wavelengths: 633nm (blue line) and 950nm (gray line); the red lines exemplify the high-precision measurement of the thickness of p-cladding-1 layer;
b) the same 633nm MOCVD reflectance data as in a) but with time scale inverted;
c) *in-situ* reflectance data (670nm) during plasma-etch process. The structure was etched through for calibration purposes.
There is a clear similarity between plasma etch *in-situ* data at R670nm (c) and R633nm MOCVD data with inverted time scale (b).

real-time *in-situ* thickness measurement is exemplified for the InP/p-cladding 1 layer, where the red fitting lines (using a virtual-interface algorithm [3]) yield a thickness of 485±1nm. The respective thicknesses measured for some other layers are also given. This performance is achieved by applying high-accuracy complex refractive index N(T) (based on *in-situ/ex-situ* XRD referencing [1]) and utilizes the following specific advantages of MOCVD: (a) all interfaces are known as they correlate with the gas switching sequencies of the precursor gases (vertical lines in Fig. 1a); (b) the wafer temperature is precisely known by emissivity-corrected pyrometry (ecp) and (c) the absolute reflectance scale can always be auto-calibrated *in-situ* at the start of process where the bare, epi-ready substrate is loaded to the MOCVD reactor. Fig. 1b repeats the 633nm MOCVD *in-situ* reflectance data with inverted time scale. Fig. 1c displays the *in-situ* reflectance data (at 670nm) measured during plasma etching ($Cl_2/H_2/Ar$ process in an Oxford PlasmaLab 100 ICP-RIE 180 equipped with a LayTec TRIton *in-situ* metrology tool). Comparison of Fig. 1b with Fig. 1c shows a clear similarity between the Fabry-Perot oscillation signatures measured in MOCVD (once its time scale is inverted) and during plasma etching. In MOCVD (Fig. 1a) the FPO signatures are developing forward (from substrate to top-layer) while they are running "backward" during etching from top-layer to substrate.

Fig. 2a shows TRIton, LayTec's *in-situ* metrology tool for monitoring of plasma etch processes, mounted on an Oxford PlasmaLab 100 ICP-RIE 180 etching chamber. A screenshot of its operating software, EtchNet, is shown in Fig. 2b.

Given this clear similarity of the *in-situ* reflectance traces for both MOCVD and plasma etching, the question arises: why is it a challenge to measure real-time thicknesses during plasma etching, with a precision comparable to that achieved in MOCVD processes (±1nm)? In table 1 we illustrate those reasons, listing the specific challenges faced when measuring *in-situ* reflectance during plasma etching.

TABLE 1: PRECISION COMPARISON BETWEEN MOCVD AND PLASMA ETCHING

Parameter	**MOCVD**	**Plasma etching**
T_{wafer}	±1K by ecp	unknown, ~±30K
N(T): complex refractive index of layer	±0.001 by XRD referencing [1]	unknown, N(T)s between RT and T_{MOCVD} values
absolute reflectance scale	±0.002 by auto-calibration to bare substrate prior to epi	±0.02 coarse calibration in separate reference run on bare substrate
internal interfaces	assigned to *in-situ* reflectance based on precursor switching	usually appear as slope change in reflectance transient

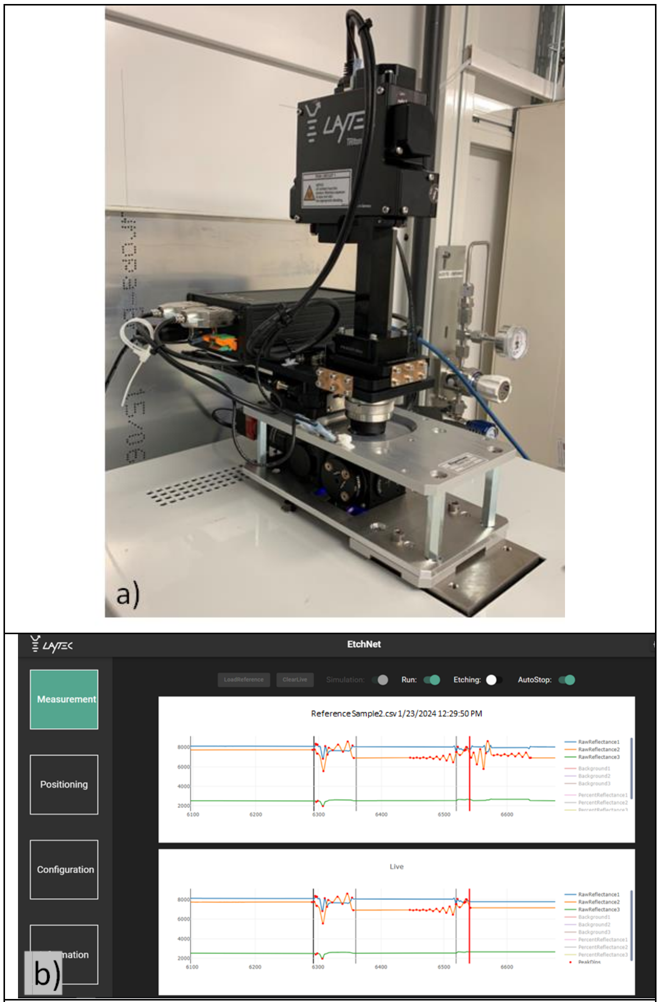

Fig. 2. LayTec's TRIton *in-situ* metrology tool for plasma etch processes: a) view of the system mounted on a Oxford PlasmaLab 100 ICP-RIE 180 b) screenshot of EtchNet, TRIton's user interface.

IMPROVING END-POINTING PRECISION DURING ETCHING

In the following we illustrate how to eliminate the 4 show-stoppers (see Tab. 1) to measure highly precise thickness in real-time, during plasma-etching process.

We start with the assignment of "interface-times" to the measured reflectance data during plasma etching, i.e., of points in time where the etch-front passes through internal interfaces. We achieved this by adding a 405nm reflectance wavelength to the plasma-etch *in-situ* reflectance metrology. At 405nm the light penetration depth into the typical ternary and quaternary materials on InP is very small (~40nm) making the reflectance measurement very interface sensitive. Fig. 3 gives respective results for a test structure consisting of a GaInAs layer sandwiched between two InP layers. We zoomed into the data of the second interface (GaInAs/InP). The thickness of the InP bottom layer is significantly thicker

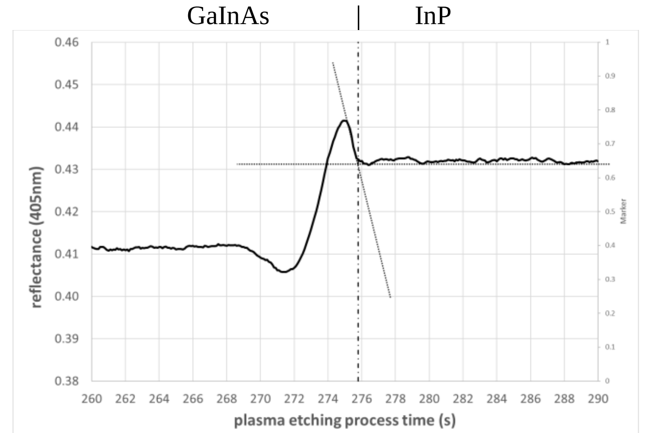

Fig. 3. Short wavelength reflectance (405nm) *in-situ* data taken while etching through a GaInAs/InP interface.

than the 405nm penetration depth of light into InP, so a clear interface signature arises in the reflectance trace measured at 405nm when the etch-front approaches this interface: a highly damped FPO (during the final nanometers of GaInAs etching) abruptly changes into the constant reflectance level of the thick (>40nm) InP layer below. A simple crossing-point of two linear fits is used in Fig. 3 to assign the interface position. However, even more precise assignments are possible when the optical properties of GaInAs and InP at this etching temperature are considered or a plasma-emission response to the change of materials is used in addition.

The accurate measurement of N(T) data for InP and its related lattice matched ternary and quaternary alloys in the 20°C to 250°C wafer temperature range is part of our intellectual properties and cannot be disclosed here in detail. Basically, we replicated our approach to the accurate determination of the optical constants in the MOCVD temperature range (550°C to 720°C) [1] and applied it to a few, well selected calibration structures under plasma etching conditions. Once the refractive index database N(T) is established for typical process temperatures during plasma-etching, the two remaining obstacles for high-precision real-time thickness measurements for optical end-pointing during plasma-etching can be tackled, namely: unknown wafer temperatures (necessary for performing real-time FPO-fits with the correct N(T) from the database) and the coarse absolute calibration of the reflectance scales. Fig. 4 gives an example how this can be achieved.

Usually, typical laser structures on InP include a relatively thick layers at the top of the stack: cladding layers, spacers or contact layers. Since these layers must be etched-through prior to end-pointing, we can use them to measure both the wafer temperature during etching and the reflectance absolute scaling correction in real-time prior to end-pointing. To reach this aim, a precise knowledge of these layers' thicknesses is essential. Therefore, we forward the highly precise MOCVD *in-situ* thicknesses results to the plasma-etch *in-situ* tool. Based on this, the algorithm for measuring the wafer temperature and the reflectance scaling correction is rather simple and straightforward. First, the positions of the two interfaces sandwiching the selected layer are determined from the 405nm reflectance interface signatures (as shown above in Fig. 3). Second, the related etch rate is calculated from the etching time between these two interfaces and the layer thickness known from MOCVD. Third, a virtual interface (VI) fit is performed to the measured 670nm reflectance signature with only two free fitting parameters: the wafer temperature and a reflectance scaling correction parameter. For illustrating the method, in Fig. 4 the dashed line was calculated with a correctly fixed etch-rate, but with a slightly off wafer temperature (fixed to 195°C) and with the reflectance scaling correction switched off (set to 1.0). Clearly one can see that the period time of FPOs for these start parameters of the subsequent VI fit is shorter than measured and that there is an offset in the reflectance trace. After the virtual interface-fit, however, a perfect agreement results between calculated and measured 670nm reflectance – yielding a wafer temperature during this etching process of 193°C and a reflectance scaling correction of 1.011.

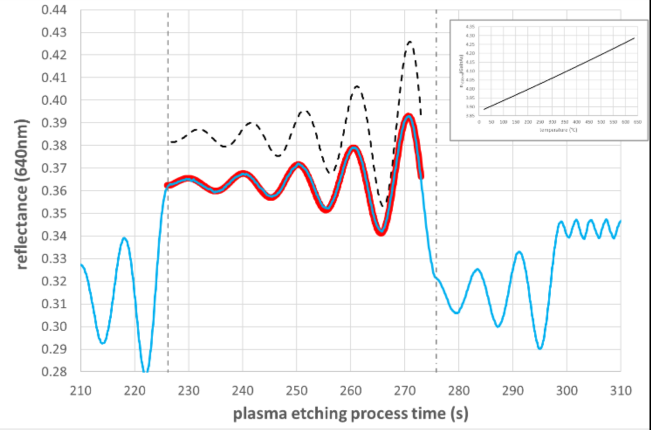

Fig. 4. Determination of wafer temperature and reflectance scaling correction by applying a virtual-interface fit (red line) to the measured 670nm *in-situ* reflectance (blue line) during etching through a InP/GaInAs/InP structure. As a reference, the VI fit calculated without reflectance correction at a slightly off wafer temperature (dashed line) shows an offset of the reflectance trace and a FPOs period time shorter than measured. The insert gives the change of the GaInAs refractive index n with temperature.

In Fig. 5 we present an example of optical end-pointing based on the algorithms described above. Again, the 1520nm laser structure of Fig. 1 was used. It should be noted that the best strategy for precise plasma etch end-pointing always depends on the specific stack of layers in the InP-based laser structure. What we described so far are some new building-blocks from our toolbox of algorithms for high-precision optical end-pointing in plasma-etch processes. This toolbox of algorithms is ongoingly expanding. In [4] we started with Look-Up-Table algorithms for optical end-pointing in Atomic Layer Etching (ALE) of advanced GaN/Si HEMT structures. Here we focus on algorithms for optical end-pointing during

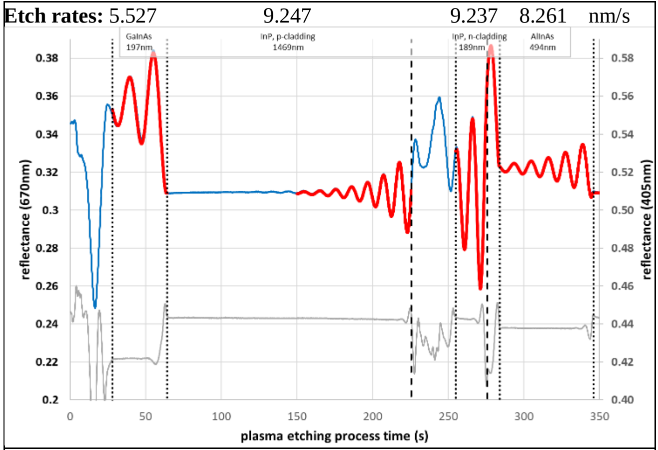

Fig. 5. End-pointing in a laser structure: R670nm (blue line), R405nm (gray line) as measured during plasma etching and fitted reflectance (red lines). The vertical lines are internal interfaces that can be precisely assigned by real-time data analysis during etching.

plasma etching of laser structures on InP. In Fig. 5 first the best fit to the GaInAs contact layer (197nm, see Fig. 1a) at the top of layer stack was performed. This determines the wafer temperature during this etching-process (192°C) and corrects the reflectance scaling (0.993). Once the temperature T_{wafer} during this specific etch-run now known, the correct $N(T_{wafer})$ for all materials in the laser stack can be picked from the N(T) database. In conjunction with the layer thicknesses known from MOCVD (see Fig. 1a) the etch-rates of all thick layers can be precisely determined (red lines = virtual interface fitting curves). The times where the etch-front is passing through several interfaces (with thick layers below) can be derived from the R405nm signatures (vertical dotted lines). Two more interfaces can be assigned based on the etch rate fits to R670nm (vertical dashed lines). Hence, a wide range of end-points in a reasonable distance after such interfaces can be assigned and triggered to the control system of the plasma-etch tool. Due to the precise, real-time corrected reflectance scale even Look-Up-Table algorithms [4] could be applied in the active layer zone (MQWs). Of course, certain specifics of the plasma etching tool (such as characteristic delay-times between etch-tool electronics acquiring the “End” command from the metrology and the actual process ending after the plasma is switched off) always also must be considered.

CONCLUSIONS

In summary, we presented how to implement highly precise *in-situ* reflectance end-pointing during plasma-etching of InP-based laser structures. A precision of ±1nm can be achieved with the following combination of methods:

- precise measurement of layer thicknesses in the InP based layer stack by *in-situ* reflectance, during the MOCVD growth process of the laser structure,
- forward the *in-situ* MOCVD results to the *in-situ* reflectance tool monitoring the subsequent plasma-etch process to significantly enhance the precision of etch-rate fitting,
- measure the wafer temperature during the plasma-etch process by *in-situ* data analysis of thick layers at the top of the laser's layer structure,
- precise measurement of etch rates in real-time by FPO analysis of *in-situ* reflectance at 670nm,
- analysis of the 405nm *in-situ* reflectance trace to determine when the etch-front passes through specific interfaces (the timing precision is enhanced by the small penetration depth of the light).

For routine end-pointing of industrial InP based laser plasma-etching, these algorithms have to be wisely combined in an etch monitoring recipe that runs in parallel and fully synchronized to the plasma-etch process and delivers the correct trigger signals for reproducibly ending the etch process at the intended position within the laser's layer stack.

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ACRONYMS

ecp: emissivity-corrected pyrometry
ICP-RIE: Inductively Coupled Plasma – Reactive Ion Etching
FPO: Fabry-Perot Oscillation
HEMT: High Electron Mobility Transistor
MOCVD: Metal-Organic Chemical Vapor Deposition
MOVPE: Metal-Organic Vapor-Phase Epitaxy
MQW: Multiple Quantum Well
PIN: P-doped – Intrinsic – N-doped
VI: Virtual Interface
XRD: X-Ray Diffraction